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Assessment of Bucharest Metro Expansion and Its Correlation with the Territorial System

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Abstract: The objective of this paper is to determine how the Bucharest metro network has developed from a topological and functional perspective. The research methodology consisted of conducting a topological analysis of the graph representing the metro network, along with a functional analysis. The topological analysis was carried out at two different moments in time and aimed to determine the connectivity indices of the graph associated with the network. The results showed a decrease in connectivity indices, indicating that the network expanded by extending its structure rather than increasing the number of connections between nodes. The functional analysis consisted in determining nodal accessibility using two models: the generalized nodal accessibility model and the Shimmel matrix and vector model. The results of this analysis led to the establishment of a hierarchy of the network's nodes. The functional analysis also included the evaluation of accessibility for the zones into which the city was divided. Accessibility was determined using an original model based on the number of metro stations (poles) that can be reached within a certain time interval. The functional analyses, as conducted, aimed to assess the evolution of various network parameters and of accessibility. The accessibility of the metro network was correlated with the population density in the analyzed zones, showing that in many cases, the development of the network did not align with the density of the served areas, which may lead to inefficiencies in metro transportation. The discussions and conclusions focused on the research results and provided directions for future development of the network, aiming to increase the use of metro transportation.

Keywords: traffic congestion; metro network; topological analyses; functional analyses; nodal and spatial accessibility



Academic Editor: Bindong Sun

Received: 3 March 2025

Revised: 16 April 2025

Accepted: 21 April 2025

Published: 27 April 2025

Citation: Dragu, V.; Oprea, F.C.; Roman, E.A. Assessment of Bucharest Metro Expansion and Its Correlation with the Territorial System. *Land* **2025**, *14*, 946. <https://doi.org/10.3390/land14050946>

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1. Introduction

The continuous worsening of traffic congestion in the city of Bucharest has led us to undertake this study, in which we conduct both a structural and functional analysis of the metro network to assess whether it is adequately prepared to meet the transportation demand arising from the social environment, as well as the level of accessibility it provides to residents. At present, travel times are steadily increasing due to traffic congestion, largely because many journeys are made using private vehicles. As a result, Bucharest has risen to the top of the European traffic congestion rankings [1].

In 2024, TomTom, a company specializing in traffic systems and mobility analysis, assessed congestion in 500 cities across 62 countries, including 254 in Europe. Bucharest ranked first in Europe and fifth globally, with a congestion level of 48%—a decrease from 55% in 2023, 52% in 2020, and 41% in 2015. It was followed in Europe by Plovdiv, Łódź (both 48%), Dublin (47%), and Hull (46%) [1].

Although congestion in Bucharest steadily increased from 2015 to 2023, 2024 marked a decline. Nevertheless, the city remains the most congested in Europe. Globally, it ranks fifth, following Mexico City and Bangkok (both 52%), Davao City, and Kumamoto (both 49%) [1].

As a primary objective of this study, we aim to identify the generally applicable causes of traffic congestion in urban areas, recognizing that such areas are complex agglomerations where transportation needs vary in purpose, destination, and time of occurrence, and—more importantly—exhibit significant variability in terms of scale, timing, and spatial distribution.

Traffic congestion has emerged because cities have continuously developed, with more than half of the world's population now living in urban areas, a percentage projected to reach 68.4% by 2050. The regions experiencing the most intense urbanization are North America, where 82% of the population resides in cities; Latin America and the Caribbean (81%); Europe (74%); and Oceania (68%), regions where congestion causes significant economic losses [2]. According to European Union statistics, traffic congestion results in economic losses amounting to nearly 100 billion euros annually [3].

Studies conducted to date have identified several causes that are generally applicable and valid worldwide [4]. Among these, the following can be mentioned: rapid and uncontrolled socio-economic development of cities, increased motorization levels that encourage the use of personal vehicles [5–7], and the imbalance between transport demand and supply; however, the precise role played by socio-economic development remains unclear [8], as does that of the increase in population size and density, which impacts the frequency of social activities [9].

Another cause of increasing traffic congestion, acknowledged by transportation planners, is the paradox whereby building *more roads actually exacerbates congestion* [10]. It is assumed that new infrastructure will lead to an increase in transport demand, further intensifying the imbalance between transport supply and demand, thereby contributing to heightened traffic congestion [11].

The second objective of this research is to identify solutions for mitigating the effects of traffic congestion. These solutions must align with the United Nations 2030 Agenda for Sustainable Development, which promotes inclusive, safe, resilient, and sustainable cities. Sustainable mobility is specifically addressed in Goal 11.2, which calls for clean, safe, affordable, and accessible transport systems for all. It also emphasizes the need to improve road safety by expanding public transport infrastructure, with particular attention to vulnerable groups such as women, children, and the elderly [12].

Reducing the effects of traffic congestion and promoting sustainable urban development are achieved through efficient and high-capacity public transportation systems [13], including metro networks. However, these solutions face several implementation barriers, such as long construction periods, high costs, and lack of flexibility, which sometimes make them unsuitable for meeting urban transport demand characterized by rapid dynamics. Other measures, such as congestion pricing and traffic restrictions in certain areas, vehicle speed control in specific areas [14], have also been adopted to reduce traffic congestion. Regardless of the approach, understanding the mechanisms and origins of traffic congestion remains a contentious issue, rooted in travel behavior [15].

Therefore, the most important measure for reducing traffic congestion remains the development and widespread use of high-capacity public transportation systems, such as metro networks, which provide large transport capacities and high travel time stability compared to surface public transportation [16]. The development of high-capacity transport networks, such as metro systems, must be integrated with land use policies and should aim to decouple economic development from increased mobility [17].

In this context, European countries and the United States are increasingly employing integrated land use–transport models for sustainable urban planning. These models facilitate the placement of points of interest within cities near public transport stations, enabling access to the network either by walking or by environmentally friendly means of transportation [18,19].

The third objective of this research was the topological analysis of urban transport networks, which included a case study applied to the Bucharest metro network. The aim was to identify how the network has been topologically developed to fully and promptly meet the transport demands arising from the social environment. As a result of the case study, values were determined for connectivity indices, generalized nodal accessibility, and Shimmel accessibility.

Connectivity indices were calculated for two key stages in the metro network's development, offering insights into its robustness and resilience over time. These indices reflect the number of alternative connections between any two nodes in the network graph [20]. Additionally, generalized nodal and Shimmel accessibility measures were used to rank nodes based on their strategic importance, defined by the minimum number of arcs required to reach all other nodes.

The accessibility study was complemented by an analysis of how effectively the metro network serves the covered territory. To this end, the city was divided into 19 zones corresponding to its neighborhoods, over which the metro network was superimposed to identify the lines and nodes (poles) belonging to each area. Accessibility was determined by counting the number of poles that could be reached within time intervals of 15, 30, and 45 min. Based on the number of reachable poles, a hierarchy of the city's areas was established. Zones with the highest values were found to have the greatest accessibility and are more likely to be chosen by users as travel destinations.

As a natural continuation of this research, an evaluation was carried out to assess how well the accessibility provided by the metro network aligns with the spatial characteristics of the territory—namely, population density. It is well known that metro network development should be prioritized in densely populated areas in order to reduce reliance on private vehicles. The objective was to compare temporal accessibility with the population density of the areas to identify a correlated development of the metro network with the density of the analyzed areas.

This paper determines the accessibility of the city's areas using an original approach aligned with *contour accessibility*, which aims to measure the number of destinations that can be reached within a specified time interval [21]. Therefore, each study area is assigned a particular accessibility value, which should correlate with the population density or number within that area. If a dependency between these decision variables exists, it can be concluded that the metro network has been developed within the urban space in accordance with socio-economic characteristics.

2. Literature Review

2.1. Topological Analyses

Topological analyses of networks have been performed in various studies to characterize the nodes and arcs within networks and establish a hierarchy of their significance in the overall structure.

Zhang et al. [22] analyze the Shenzhen metro network as a random network to study its topological complexity. The results obtained include proving the characteristics of scale-free networks in both Space L and Space P through the eigenvector centrality distribution and the truncated power-law distribution of cumulative degree. Such scale-free networks exhibit robustness against random faults but remain vulnerable to deliberate attacks.

Yang et al. [23] incorporate factors such as the public transport system configuration and the areas around the stations for evaluation. They introduce the Centrality of Station Index (CSI) to assess the importance of stations within the integrated public transport system. CSI is an improved metric that combines the gravitational model with the degree centrality index of complex networks. This enhancement replaces the simple count of nodes with weighted connections between stations, providing a more accurate measure of centrality. By integrating public transport operation, station configurations, and the surrounding areas, a Public Service Accessibility Index is developed to quantify accessibility at the community level.

Expanding on topological methods, Yi et al. [24] extend research from transportation networks to urban form, determining various centrality indices based on spatial big data concerning urban form, function, and location potential within the Seoul metropolitan area. They conduct a comparative analysis of morphological differences in urban spatial structure among the centrality indices, and specific tests reveal statistically significant mutual correlations between all centrality indices.

Cai et al. [25] propose an innovative algorithm called the k-dis-weight-shell, designed to quantify the centrality of spatial interaction of geographic nodes across various spatiotemporal scales. Through a comprehensive approach, this algorithm combines network topology with mobility characteristics such as travel distance and flow to generate a detailed classification of spatial interaction centrality. To increase analytical precision, a continuous spatial wavelet transform is employed, enabling the estimation of the radiation radius of geographic nodes while accounting for the distinct effects of long-distance and short-distance travel.

Building on previous research into urban network structures, Herrera-Acevedo et al. [26] perform a comprehensive analysis examining the impact of urban networks and socio-demographic factors on urban mobility readiness across 62 cities worldwide. The study integrates complex network analysis, principal component analysis, and multiple linear regression models to uncover significant relationships between network metrics—such as average node degree, clustering coefficient, and graph diameter—and urban mobility performance. The results emphasize the strategic role of network structure in shaping urban mobility and offer valuable insights for improving the efficiency of transportation systems in rapidly growing urban areas.

Zhou et al. [27] propose a comprehensive approach to railway transit network planning, considering both network configuration and passenger route allocation. This model aims to simultaneously optimize the objectives of transport operators, such as minimizing operating costs, and passenger requirements, such as reducing travel time. The problem is formulated as a Mixed-Integer Nonlinear Programming (MINLP) model with linear constraints, enabling a rigorous analysis of the interaction between line planning and passenger assignment.

Shifting focus, Niu and Wang [28] investigate the structure of China's railway network, analyzing both conventional and high-speed networks from a topological and functional perspective. Centrality indices such as degree centrality, closeness centrality, and betweenness centrality are calculated to evaluate network connectivity. This approach enables the classification of subnetworks and the assessment of the railway infrastructure's development level.

Also within the realm of topological analysis, Kaza and Nesse [29] explore the regional structure of the United States through labor market centrality. Commuter flows between counties are used to identify regional hierarchies and analyze centrality at the county level. The topological indices applied in the study highlight the role of each county within

the overall network structure, providing a clear perspective on how these hierarchies are formed and maintained.

Regarding vulnerability and reliability analysis, Taylor [30] addresses these concepts from the perspective of technical infrastructure networks. Reliability is defined as the probability that network performance maintains a certain level of service under recurrent disturbance conditions, while vulnerability refers to the decline in performance following a specific non-recurrent disruption. Taylor also describes the main methods for analyzing vulnerability across various transport networks.

Complementary to this approach, Zhu et al. [31] analyze the robustness of metro networks through a defense–attack strategy. The proposed model involves protecting critical network nodes and simulating an attack on the network. Strategies for identifying influential nodes include eight different approaches, among which the breadth-tree coefficient strategy is introduced as a novel and efficient method. Simulations conducted for five metro networks demonstrate that attacks targeting nodes with the highest betweenness centrality values are the most effective at disrupting the network. However, the robustness of the network can be significantly improved by applying the proposed strategy.

At the national level, Raicu and Costescu [20,32] conduct a detailed analysis of transport networks, focusing on their components, multi-relational nature, and topological properties. Their study highlights the complex relationships between transport networks and the territorial system, emphasizing how these systems interact and influence each other. Additionally, they discuss transport network development in relation to infrastructure investments and resource allocation strategies, proposing coherent directions for social and territorial development.

Building on this approach to transport networks, Ebrahimi and Popa [33] focus on assessing the operational robustness of the Bucharest metro system using graph theory. Their analysis employs specific network operation data to examine the types of disruptions that may occur along metro lines, considering the placement of stations and lines. The results suggest that the Bucharest metro network can withstand up to 45% of node failures before its performance is severely compromised.

The connection between accessibility and vulnerability is clearly emphasized by Hu et al. [34] and Serdar et al. [35], who demonstrate that disruptions in the functioning of nodes and arcs can adversely affect the overall accessibility of the network. Incorporating these perspectives into our study helps identify critical nodes and develop effective strategies for improving network robustness.

2.2. Functional Analyses

In accessibility studies, various evaluation methods have been proposed to measure the efficiency of transportation networks and their relationship with urban space utilization. Mazzulla and Pirrone [36] and Zhu et al. [37] conducted a comprehensive assessment of accessibility measures, dividing them into passive and active measures. They proposed a conceptual framework to guide the selection of appropriate measures based on the study context and specific parameters. The framework highlighted two contrasting approaches to accessibility: one focused on the physical distance between locations and the other on individuals' preferences and perceptions. These distinctions are particularly relevant to the present study, as accessibility was measured not only by proximity to stations but also by the broader network connectivity and its alignment with urban characteristics.

In the same direction, Bosch-Checa et al. [38] highlighted the importance of high-resolution spatial analysis for evaluating urban mobility services. By examining the percentage of the population located within walking distance of various public transport systems and shared mobility services, these studies revealed accessibility disparities be-

tween transport modes and different urban areas. This approach is also applicable in the context of Bucharest, where the aim is to evaluate the accessibility of the metro network and how it integrates with the city's urban and social characteristics.

In this context, Kuhnel et al. [39] emphasized that the relationship between public transport services and their usage is essential for evaluating transportation networks. Their study suggested that indicators such as cumulative opportunity accessibility—comparing public transport with private car travel—are more effective in reflecting public transport usage than traditional metrics, such as travel time to central districts.

On the other hand, Bhellar et al. [40] aimed to assess accessibility in the city center through travel rate analysis and isochrone curve modeling within a GIS framework. The study's findings demonstrated that spatially dispersed locations generate substantial traffic volumes due to limited access to efficient public transportation. By categorizing trips according to their purpose, the analysis revealed that most journeys were undertaken for health services, shopping, and returning home. The application of isochrone maps provided critical insights into public transportation development, highlighting areas for improving network efficiency and accessibility.

Dragu et al. [41] address spatial accessibility and territorial coverage by metro services, concluding that less than half of the area is served by this network. Their analysis focused on various points of interest such as shopping centers, educational institutions, sports facilities, and intermodal passenger hubs. Conclusions were drawn based on the accessibility to these points using the metro network.

Supporting these findings, Lindner et al. [42] emphasize that accessibility varies significantly depending on the time of day. Accessibility was calculated through public transportation for various time intervals, and the median method proved to be the most suitable for aggregating the results.

Accessibility analyses represent a fundamental aspect in the study of traffic congestion, as highlighted by Zini et al. [43], who emphasize that reducing traffic congestion can be achieved through a competitive public transport system capable of ensuring high accessibility for social mobility. However, for the analyzed area, private cars remain the preferred option, registering better usage indicators. This preference varies significantly across different parts of the city, thus generating inequalities in terms of social and environmental sustainability. The study provides valuable insights for policymakers and researchers concerned with improving public transport.

The issue of accessibility equity is addressed by Guo et al. [44], who analyze job accessibility for commuters. Utilizing multiple geographic data sources and extending the traditional two-step floating catchment area method to include travel characteristics, the study demonstrates that accessibility is deeply influenced by both the socio-economic status of the population and the location of residences and workplaces.

Accessibility analyses are further complemented by the study conducted by Cheng et al. [45], which explores the contribution of Free-Floating Bike-Sharing systems to improving public transport accessibility, serving as an essential connection for first-mile trips. Data collected from Nanjing, China indicate a significant increase in accessibility through the integration of various transportation modes, thereby providing better connectivity and more efficient use of the public transport network.

In line with this research, Zhan et al. [46] analyze the factors influencing travel time reduction, focusing on the characteristics of subway stations and access methods to these stations. The study emphasizes the importance of improving accessibility conditions to enhance the efficiency of public transport networks, suggesting that strategic interventions in this regard can significantly contribute to optimizing urban mobility and alleviating traffic congestion.

Recent research has extensively explored the complex relationship between metro networks and urban spatial form, focusing on aspects such as spatial restructuring, accessibility, land use optimization, and socio-economic impacts. While the approaches and methodologies vary, a common thread emerges: the critical role of metro networks in shaping urban development and accessibility.

2.3. Analyses of Transportation and Land Use Interaction

Bothe et al. [47] initiated this discourse by examining employment growth disparities between metro-served and non-metro-served areas in Copenhagen. Their findings revealed that metro-connected areas experience higher employment growth, suggesting a foundational influence of metro networks on spatial economic patterns. Expanding on this, Liu et al. [48] utilized big data to investigate how metrorail accessibility influences urban spatial form. Their findings demonstrated a tendency towards monocentric patterns, where accessibility diminishes progressively from urban cores, highlighting the spatial imbalance that metro networks can exacerbate if not carefully integrated with urban planning.

Furthering the spatial dimension, Lei et al. [49] examined metro networks' dynamic role in guiding urban population distribution. Unlike previous studies that primarily focus on adaptation, their analysis emphasized the proactive influence metro systems can exert on urban growth, suggesting a dual relationship between transport infrastructure and population distribution. Complementing this perspective, Chen et al. [50] used smart card data to uncover how built environment features affect metro ridership over time, reinforcing the idea that transport systems and urban form are intricately linked.

Further enriching this discussion, Bi et al. [51] employed topic modeling techniques to unravel the nuanced effects of the built environment on bicycle–metro integration. Their research emphasized the need for multimodal transport systems that enhance accessibility across different urban contexts. A similar focus on multimodal integration was highlighted by Guo and He [52], who studied how dockless bikeshare systems act as feeder modes for metro networks, emphasizing the importance of designing interconnected urban transport systems.

Adopting a different analytical lens, Meng and Ishida [53] applied space syntax to explore the relationship between Beijing rail transit and urban planning, arguing that alignment between infrastructure and spatial frameworks is essential for achieving cohesive urban growth. Complementary to this view, Zhang et al. [54] examined the cultural and social dimensions of metro systems, suggesting that beyond their functional role, metro stations also contribute to urban identity and place perception.

The role of metro systems in urban revitalization was further examined by Łukasziewicz et al. [55], who demonstrated how tram networks contribute to enhancing urban aesthetics and connectivity in Warsaw.

With respect to practical implementation, Zhao et al. [56] emphasized the importance of efficient land use planning around metro stations to optimize ridership and accessibility. Their balanced ridership models highlight the need for coordinated land use and transport planning to enhance urban accessibility. Berta and Emagnu [57] further reinforced this point by demonstrating how urban land use characteristics impact road network accessibility, suggesting that integrated planning approaches are essential for equitable urban development.

Some studies suggest the necessity of integrating metro networks with broader urban planning strategies to achieve balanced growth, socio-economic equity, and improved accessibility.

3. Materials and Methods

3.1. Topological Analyses of Metro Networks

The topological analysis of the metro network conducted in this study aims to achieve three main objectives:

1. Calculate the network connectivity indices at two distinct points in time to assess changes in connectivity.
2. Determine the generalized nodal accessibility matrix and vector, which measure the overall accessibility of each node within the network.
3. Calculate the Shimbel accessibility matrix and vector, providing the Shimbel nodal index to evaluate network efficiency and accessibility.

These objectives arise from the need to examine the topological evolution of the metro network between the two analyzed time points to determine how the network has developed—whether through territorial expansion or by increasing the number of connections to enhance robustness and resilience.

The research methodology involved the following steps to achieve the three objectives. These steps are described below:

Step 1. Network formalization and representation: Formalizing the metro network and representing it as a planar graph.

Step 2. Node and arc identification: Determining the number of nodes and arcs of the metro network graph at two time points of analysis (2009 and 2024).

Step 3. Connectivity indices calculation: Calculating the network connectivity indices (α_p , γ_p , β_p) for the metro network at both time points.

Step 4. Adjacency matrix calculation: Determining the adjacency matrix representing the metro network (direct accessibility matrix).

Step 5. Direct accessibility vector calculation: Calculating the direct accessibility vector.

Step 6. Matrix exponentiation: Raising the direct accessibility matrix to the power equal to the network's diameter.

Step 7. Generalized nodal accessibility vector calculation: Determining the generalized nodal accessibility vector.

Step 8. Node characterization: Characterizing the network nodes in terms of generalized nodal accessibility.

Step 9. Shimbel matrix calculation: Determining the Shimbel matrix.

Step 10. Shimbel vector calculation: Calculating the Shimbel nodal vector.

Step 11. Comparison of accessibility vectors: Comparing the generalized nodal accessibility vector with the Shimbel vector.

These research steps are outlined in Section 4.1, The topological analysis of the metro network, and they address the research question: *How has the metro network been topologically developed to fully and timely meet the transportation demands arising from the social environment?*

The following section briefly presents the research methodology and the mathematical models that form the basis for determining connectivity and nodality properties, in accordance with the specialized literature [20,25,58].

The reliability of network connections is described through the property of connectivity. This property defines the multitude of connections provided by the network within the territorial system. If the network is viewed as a mesh, then connectivity serves as an indicator of the mesh's density [20,59].

It can be concluded that when the mesh is denser, the network's vulnerability is low, and therefore, the probability of a disruption between any two nodes is also low, resulting in a high degree of functional reliability for the network [26,49].

Connectivity is defined through the indices α , γ , and β . The definition of these connectivity indices begins with the graph associated with the network, corresponding to the $[M_{ij}]$ matrix which represents the metro network graph. The elements of the $[M_{ij}]$ matrix are defined as follows:

- $M_{ij} = 1$ if there is a direct connection between node i and node j ;
- $M_{ij} = 0$ otherwise [60,61].

Based on the number of nodes ($n + 1$) and the number of links ($\sum_{i,j} M_{ij}/2$), the three indices are mathematically defined to assess the structural properties of the network [20].

$$\alpha = \frac{\text{number of circuits}}{\text{max.number of circuits}}; \gamma = \frac{\text{number of links}}{\text{max.number of links}}; \beta = \frac{\text{number of links}}{\text{number of nodes}}.$$

Considering these definition relations, for a planar graph, the formulas for determining the α_p , γ_p , and β_p indices can be expressed as follows [20]:

$$\alpha_p = \frac{\sum_{i,j} M_{ij} - 2n}{2(2n - 3)}, \quad (1)$$

$$\gamma_p = \frac{\sum_{i,j} M_{ij}}{6(n - 1)}, \quad (2)$$

$$\beta_p = \frac{\sum_{i,j} M_{ij}}{2(n + 1)} \quad (3)$$

The α_p index ranges between 0 and 1. It is zero when the graph representing the network has no circuits and reaches 1 when the graph contains the maximum possible number of circuits. Similarly, the γ_p index also varies between 0 and 1. However, the β_p index does not have well-defined variation limits, as is the case with the first two indices.

Nodality permits the characterization of network nodes in terms of relational capabilities for the system. If connectivity allows for network-wide assessment of the possibilities of establishing direct and alternative links between nodes, then nodality differentiates between system elements according to the relations between them [20,24]. As with other properties, several nodality indices can be highlighted. In this paper, two nodality indices were calculated: generalized nodality and Shimbel nodality.

For defining the generalized nodality index, we are considering a non-oriented graph associated with the analyzed transport network and that corresponds to the $[M_{ij}]$ matrix. The $[M_{ij}]$ matrix elements are as follows:

- $M_{ij} = 1$, if M_{ij} or $M_{ji} = 1$;
- $M_{ij} = 0$, if M_{ij} or $M_{ji} = 0$.

The associated matrix $[M_{ij}]$ is given. By hypothesis, it has $M_{ij} = 0$ for all $i = j$. From matrix $[M_{ij}]$, the following can be calculated:

$$N_{1,i} = \sum_{j=1}^n M_{ij}, \quad i = 1, n \quad (4)$$

The N_1 nodality vector elements indicate the number of links of node i with all other nodes. The N_1 vector is called direct accessibility vector.

When calculating M^2 and N_2 , we obtain indirect accessibility. The M^2 matrix elements show the number of links with two stops between nodes on the matrix row and column.

Similarly, M^3 , N_3 , $\dots$, M^n , N_n can be calculated.

The nodality vector allows for a hierarchy of nodes without considering the nodes degree [28,60].

After performing a number of p iterations, all nodes are connected with at least a p degree path. In particular, the farthest nodes are linked with a p degree path. Then, the network diameter is equal to p .

Summing up the nodality matrices of order $1, 2, \dots, p$, we obtain a nodality matrix where each element indicates the number of relations of all orders between nodes corresponding to that item.

This is the matrix of generalized nodal accessibility, M_g . From this matrix, we can obtain the generalized nodality vector, N_g , for all network nodes.

$$\sum_{n=1}^p M^n = M_g \quad (5)$$

The Shimbel nodality index eliminates the redundancy implied by the model for determining the generalized nodal. The redundancies are explained by the existence of the direct links in network with return in the same node. The successive calculations of matrices amplify this redundancy, and the generalized nodality vector puts the privileged nodes at the top of the overall hierarchy.

To avoid this redundancy, retaining only the shortest paths between nodes, the following procedure can be followed: The matrices $P_1, P_2, \dots, P_n$ are calculated from matrices $M, M^2, \dots, M^n$. To determine matrix P_i from matrix M^i , the place of new items is marked in relation to matrix M^{i-1} . The main diagonal elements are equal to zero. If i has the same value as any nonzero element, it cannot be a part of matrix P_i .

3.2. Functional Analyses of Metro Networks

Functional analyses of transport networks extend beyond topological analyses by incorporating both spatial characteristics and network operational parameters. In addition to the planar and profile configuration of the network, several key factors are assessed, including travel time between stations, dwell time at stops, headways between transport units, the number of active vehicles on a route, passenger capacity, and other parameters that characterize vehicle movement within the public transport system [41]. These functional attributes enable the evaluation of accessibility across different locations or areas within a given territory, based on the effectiveness of the public transport system. Equal opportunities for accessibility and mobility can be regarded as fundamental rights for all citizens and a universal service provided, regardless of where people live. Today, accessibility has gained significant importance in human activities due to its multifaceted nature, as well as its dynamic and versatile character [62].

The functional analysis aimed to determine the accessibility of the analyzed areas using the metro network for transportation. The objectives of the analysis are as follows:

1. Identifying the number of metro poles within each analyzed area.
2. Evaluating the accessibility characteristics of the 19 analyzed areas, including the number of metro lines and arcs present within each area.
3. Measuring area accessibility by determining the number of metro poles that can be reached within a specified time interval.

To achieve these three objectives, the research methodology involved the following steps:

Step 1: Creating a map that divides the city into 19 distinct areas of analysis.

Step 2: Assessing the characteristics of each area, including area size, population count, and population density.

Step 3: Overlaying the metro network map onto the city map segmented into study areas to develop an integrated territory–metro network scheme.

Step 4: Assigning each metro pole to its corresponding area of analysis.

Step 5: Calculating the number of arcs and metro lines present within each area of analysis at the two study points (2009 and 2024).

Step 6: Identifying both directly accessible poles and indirectly accessible poles (reachable with one transfer) for each area of analysis.

Step 7: Measuring the number of poles that can be reached within specified time intervals (15, 30, and 45 min). These calculations are made for each pole, and the results are aggregated to establish the overall accessibility of each area.

Step 8: Creating graphical representations to visualize changes in accessibility between the two study points.

Step 9: Analyzing the relationships between the territorial system and accessibility provided by the metro network.

These steps of the research methodology are covered in Section 4.2, The accessibility analysis of the metro network. They address the following research question: *How has the accessibility of the 19 areas of the city changed between the two points of analysis, considering the use of the metro network for transportation?*

The analysis aimed to evaluate the accessibility provided by the Bucharest metro network across 19 study areas at two distinct points in time, separated by a 15-year interval. The research methodology used for these assessments is based on contour accessibility, which focuses on measuring the number of destinations that can be reached within a specified time interval [21].

Following these research steps also addresses the following question: *Does the accessibility of the areas align with their spatial characteristics?* Specifically, this refers to population density, considering that metro network development should ideally focus on densely populated areas to reduce reliance on private vehicles.

The following section presents several considerations regarding the evolution of the accessibility concept, emphasizing its importance in meeting the mobility needs of the population.

The concept of accessibility was first introduced by Hansen in 1959. He defined accessibility as the opportunity for interaction between human activities facilitated by the transport system. This concept serves as a measure of the spatial distribution of activities across a given territory, reflecting the desire and ability of social entities to overcome physical separation barriers [63].

In 1979, Morris defined accessibility as the ease of reaching a specific activity from a given location using a particular transport system [64]. Shen developed an accessibility model designed to determine an indicator of accessibility potential [61]. Thus, researchers have conducted numerous studies on determining transport system accessibility, employing various methods based on the geometric and topological characteristics of transport networks. Accessibility assessment methods that rely on geometric properties include the distance-based method [65], the cumulative opportunities method, and the gravity model approach [66].

Certain accessibility studies assess travel time under the assumption of a constant travel time, disregarding variations caused by network dynamics and operational conditions. However, relying on static travel time values can lead to a systematic overestimation of accessibility, thereby compromising the validity and reliability of accessibility assessment methodologies. This misrepresentation may result in travel demand miscalculations, causing individuals to underestimate actual journey times, ultimately leading to delays

in reaching their intended destinations and potential inefficiencies in transport system planning [67].

From the perspective of lifestyle evolution driven by increasing travel speeds, fundamental questions arise: Do we actually gain time? Can the time saved be effectively reallocated to other activities? Observations suggest that, under the assumption of a relatively constant daily travel time budget—as proposed by Zahavi’s hypothesis, which estimates an average of one hour of travel per day—the primary effect is an increase in travel distances rather than a reduction in total travel time. Empirical data indicate that average daily travel distances have expanded significantly, reaching 40 km in France and 70 km in the United States [68].

Studies on urban mobility and accessibility also encompass a policy-oriented component, focusing on strategies aimed at reducing private car dependency. These approaches include concepts such as New Urbanism, Smart Growth, Transit-Oriented Development (TOD), Compact City, and the 15-Minute City. This perspective, on one hand, appears to draw from accessibility theory, but on the other hand, it aligns with the “travel avoidance” concept, integrating the “avoid” component of the A-S-I framework (Avoid, Shift, Improve), which classifies and prioritizes transport interventions accordingly. Furthermore, urban polycentrism is increasingly recognized as a factor that enhances urban functionality while simultaneously boosting the demand for public transportation, fostering a more sustainable and efficient mobility system [43,69].

The development of a composite index for measuring accessibility has been a focal point for transport researchers since the concept was first introduced. Such an index represents a key metric in evaluating public transport systems and their effectiveness in meeting mobility needs. Over time, six primary accessibility measures have been identified, including the *Spatial Separation Measure*, *Contour Measure*, *Cumulative Opportunities Accessibility Measure*, *Gravity Measure*, *Utility Measure*, and *Time–Space Measure*. These foundational approaches have led to the emergence of 21 widely used accessibility models that are currently applied in transport planning and accessibility assessments worldwide [21].

The *contour measure of accessibility* is a widely used method for assessing the accessibility of public transport systems. This approach involves measuring the number of destinations reachable within a specific travel time from a given origin using public transportation. The *contour measure of accessibility* serves as an effective tool for evaluating the efficiency of public transport systems in connecting individuals to key destinations, such as employment centers, educational institutions, healthcare facilities, and other essential services. Among accessibility indicators, the contour measure holds the highest generalization capacity, making it one of the most comprehensive methods for assessing the accessibility of a transport network [21].

In this study, the concept of accessibility was applied by calculating the number of metro poles that can be reached within specific time intervals. These results were then aggregated for the 19 study areas, allowing for conclusions about the accessibility of each area and correlations with various socio-economic development factors.

The data and information used in this study are publicly available and were collected from relevant online sources, then processed by the research team. To create the map dividing Bucharest into 19 zones, this study used the zoning established for the development of the transport model within the Sustainable Urban Mobility Plan (SUMP) for Bucharest and Ilfov Region 2016–2030 [70], where the city was initially divided into 72 functional zones. Over this base map, a new division into 19 zones was created, corresponding to the city’s neighborhoods, and overlaid with the metro network map showing station locations, as presented on the METROREX website [71].

Population data for the city were obtained from the National Institute of Statistics of Romania [72] and processed according to their affiliation with the 19 study areas. This study was conducted for the metro network at two different time points, corresponding to distinct stages of metro network development.

4. Case Study

4.1. The Topological Analysis of the Metro Network

In this case study, the analysis focuses on the metro network, as it represents the most significant public transport system in terms of passenger capacity and travel time reliability. Unlike surface transport modes, the metro system ensures predictable and stable journey durations, making it a critical component of the city's mobility infrastructure. However, despite its importance, the metro network currently accounts for only 11% of the total public transport network length, with the remaining 89% being operated by the Bucharest Public Transport Company (STB) through tram, trolleybus, and bus networks. Similarly, metro ridership represents only 11.7% of the total number of public transport passengers in the city. Given these figures, any future metro expansion proposals must be thoroughly analyzed and aligned with the socio-economic development of the areas served to ensure efficient and sustainable integration within the overall urban mobility system [71,73].

The Bucharest Metro commenced operations on 16 November 1979, initially spanning 8.1 km with six stations, primarily following the right bank of the Dâmbovița River. Today, the network has expanded to a total length of 79.36 km, consisting of five metro lines and 64 stations. Among these, six stations serve as interchange hubs for two metro lines, but since they share the same physical location, they have been considered a single node in the network graph for the purposes of this analysis. The metro system currently serves an urban area of 232.84 km², resulting in a network density of 0.332 km/km². This case study evaluates both the topological properties of the metro network and its accessibility, the latter being assessed based on the number of stations reachable within a given travel time threshold. To determine the generalized nodality index, an M-matrix of direct accessibility was constructed, from which the N₁ vector of direct accessibility was derived (Table 1).

Table 1. Direct accessibility matrix and vector.

		M ₁	M ₂	M ₃	M ₄	M ₅	M ₆	M ₇	M ₈	M ₉	M ₁₀	M ₁₁	M ₁₂	M ₁₃	M ₁₄	M ₁₅		
M =	M ₁	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	M ₁	1
	M ₂	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	M ₂	1
	M ₃	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	M ₃	1
	M ₄	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	M ₄	1
	M ₅	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	M ₅	1
	M ₆	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	M ₆	1
	M ₇	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	M ₇	1
	M ₈	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	M ₈	1
	M ₉	1	0	0	0	0	0	0	0	0	1	0	0	0	1	0	M ₉	3
	M ₁₀	0	1	0	0	0	0	0	0	1	0	1	0	1	0	0	M ₁₀	4
	M ₁₁	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	M ₁₁	3
	M ₁₂	0	0	1	1	0	0	0	0	0	0	1	0	0	0	0	M ₁₂	3
	M ₁₃	0	0	0	0	1	0	0	0	0	1	1	0	0	1	0	M ₁₃	4
	M ₁₄	0	0	0	0	0	0	0	1	1	0	0	0	1	0	1	M ₁₄	4
	M ₁₅	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	M ₁₅	3

The 15 nodes representing the current metro network graph are as follows: M₁-Dep. Străulești, M₂-Pipera, M₃-Pantelimon, M₄-Anghel Saligny, M₅-T. Arghezi, M₆-Râul

Doamnei, M₇-Valea Ialomiței, M₈-Preciziei, M₉-Basarab, M₁₀-Pța. Victoriei, M₁₁-Dristor, M₁₂-N.Grigorescu, M₁₃-Pța. Unirii, M₁₄-Eroilor, and M₁₅-Romancierilor.

An analysis of the direct accessibility vector values (Table 1) shows that the highest accessibility is achieved by three nodes: M₁₀ (Pța. Victoriei), M₁₃ (Pța. Unirii), and M₁₄ (Eroilor). Each of these nodes has four direct connections to neighboring nodes and is positioned on the network's central ring, ensuring excellent territorial accessibility.

Figure 1 illustrates the map of Bucharest, divided into 19 study areas for accessibility analysis, over which the metro network has been overlaid. This mapping was conducted using TransCAD 7.0 (Caliper Corporation, Newton MA, USA), a specialized software program for transportation network analysis and modeling. The study areas correspond to the city's districts, reflecting the territorial division used in the analysis. The metro network is color-coded to indicate different phases of development: red lines represent the metro network as it existed in 2009, and green lines indicate extensions and expansions implemented after 2009 up to the present day.

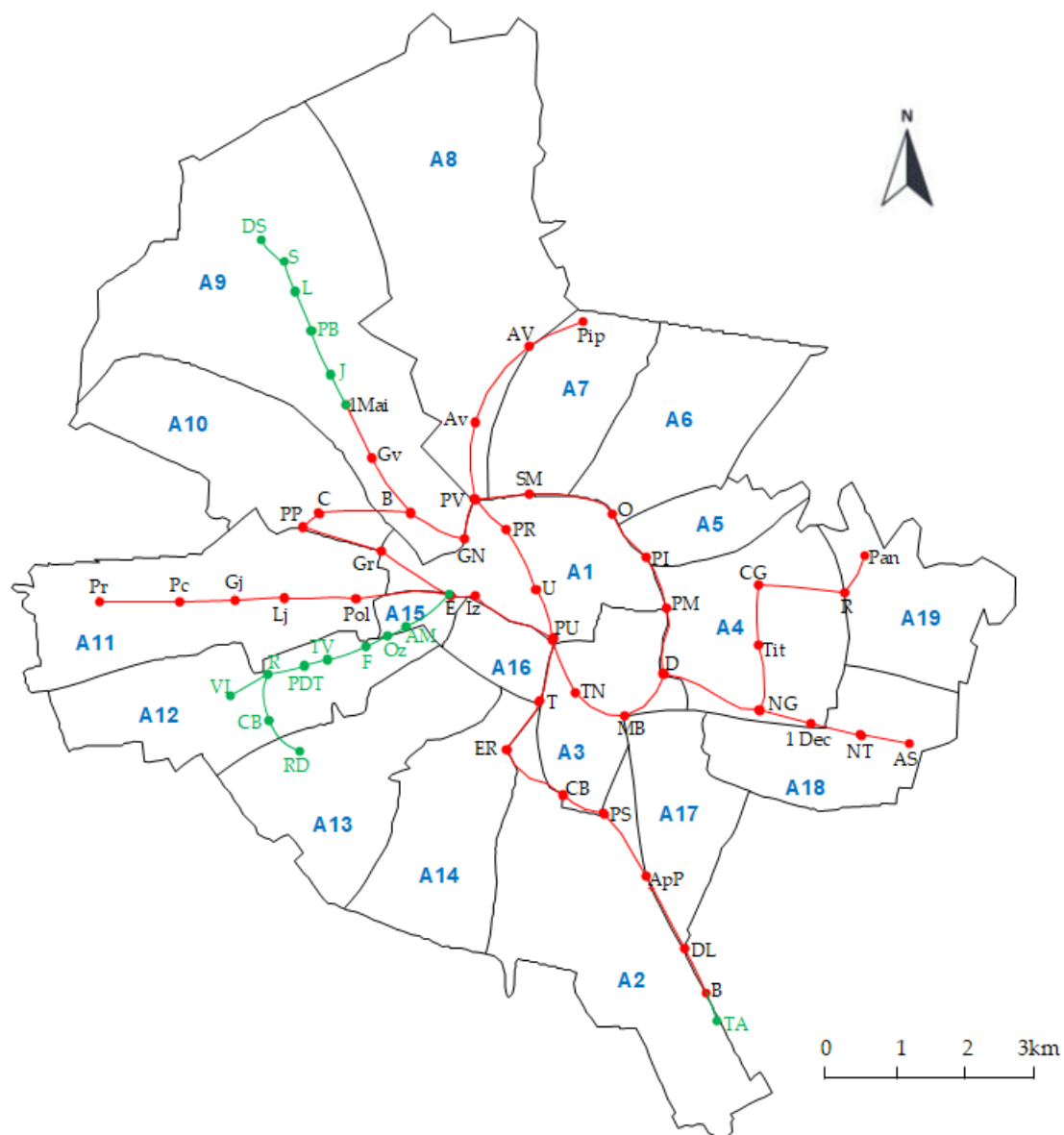


Figure 1. The state of the metro network in the study areas.

The graph analysis of the Bucharest metro network reveals that the system exhibits connexity properties, as there are no isolated nodes in either of the examined cases—the

2009 network or the 2024 network. Additionally, in certain instances, the network provides alternative connections, which are quantified using connectivity indices.

Table 2 presents the connectivity index values obtained for the metro network graph at two different time points (2009 and 2024). These indices were computed using Equations (1)–(3).

Table 2. Connectivity indices of the Bucharest metro network.

Topological Characterization of the Network		Year		Dif.
		2009	2024	
	Nodes No.	12	15	+3
	Links No.	13	16	+3
	$\sum_{i,j} M_{ij}$	26	32	+6
Connectivity indices	α_p	0.1052	0.0800	−0.0252
	γ_p	0.4334	0.4103	−0.0231
	β_p	1.0834	1.0667	−0.0167

Over a 15-year period, the Bucharest metro network has expanded by three additional nodes and links, as indicated in Table 2. However, despite this expansion, the connectivity indices have shown a decline. This reduction can be attributed to the development strategy adopted for the network, which prioritized line extensions and the construction of a new route to enhance coverage in previously unserved urban areas, rather than reinforcing the existing network through additional interconnections between established nodes. In essence, metro network expansion involves a strategic trade-off between two key objectives: extending coverage to new urban areas to improve spatial accessibility and enhancing network resilience by introducing additional connections between existing nodes, thereby reducing network vulnerability and increasing redundancy in travel routes.

Table 3 presents the abbreviations of metro station names used in Figure 1, along with their corresponding study area assignments.

In Table 3, stations located on the boundary line between areas have been considered accessible to residents of all adjacent areas. As a result, some stations are listed as belonging to multiple areas in Table 3.

From the direct accessibility vector, it is evident that nodes M_{10} —Piața Victoriei, M_{13} —Piața Unirii, and M_{14} —Eroilor exhibit the highest direct accessibility, each having four connections.

The sum of all connections in the direct accessibility matrix (32), divided by 2, provides the total number of links in the analyzed network. By 2024, the graph representing the Bucharest metro network consists of 15 nodes and 16 links, reflecting an increase of 3 nodes and 3 links compared to the 2009 network configuration.

By computing M^2 and N_2 , the indirect accessibility is obtained. It is observed that M^2 already contains a second-order connection M_1 — M_1 , specifically M_1 — M_9 — M_1 , as well as three second-order connections for M_9 — M_9 , corresponding to M_9 — M_1 — M_9 , M_9 — M_{10} — M_9 , and M_9 — M_{14} — M_9 . These redundancies appear along the main diagonal of the M_2 matrix. After eliminating these redundancies, it becomes evident that the most strategically positioned node is M_{13} —Piața Unirii, as it has the highest number of two-link connections (12 in total, of which 8 are non-redundant).

Next, the M^3 , M^4 , M^5 , and M^6 matrices were computed, leading to the derivation of the corresponding nodality vectors N_3 , N_4 , N_5 , and N_6 , as well as the generalized nodality vector N_g . The calculations were performed up to the sixth power of the matrix, as this represents the diameter of the metro network in its current configuration. The nodality vectors and the generalized nodality vector are presented in Table 4.

Table 3. Abbreviations used in Figure 1 and station assignments to study areas.

Line	Station Name		Area	Line	Station Name		Area
	Integral	Short			Integral	Short	
L1	Pantelimon	Pan	A19	L2	Pța. Sudului	PS	A2, A3
L1	Republica	R	A4, A19	L2	Ap. Patriei	ApP	A2, A17
L1	C. Georgian	CG	A4	L2	D. Leonida	DL	A2, A17
L1	Titan	Tit	A4	L2	Berceni	B	A2
L1	N. Grigorescu	NG	A4	L2	T. Arghezi	TA	A2
L1	Dristor	D	A3, A4	L3	Preciziei	Pr	A11
L1	M. Bravu	MB	A3, A17	L3	Păcii	Pc	A11
L1	Timpuri Noi	TN	A3	L3	Gorjului	Gj	A11
L1	Pța. Unirii	PU	A1, A16	L3	Lujerului	Lj	A11
L1	Izvor	Iz	A1, A16	L3	Politehnica	Pol	A11
L1	Eroilor	E	A1, A15	L3	1 Decembrie 1918	1 Dec	A4
L1	Grozăvești	Gr	A1, A10	L3	Nicolae Teclu	NT	A18
L1	P. Poenaru	PP	A10	L3	Anghel Saligny	AS	A18
L1	Crângași	C	A10	L4	Dep. Străulești	DS	A9
L1	Basarab	B	A9	L4	Străulești	S	A9
L1	Gara de Nord	GN	A1, A9	L4	Laminorului	L	A9
L1	Pța. Victoriei	PV	A1, A8, A9	L4	Parc Bazilescu	PB	A9
L1	Șt. cel Mare	SM	A1, A7	L4	Jiului	J	A9
L1	Obor	O	A1, A6	L4	1 Mai	1 Mai	A9
L1	Pța. Iancului	PI	A1, A5	L4	Grivița	G	A9
L1	Pța. Muncii	PM	A1, A3, A4	L5	Valea Ialomiței	VI	A12
L2	Pipera	Pip	A7	L5	Râul Doamnei	RD	A13
L2	Aurel Vlaicu	AV	A8	L5	C. Brâncuși	CB	A12
L2	Aviatorilor	Av	A8	L5	Romancierilor	R	A12
L2	Pța. Romană	PR	A1	L5	Parc Dr. Taberei	PDT	A12
L2	Universitate	U	A1	L5	T. Vladimirescu	TV	A12
L2	Tineretului	T	A3, A14, A16	L5	Favorit	F	A12
L2	Eroii Revoluției	ER	A14	L5	Orizont	Oz	A12, A15
L2	C. Brâncoveanu	CB	A3	L5	Acad. Militară	AM	A15

Table 4. Nodality vectors for the current network configuration.

Node Vector	M ₁	M ₂	M ₃	M ₄	M ₅	M ₆	M ₇	M ₈	M ₉	M ₁₀	M ₁₁	M ₁₂	M ₁₃	M ₁₄	M ₁₅
N ₁	1	1	1	1	1	1	1	1	3	4	3	3	4	4	3
N ₂	3	4	3	3	4	3	3	4	9	11	11	5	12	11	6
N ₃	9	11	5	5	12	6	6	11	25	36	28	17	37	31	17
N ₄	25	36	17	17	37	17	17	31	76	101	90	38	107	90	43
N ₅	76	101	38	38	107	43	43	90	216	309	246	124	318	257	124
N ₆	216	309	124	124	318	124	124	257	642	881	751	322	919	748	343
N _g	330	462	188	188	479	194	194	394	971	1342	1129	509	1397	1141	536

An analysis of the values presented in Table 4 indicates that the generalized nodality vector ranks M₁₃—Piața Unirii (1397) as the most accessible node, followed by M₁₀—Piața Victoriei (1342) in second place and M₁₄—Eroilor (1141) in third, based on the highest generalized nodal accessibility values. This hierarchy remains consistent throughout the accessibility calculations, as these three nodes were already ranked highest in terms of direct accessibility, each having four direct connections to neighboring nodes. Their central positioning within the network, as illustrated in Figure 1, further reinforces their high accessibility ranking. Conversely, at the bottom of the ranking, the nodes M₃—Pantelimon and M₄—Anghel Saligny exhibit the lowest accessibility values (188 each), closely followed

by M_6 —Râul Doamnei and M_7 —Valea Ialomiței with a generalized nodal accessibility value of 194. These nodes represent four of the eight terminal nodes of the metro network. However, the analysis suggests that half of the terminal nodes still maintain relatively good accessibility, supported by the multiple connections available within the system.

To eliminate the redundancies introduced by generalized nodality, the Shimbel matrix and vector are computed following the methodology outlined in Section 3.1 of this study.

The Shimbel matrix and vector are presented in Table 5.

Table 5. Shimbel matrix and vector for the current network configuration.

		M ₁	M ₂	M ₃	M ₄	M ₅	M ₆	M ₇	M ₈	M ₉	M ₁₀	M ₁₁	M ₁₂	M ₁₃	M ₁₄	M ₁₅	N
P ₆ ⁽²⁰²⁴⁾	M ₁	0	3	5	5	4	4	4	3	1	2	3	5	3	2	3	47
	M ₂	3	0	4	4	3	5	5	4	2	1	2	3	2	3	4	45
	M ₃	5	2	0	4	4	6	6	5	4	3	2	1	3	4	5	54
	M ₄	5	4	2	0	4	6	6	5	4	3	2	1	3	4	5	54
	M ₅	4	3	4	4	0	4	4	3	3	2	2	3	1	2	3	42
	M ₆	4	5	6	6	4	0	2	3	3	4	4	5	3	2	1	52
	M ₇	4	5	6	6	4	2	0	3	3	4	4	5	3	2	1	N ₆ ⁽²⁰²⁴⁾ 52
	M ₈	3	4	4	4	3	3	3	0	2	3	3	4	2	1	2	41
	M ₉	1	2	5	5	3	3	3	2	0	1	2	3	2	1	2	35
	M ₁₀	2	1	3	3	2	4	4	3	1	0	1	2	1	2	3	32
	M ₁₁	3	2	2	2	2	4	4	3	2	1	0	1	1	2	3	32
	M ₁₂	4	3	1	1	3	5	5	4	3	2	1	0	2	3	4	41
	M ₁₃	3	2	3	3	1	3	3	2	2	1	1	2	0	1	2	29
	M ₁₄	2	3	4	4	2	2	2	1	1	2	2	3	1	0	1	30
	M ₁₅	3	4	5	5	3	1	1	2	2	3	3	4	2	1	0	39

The Shimbel nodality vector no longer retains the same significance as the generalized nodality vector. Instead, each value assigned to a node represents a measure of connectivity based on the shortest paths from that node to all other nodes in the graph representation of the metro network. In this context, lower values in the Shimbel nodality vector indicate that a node can reach all other nodes by traversing fewer links, meaning it has higher accessibility relative to the rest of the network. This approach provides a measure of topological accessibility, which is independent of operational characteristics or network performance parameters.

An analysis of the values presented in Table 5 shows that the Shimbel nodality index ranks M_{13} —Piața Unirii (29) as the most accessible node, followed by M_{14} —Eroilor (30) in second place. The third position is shared by M_{10} —Piața Victoriei (32) and M_{11} —Dristor (32). This ranking largely aligns with the results obtained from the generalized nodality vector, except for the inclusion of M_{11} —Dristor, which demonstrates high accessibility despite its network position.

4.2. The Accessibility Analysis Using the Metro Network

The accessibility of the metro network has been assessed for both the current (2024) and the 2009 configurations, considering that the network is represented by its stations, which function as network nodes—with 43 nodes in 2009 and 58 nodes in 2024.

Table 6 presents the characteristics of the 19 territorial areas, including their surface, population, and population density, along with key attributes of the metro network, such as the number of nodes, links, and metro lines serving each area. In this table, NA represents the number of links originating from a given node, NL indicates the number of metro lines passing through that node, and Dif. denotes the difference between values recorded in 2024 and 2009. When a node functions as a terminus station, the number of links (NA) is

equal to the number of lines (NL). For intermediate nodes, these values differ depending on the network's topological and operational structure. For instance, the Basarab node has $NA = 3$, as represented in the network graph, while its NL value is 2, reflecting the operational characteristics of the metro system. This difference arises because two metro lines pass through Basarab station: L1 (Dristor—Pantelimon) and L4 (Depou Străulești—Gara de Nord).

Table 6. Characteristics of the areas and the metro network.

Area	Surface [km ²]	Population [inhab.]	Population Density [inhab./km ²]	Nodes No.	NA		NL		Dif.	
					2009	2024	2009	2024	NA	NL
A1	10.28	131,978	12,841	12	28	29	18	19	1	1
A2	19.67	178,875	9093	5	7	9	4	5	2	1
A3	8.76	68,727	7845	7	15	15	10	10	0	0
A4	13.71	183,796	13,404	7	16	16	9	9	0	0
A5	4.22	47,985	11,372	1	2	2	1	1	0	0
A6	11.32	67,250	5939	1	2	2	1	1	0	0
A7	9.23	69,568	7536	2	3	3	2	2	0	0
A8	27.18	359,012	13,210	3	7	7	4	4	0	0
A9	33.90	397,666	11,732	10	11	21	8	13	10	5
A10	13.02	81,736	6279	3	6	6	3	3	0	0
A11	16.65	186,794	11,216	5	9	9	5	5	0	0
A12	13.93	102,715	7376	7	0	13	0	7	13	7
A13	12.51	57,131	4568	1	0	1	0	1	1	1
A14	9.52	60,992	6404	2	4	4	2	2	0	0
A15	1.37	8648	6300	3	3	8	2	5	5	3
A16	2.52	23,137	9164	3	8	8	6	6	0	0
A17	6.64	34,626	5216	3	6	6	4	4	0	0
A18	8.85	24,635	2783	2	3	3	2	2	0	0
A19	9.55	57,659	6037	2	3	3	2	2	0	0
Total	232.80	2,142,929		79	133	165	83	101		

An analysis of Table 6 reveals that area A1 has the highest number of nodes (12), which aligns with the mobility needs of residents, as this area represents the central area of the city. The higher node density in this region reflects the importance of the city center in the overall transport network structure. Area A1 also exhibits a population density of 12,841 inhabitants/km², which is significantly higher than the city's average density of 9203 inhabitants/km². This distribution supports the mobility demands of the area, aligns with the radial-ring urban development model of Bucharest, and corresponds to the presence of major tourist attractions that generate high passenger flows.

The second-highest number of nodes is found in area A9, which contains 10 nodes. This distribution appears to be well aligned with the spatial characteristics of the area, as area 9 is the largest among the 19 study areas, covering 33.9 km², and has a population density (11,732 inhabitants/km²) higher than the city average. The expansion of the metro network between 2009 and 2024 has significantly improved accessibility in this area. Given its higher-than-average population density, the network extension has contributed to shortening travel distances both from residential areas to the nearest metro station and from the last station to final destinations, thereby enhancing overall mobility efficiency in the region.

At the opposite end of the spectrum, the lowest number of nodes (only one node each) is found in areas A5, A6, and A13. In these areas, network development does not fully align with population density patterns. While area A5 has a population density higher

than the city average (11,372 inhabitants/km²), areas A6 and A13 have lower population densities compared to the urban mean. However, area A13 includes a significant sports attraction, the Ghencea Stadium, which, during events, generates a high influx of visitors requiring rapid evacuation at the event's conclusion. The expansion of the metro network with Line 5, completed in 2020, led to the construction of the Râul Doamnei node, which effectively meets the mobility demands of the area. Another significant development was the addition of seven nodes in area A12 in 2020. As this is a densely populated district and a key urban area, this extension enhances accessibility and improves high-capacity public transport services for local residents.

Table 7 presents accessibility in terms of travel time for each area when using only the metro system. PDA represents the number of directly accessible nodes, PIA indicates the number of nodes accessible with one transfer, and PA denotes the number of nodes reachable within 15, 30, and 45 min. The calculation of these indicators was based on standard metro network operational parameters, considering a headway of 6 min, a station dwell time of 30 s per stop, and a transfer time of 6 min.

Table 7. Accessibility characteristics of the areas.

Area	PDA		PIA		PA 15		PA 30		PA 45	
	2009	2024	2009	2024	2009	2024	2009	2024	2009	2024
A1	266	283	236	366	124	133	400	437	473	597
A2	52	70	112	140	22	30	51	63	117	145
A3	143	146	148	208	70	71	218	228	277	323
A4	150	150	142	242	60	60	173	174	262	291
A5	20	20	22	37	6	6	31	31	37	43
A6	20	20	22	37	7	7	31	31	39	47
A7	33	34	50	65	14	14	50	51	68	78
A8	48	55	76	86	23	25	80	85	89	120
A9	72	132	98	223	39	81	115	196	168	326
A10	60	60	66	111	26	27	101	109	124	167
A11	70	70	130	180	31	32	90	104	175	218
A12	0	60	0	199	0	49	0	100	0	212
A13	0	8	0	29	0	4	0	9	0	18
A14	26	28	56	56	18	18	67	70	83	94
A15	28	55	14	76	12	30	36	101	42	150
A16	81	83	44	73	41	42	117	129	126	159
A17	54	56	70	85	22	24	61	65	100	113
A18	28	28	52	72	9	9	34	34	71	76
A19	40	40	44	74	9	9	28	28	61	64
Total	1191	1398	1382	2359	533	671	1683	2045	2312	3241

Table 8 presents the variations in area accessibility, expressed in both absolute values (Dif) and percentage values (PC), calculated based on the differences between the two study periods. The numerical and percentage values were determined using the data from Table 7.

In Table 8, two areas (A12 and A13) do not have calculated percentage variations in accessibility, as their initial accessibility values were zero. The absolute variation in accessibility ranges from zero to 212, observed in A12 for PA45, while percentage variations span from 0% to 442.9%, recorded in area 15 for PIA. The highest absolute increase in accessibility corresponds to area 12, where the largest metro network expansion occurred, with the construction of Line L5, adding eight new stations within the area. Conversely, the greatest percentage increase in accessibility is observed in a central area with longer indirect travel times, facilitating access to a greater number of destinations. A comparative

analysis of percentage variations across all accessibility indicators places area 15 and area 9 at the top of the ranking. This result highlights a central area (A15) and an area (A9) where network expansion, including five new stations, has significantly improved accessibility.

Table 8. Variation in accessibility of the study areas.

Area	PDA		PIA		PA 15		PA 30		PA 45	
	Dif1	PC1	Dif2	PC2	Dif3	PC3	Dif4	PC4	Dif5	PC5
A1	17	6.4	130	55.1	9	7.3	37	9.3	124	26.2
A2	18	34.6	28	25.0	8	36.4	12	23.5	28	23.9
A3	3	2.1	60	40.5	1	1.4	10	4.6	46	16.6
A4	0	0.0	100	70.4	0	0.0	1	0.6	29	11.1
A5	0	0.0	15	68.2	0	0.0	0	0.0	6	16.2
A6	0	0.0	15	68.2	0	0.0	0	0.0	8	20.5
A7	1	3.0	15	30.0	0	0.0	1	2.0	10	14.7
A8	7	14.6	10	13.2	2	8.7	5	6.3	31	34.8
A9	60	83.3	125	127.6	42	107.7	81	70.4	158	94.0
A10	0	0.0	45	68.2	1	3.8	8	7.9	43	34.7
A11	0	0.0	50	38.5	1	3.2	14	15.6	43	24.6
A12	60	-	199	-	49	-	100	-	212	-
A13	8	-	29	-	4	-	9	-	18	-
A14	2	7.7	0	0.0	0	0.0	3	4.5	11	13.3
A15	27	96.4	62	442.9	18	150.0	65	180.6	108	257.1
A16	2	2.5	29	65.9	1	2.4	12	10.3	33	26.2
A17	2	3.7	15	21.4	2	9.1	4	6.6	13	13.0
A18	0	0.0	20	38.5	0	0.0	0	0.0	5	7.0
A19	0	0.0	30	68.2	0	0.0	0	0.0	3	4.9
Average	10.90	15.00	51.42	73.00	7.26	19.40	19.05	20.10	48.90	37.60

Figure 2 graphically represents the number of links in each urban area of the city at two points in time: 2009 and 2024. The number of links was chosen for graphical representation as it reflects the network's connection to the territory through existing connections with neighboring nodes.

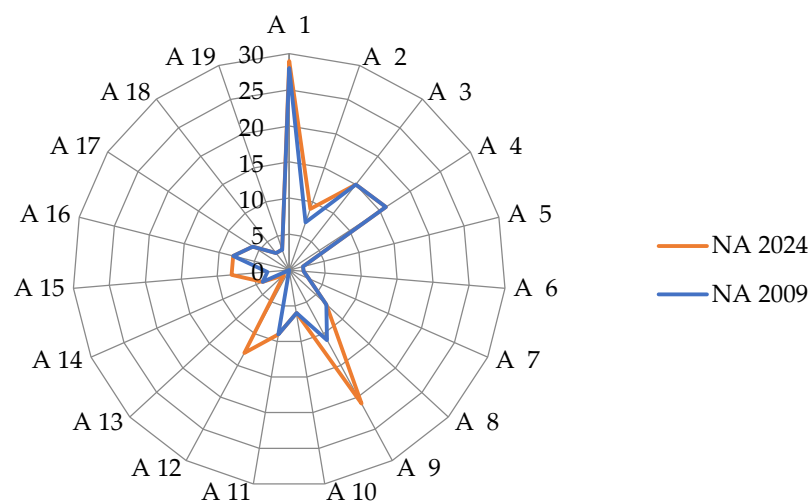


Figure 2. Number of links in each area.

Figure 2 illustrates that out of the 19 areas, only 5 experienced an increase in the number of links. Among these, two areas (A1 and A13) saw a minor increase of one link each, A2 recorded an increase of two links, while A12 and A9 exhibited significant growth, with ten and thirteen additional links, respectively. The substantial expansion in A12 and

A9 is primarily attributed to the extension of Line L4 and the construction of the new Line L5, which was predominantly developed within area A12. The implementation of Line L5, which primarily serves A12 (with only one node extending into A13), is highly beneficial, as the area is predominantly residential. Despite having a lower-than-average population density, the high reliance on private vehicles for daily commuting has contributed to severe congestion. The metro expansion in this area encourages a shift towards high-capacity public transportation, reducing dependence on private cars. In area A9, metro network expansion was accompanied by the development of an intermodal park and ride terminal near Străulești Station, facilitating seamless transit for commuters from the northern outskirts of the city. This infrastructure enhancement is especially beneficial for local residents, as A9's population density surpasses the citywide average, highlighting the critical need for improved public transport.

Figure 3 graphically represents the number of accessible nodes within 15 min (PA 15) for each urban area of the city at two points in time, 2009 and 2024, reflecting the evolution of the metro network.

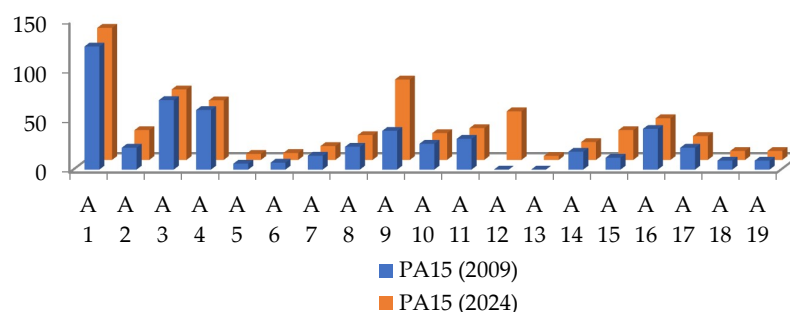


Figure 3. Number of accessible nodes within 15 min.

The results of this analysis align with topological studies that examined the positioning and connectivity of network nodes, as well as with functional analyses that focused on operational parameters such as travel times, dwell times, and transfers within the network.

The areas with the highest accessibility, measured by the maximum number of nodes reachable within 15 min, are A1 (133 nodes), A9 (81 nodes), and A3 (71 nodes). Among these, only area A3 has a population density lower than the citywide average. Conversely, the areas with the lowest accessibility—characterized by the minimum number of nodes reachable within 15 min—are A6 (7 nodes), A5 (6 nodes), and A13 (4 nodes). Notably, area A6 has a population density higher than the citywide average, suggesting that metro network development has not fully aligned with urban growth patterns. When considering nodes accessible within 30 min (PA 30), the accessibility ranking undergoes a slight adjustment, with the new hierarchy being A1 (437 nodes), A3 (228 nodes), and A9 (196 nodes). However, this shift does not have a substantial impact on functional characteristics.

Figure 4 graphically represents PA 15 accessibility in 2024 alongside population density across the study areas.

In Figure 4, the PA 15 accessibility graph should ideally closely follow the shape of the population density graph across all study areas. Such alignment would indicate a strong correlation between accessibility and urban development. However, in reality, this correlation is evident in only a few areas, namely, A1, A9, A16, and A18, and partially in A3 and A12. This suggests that only six out of the nineteen areas exhibit an accessibility pattern that aligns with territorial development. The analysis was conducted for a 15 min travel time threshold, as it reflects contemporary urban planning trends aimed at establishing a 15 min city model. This concept focuses on minimizing daily travel time, thereby enhancing urban quality of life. The same lack of correlation between accessibility and population

density is observed for PA 30 and PA 45, which is why graphical representations for these cases were omitted from this study.

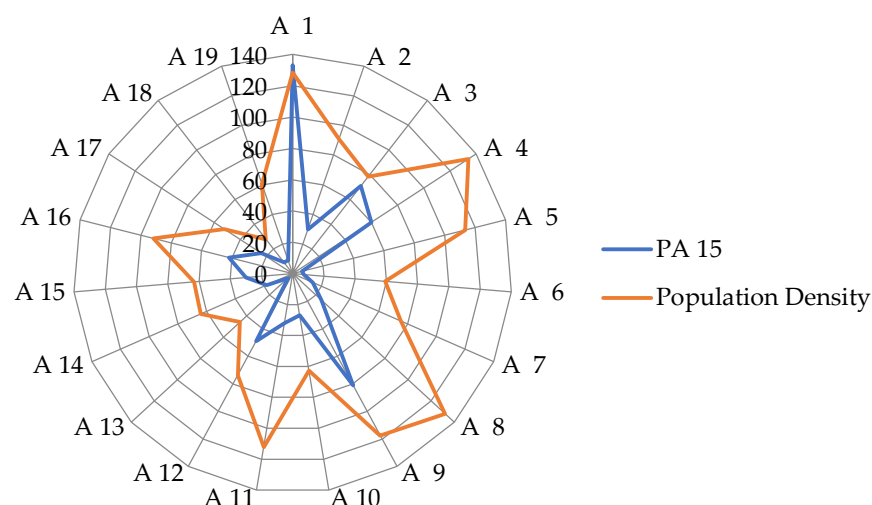


Figure 4. Number of accessible nodes within 15 min and population density.

5. Discussion

5.1. On the Topological Analysis

The topological analysis conducted on the Bucharest metro network graph revealed an increase of three links and three nodes, while the number of stations expanded by 16, distributed across three metro lines: L5, L2, and L4. The network now extends to a total length of 79.36 km, serving an urban area of 232.84 km².

The connectivity indices calculations revealed a decline in their values during the analyzed period (Table 2), as the metro network was expanded geographically without prioritizing the creation of multiple interconnections between the nodes of the graph representing the network. As a result, the network's resilience to operational disruptions has not been significantly enhanced. Future metro network development decisions must strike a balance between expanding service coverage to new areas and enhancing internal connectivity through additional links between existing nodes, ensuring a more robust and efficient transport system.

The same observation is made in [33], namely, that the Bucharest metro network lacks multiple links, which leads to the conclusion that the effective conductance of the network graph is relatively low. The study also highlights an advantage of reduced connectivity, namely, that it can increase the informational resilience of the network by decreasing the probability of failures propagating throughout the system. Although the network's capacity to withstand failures is not high, it provides a reasonable level of robustness, being able to maintain functionality even after the removal of up to 45% of its nodes. Low values of connectivity have also been recorded for the Madrid metro network [74], which, compared to the Bucharest network, comprises 243 nodes and 280 arcs. The network nodes were considered as stations, and the arcs as the connections between them.

The connectivity indices α and γ have values ranging between zero and one, and the values obtained from the calculations fall within these limits for both analyzed instances of the Bucharest metro network, which validates the determinations made in this study. Values closer to unity indicate that the analyzed network has good connectivity, meaning it features multiple links between nodes, making the network less vulnerable and therefore capable of fulfilling its function of transferring flows even in the case of link disruptions. Thus, alternative paths exist. As for the β index, no quantitative evaluations can be made, as it reflects the development of the network in terms of the number of links relative to

the number of nodes. The links are important for the connection between nodes and the network's connectivity, while the nodes are important for access to the network and their territorial area of influence.

For metro networks, connectivity indices are generally low because the implementation of alternative or multiple links is extremely costly due to the high investment values and long execution times. These aspects are also identified in [75], similar to the conclusions reached in our own study. Decisions regarding the development of metro networks target territorial expansion rather than the multiplication of connections. Study [75] performs a comparative analysis of the Shenzhen and Zhengzhou metro networks, which validates the proposed methods.

The limited increase in metro network connectivity is also reported in the city of Nanjing, where between 2005 and 2018, the network expanded by nearly 340 km [76]. It is true that the results regarding improved accessibility and meeting mobility needs have significantly improved; however, the properties defining vulnerability and resilience do not improve in the case of metro networks, as they are extended territorially to cover larger urban areas.

The decision to extend the network must strike a balance between serving new areas and establishing new connections between already existing nodes. Under the current conditions, the decision to establish multiple links should potentially be prioritized, considering that ensuring traffic continuity in the event of failures or attacks on the network is directly dependent on the network's connectivity.

The topological analysis aimed at determining the generalized nodality vector provided a hierarchical ranking of nodes based on the connections established by the graph's links. The hierarchy ranked M_{13} —Piața Unirii in first place, followed by M_{10} —Piața Victoriei in second place, and M_{14} —Eroilor in third place. These are also transfer nodes centrally located within the territory, on the ring that constitutes the backbone of the metro network, serving as points of administrative (M_{10}), healthcare (M_{14}), and commercial (M_{13}) attractiveness.

To eliminate redundancies introduced by the generalized nodality vector, the Shimbél matrix and vector were also employed in the topological analysis. This assessment ranked M_{13} in first place, M_{14} in second, and two nodes— M_{10} and M_{11} (Dristor)—in third place. A comparison of the two analyses indicates that they yield relatively similar results regarding the positioning of nodes within the network. However, it is notable that nodes with a higher number of direct connections to neighboring nodes and a central location within the network tend to provide multiple alternative connections, thereby enhancing overall urban accessibility.

5.2. On the Functional Analysis

The functional analysis focused on dividing the city into 19 areas and determining their surface areas, population numbers, and population densities. This zoning framework was then overlaid with the metro network graph, which included stations positioned as network access nodes (poles). This approach enabled a correlated analysis between the metro network and the territorial system, leading to conclusions concerning the territorial coverage provided by the metro network.

The circular configuration with radial extensions is considered the most suitable network layout in terms of both functionality and accessibility [60]. The study conducts a functional and topological analysis of three network structures—star, triangle, and circle—concluding that the circular configuration is more advantageous, as it allows for the existence of multiple circuits. The Bucharest metro network features a central ring from which

external branches have been developed, making it advantageous in terms of functionality and robustness, as also indicated in [33].

It is emphasized that evaluations should not be limited to topological aspects but should also incorporate functional analyses, such as service frequency and the coordination of timetables at transfer nodes—factors that were likewise included in the functional assessment we conducted [60].

The accessibility assessment based on metro network usage aimed to determine the number of directly accessible nodes, the number of indirectly accessible nodes (requiring a transfer between metro lines), and the number of nodes reachable within 15, 30, and 45 min. The analysis was conducted for all 19 study areas. The obtained values were examined in terms of the benefits derived from network expansion at the two time points under study. Additionally, accessibility levels were compared against population density in each analyzed area to evaluate the alignment between network development and urban distribution patterns.

The accessibility analysis at the two time points revealed that accessibility did not always increase in the areas with the highest population density. This finding underscores the need for metro network expansion studies to be closely aligned with urban development plans, ensuring a more balanced and efficient integration of public transport infrastructure with population distribution and mobility demands.

The lack of correlation between the development of the metro network and population density, as well as urban spatial characteristics—resulting in significant heterogeneity—is also highlighted in [49]. This study analyzed the metro network of Xi'an, China, at two points in time: 2011 and 2021. The topological analyses revealed a decline over time in the values of certain indices and indicators, and the correlation between metro network expansion and population density was found to be inconsistent.

Similar conclusions regarding territorial accessibility through the metro network are presented in [77], aligning with the findings of the present study. In [77], two accessibility concepts are defined and measured: attraction accessibility and radiation accessibility. The former depends on the ease of access to the nearest metro station, while the latter is influenced by the station's position within the network. Transfer stations exhibit the highest radiation accessibility, whereas terminal stations tend to have lower accessibility. This conclusion confirms our own findings, as the nodes with the highest accessibility correspond to inter-line transfer points.

The same concept of attraction accessibility is also addressed in study [78], which examines the improvement of urban area accessibility by increasing the accessibility of public transport stations. This is achieved through the use of electric scooters to reduce the travel time from home to the nearest public transport line. As a result, the territorial accessibility of public transport networks is enhanced through environmentally friendly multimodal travel.

The population density graph and the accessibility graph for 2024 indicate that only 6 out of the 19 areas exhibit a strong correlation between these two variables, representing approximately 32% of the study areas. This finding further reinforces the importance of prioritizing metro network development in alignment with the socio-economic characteristics of urban areas.

It can be stated that balancing the mobility needs of the city is also achieved through the use of other surface urban public transport modes. However, a comprehensive analysis of this aspect will be conducted in a future study by the research team.

6. Conclusions

The motivation for this study stems from the increasingly complex urban challenges confronting Bucharest, particularly the sharp rise in motorization and population density. These dynamics have intensified and diversified territorial activities, leading to escalating road traffic congestion and a consequent decline in residents' quality of life.

A review of the relevant literature highlights that the enhanced utilization of high-capacity urban public transport systems—most notably metro networks—is among the most effective approaches for mitigating congestion.

This research undertakes an integrated topological and functional analysis of the Bucharest metro network, with a focus on its evolution between 2009 and 2024. The year 2009 was chosen as a baseline, marking the last major phase of network expansion.

The topological analysis involved the calculation of connectivity indices at two time points, along with the application of the generalized nodality matrix and vector, and the Shimbel matrix and vector. Results indicate that, although the network expanded by 12.41 km (18.6%) during the period under analysis, connectivity indices declined by nearly 24%, with potential implications for the network's resilience and vulnerability.

The generalized nodality vector ranked the top three nodes as M13—Piața Unirii, M10—Piața Victoriei, and M14—Eroilor. This reflects the privileged position of these nodes within the network, indicating that travel from these points in any direction can be achieved with a minimal number of arc traversals. Their strategic location suggests a potential for prioritizing socio-economic development in their immediate vicinity.

The analysis of the metro network using the Shimbel nodality index yielded results identical to those obtained through the generalized nodality vector, thereby validating the findings produced by both methodological approaches. The functional analysis contributed to this study in several ways: by determining the number of metro stations (poles) in each urban zone, evaluating the accessibility characteristics of the 19 designated analysis zones, and assessing accessibility in terms of the number of metro stations that could be reached within specific time intervals.

The resulting accessibility characteristics enabled the ranking of the study zones in terms of accessibility and provided insights into the areas with the lowest levels of accessibility, which should be prioritized in future metro network development efforts. Specifically, zones A13, A5, and A6—identified as having the fewest metro stations—should be targeted for future network extensions. These zones are predominantly residential and have direct connections to peri-urban areas that exhibit strong potential for future residential development.

Notably, by 2024, all urban zones had access to at least one metro station, illustrating the network's comprehensive spatial coverage across the city. Furthermore, the time-based accessibility analysis consistently ranked Zone A1 as the most accessible in both 2009 and 2024. This outcome suggests that recent expansions have effectively targeted previously underserved areas, a finding that aligns closely with the conclusions drawn from the topological analysis.

The scientific contributions of this study lie in the application and development of topological concepts from graph theory—particularly the concept of connectivity, which was further refined and adapted for the context of transport network analysis. Applying these principles to metro network evaluation yields relevant, evidence-based insights into how such networks can be developed or expanded to enhance overall capacity and resilience against external disruptions, ultimately reducing network vulnerability.

This study also highlights several limitations, notably the inherent variability of transport demand, which is driven by rapid and ongoing socio-economic transformations. Such changes frequently surpass the pace of public transport network development, resulting

in a growing dependence on private vehicles. Moreover, the slow progression of network expansion—due to high capital investment requirements and extended implementation periods—underscores the importance of designing transport infrastructure with long-term adaptability and resilience in mind.

Future research directions stem from the fact that Bucharest currently ranks first in Europe in terms of traffic congestion. This situation reinforces the need for further studies aimed at identifying the root causes of congestion and developing proposals to reduce it, particularly by enhancing the appeal and effectiveness of urban public transport systems.

Author Contributions: Individual contributions of the authors, Conceptualization, V.D.; Methodology, V.D., F.C.O., and E.A.R.; Validation, V.D.; Formal analysis, E.A.R.; Investigation, F.C.O.; Writing—original draft preparation, V.D. and E.A.R.; Writing—review and editing, V.D. and E.A.R.; Visualization, F.C.O. and E.A.R.; Supervision, V.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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

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