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Street Network Orientation, Entropy and Circuity of Eight Metropolitan Cities in Indonesia

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Abstract: Population growth and urban development in Indonesia have led to an increased demand for efficient road infrastructure to support economic activities and human mobility. The street network plays a crucial role in shaping the spatial structure and morphological characteristics of a city. This study aims to identify street network orientation, entropy, and circuity patterns and to classify their typologies across eight metropolitan cities in Indonesia. The analysis utilized secondary data from OpenStreetMap (OSM), processed through the OpenStreetMap NetworkX (OSMnx) software. The three main variables analyzed were orientation, entropy, and circuity. The results reveal that metropolitan cities in Indonesia exhibit varying street network patterns, which include both grid-like and dispersed forms. Based on the clustering analysis, the cities were grouped into four clusters: Cluster 1 comprises only Medan; Cluster 2 includes Surabaya; Cluster 3 comprises Bandung, Jakarta, Makassar, and Semarang; and Cluster 4 contains Bandar Lampung and Palembang. The results show that cities in different clusters require distinct planning approaches due to the varying characteristics of their street networks. These findings provide valuable insights into the organization and structure of urban street networks, offering a foundation for more efficient and sustainable transportation infrastructure planning at the national level.

Keywords: circuity, entropy, Indonesia, metropolitan, orientation, street network

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1. Introduction

Morphology is the study of the shape of a city [1], which is composed of three main components: land use, street network patterns, and building patterns [2]. As population growth tends to lead to the natural expansion of street networks, often without careful planning, it can impact the regularity of these networks.

Indonesia, home to 281.6 million inhabitants [3], continues to experience growth, particularly in its metropolitan and provincial capital cities. Urban population growth is driven by factors such as mortality, natality, and migration [4]. Migration, a natural phenomenon, is often linked to economic development and improved living standards, as people move in search of better job opportunities, healthcare, and education [5]. This increased population puts pressure on the need for adequate street network infrastructure to support economic activities and mobility [6].

The street network regulates urban transport dynamics, whether planned or unplanned, regular or irregular [7]. By modeling the street network, it is possible to calculate its orientation, entropy, and circuity, providing insight into its regularity and efficiency. Understanding the patterns of urban street networks helps assess the organization and functionality of the street network in metropolitan cities, which often display varying patterns [8].

The structure of space in a city is influenced by the dynamics of socioeconomic activities and several factors such as the region's hierarchy, urban system, connectivity, and center-periphery relationships. The street network is a key element in regional development, connecting urban and rural areas and enabling the flow of people and goods [9]. Roads serve as vital infrastructure, promoting regional development and contributing to equitable growth [10].

Street networks tend to form patterns based on movement dynamics. A common pattern in planned cities is the orthogonal grid, which was used during the Middle Ages to maximize sunlight exposure on east–west roads during the winter [11]. In contrast, cities that developed organically, based on population dynamics and land use changes, may still exhibit well-structured networks despite less clearly defined spatial orientations.

Street network modeling can be done through infrastructure engineering, which involves trip generation and attraction models to estimate the impact of transportation on the surrounding environment. This process involves estimating both the number of trips originating from a zone and the number of trips attracted to it [12].

In this study, street network grouping is based on three factors: orientation, entropy, and circuity, all of which are analyzed using OpenStreetMap (OSM) and OpenStreetMap NetworkX (OSMnx). The orientation reflects the diversity of street directions in a city, measured by the orientation distribution value (H), which is represented in a polar diagram with 36 bins corresponding to cardinal directions. Planned cities typically exhibit an orthogonal grid pattern [7]. Entropy measures the degree of regularity in a street network, with higher entropy values indicating a grid-like structure, while lower values reflect more organic and diffuse development [7]. Finally, circuity is the ratio of actual travel distance to the straight-line distance between the origin and destination, and is used to assess the efficiency of the street network. A higher circuity value indicates that travel distances are longer than the straight-line route [13].

While previous studies have analyzed street networks in developed countries [7], there is a lack of quantitative analysis regarding the morphological typologies of Indonesia's rapidly growing metropolitan areas. This study aims to fill that gap by employing a quantitative approach to identify the orientation, entropy, and circuity patterns of street networks in eight Indonesian metropolitan cities. Unlike traditional qualitative morphological studies, this research utilizes OSMnx to computationally classify city typologies, offering a novel foundation for efficient transportation infrastructure planning at the national level.

2. Materials and Methods

2.1. Study Area

The study area was selected based on population criteria, specifically targeting provincial capitals with a population exceeding one million people, which are classified as metropolitan cities. Metropolises typically have a large and complex urban structure, often accompanied by more intricate social dynamics compared to smaller cities. One key contributing factor is population mobility. Higher levels of population mobility lead to increased transportation demands and a greater need for road infrastructure [6]. Cities that are object of research can be seen in Table 1.

Table 1. Study area

No.	City	Area [km^2]	Population
1	Bandar Lampung	183.77	1,100,109
2	Bandung	167.31	2,506,203
3	DKI Jakarta*	660.98	10,672,100
4	Makassar	175.77	1,474,393
5	Medan	281.99	2,474,166
6	Palembang	352.51	1,772,492
7	Semarang	373.78	1.694,740
8	Surabaya	326.81	3,009,286

* DKI Jakarta (Daerah Khusus Ibukota Jakarta) – Special Capital Region of Jakarta.

Source: [3]

The research sites were located across three islands and included eight distinct provincial capitals in Indonesia. Metropolitan cities typically exhibit high levels of mobility and serve as hubs of urban activity, supporting a wide range of economic, social, and infrastructural functions.

The eight cities included in this study are: Bandar Lampung, Bandung, Jakarta, Makassar, Medan, Palembang, Semarang, and Surabaya as seen in Figure 1.

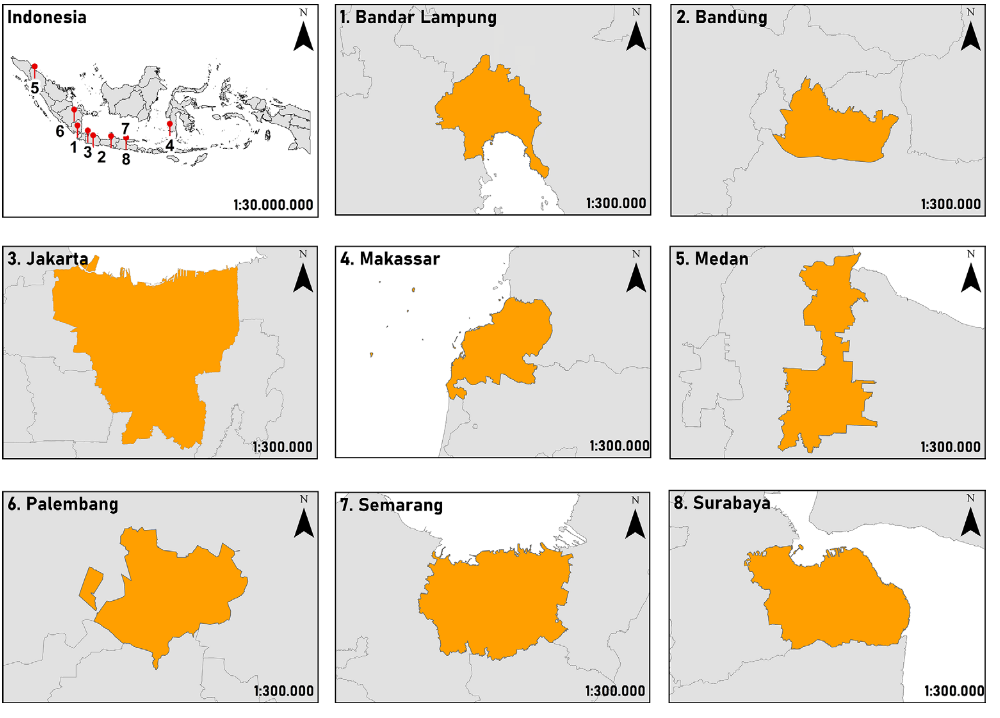

Fig. 1. Study area of the metropolis cities in Indonesia
Source: https://tanahair.indonesia.go.id/portal-web/

2.2. Methods

This study utilizes OpenStreetMap NetworkX (OSMnx), a free, Python-based, open-source tool for acquiring data on administrative boundaries, buildings, and street networks sourced from OpenStreetMap (OSM), a web-based mapping platform built on voluntary contributions from users around the world. OSM has grown rapidly and has provided urban researchers with access to a rich, open-source repository of global geospatial data. Several early studies indicate that OSM road network data can be effectively used to identify urban structural patterns. Recent studies also suggest that the quality of OSM data has improved, particularly for larger cities [8]. OSMnx enables complex visualization and analysis of street network data. It can download street network data and generate a topologically corrected network, which is then projected and can be exported in various formats such as Shapefile, SVG, and GraphML for further use [14]. OSMnx allows users to download data for any place name, address, or polygon worldwide using OSM data [15]. In this research, OSMnx was used to obtain shapefiles of administrative boundaries and street networks from OpenStreetMap. These shapefiles were then processed and utilized in the ArcGIS platform to generate street network maps for each city.

To better understand street network entropy, we calculated the degree of order and disorder within each city using Shannon entropy, which describes the pattern and distribution of street orientations [16]. Shannon entropy was used to quantify the street network's structure, following the method developed by Geoff Boeing [7]. This approach involves calculating the bearing of each street segment and grouping them into 36 equal-sized bins using a polar histogram to represent the full 360 degrees of street orientation. This study uses three variables:

– orientation,
– entropy,
– circuity.

Street network **orientation** refers to the diversity of directions in which roads are laid out in a city, as indicated by the distribution of their orientations. A street network with a perfect orientation distribution has a value of 1.386 nats, while one with the maximum orientation distribution has a value of 3.584 nats [7]. The **entropy** of a street network reflects the degree of regularity within the network. Entropy values close to 1 indicate a higher level of regularity in a city's street network, while values farther from 1 indicate lower regularity [7]. **Circuity** represents the ratio of the average actual distance traveled to the straight-line distance between the origin and the destination of a trip. It is used to measure the efficiency of a street network – specifically, how much farther people must travel when following the street network compared to a straight-line route. A circuity value of 1 means that the travel distance matches the straight-line distance. A circuity value greater than 1 indicates that the street network requires longer travel distances than a straight-line path [13]. To obtain the values for street network orientation, entropy, and circuity, three equations were used.

Equation (1) calculates the orientation distribution of the street network in a polar histogram:

$$H_o = -\sum_{i=1}^{n} P(o_i)\log P(o_i) \tag{1}$$

where H_o represents the Shannon entropy value, n is the total number of bins, i indexes each bin, and $P(o_i)$ represents the proportion of orientation on the i-th bin.

The process of the orientation analysis can be seen in Figure 2.

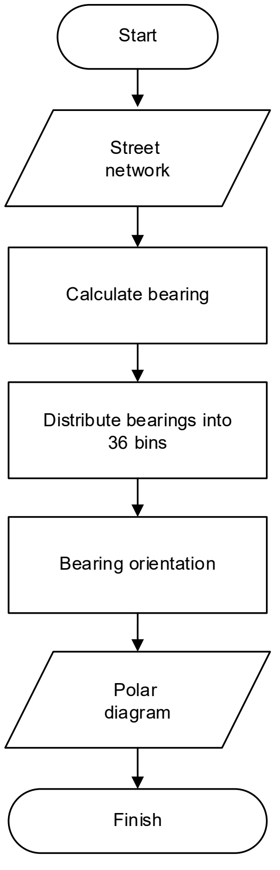

Fig. 2. Flowchart of orientation analysis

Equation (2) is used to measure orientation order and disorder:

$$\varphi = 1 - \left(\frac{H_o - H_g}{H_{\max} - H_g} \right)^2 \tag{2}$$

where φ represents the degree of order, where values closer to 0 indicate complete disorder or uniformity, and values closer to 1 indicate a perfectly ordered or grid-like street network. The maximum entropy (H_{max}) value is 3.58 nats while the perfect grid entropy value (H_g) is 1.386 nats [7]. In this case, "perfect" refers to a grid-shaped road network with street orientations occurring in four orthogonal directions. A nat is a dimensionless natural unit of information, used in this context because Shannon entropy is calculated using the natural logarithm.

The process of the entropy analysis can be seen in Figure 3.

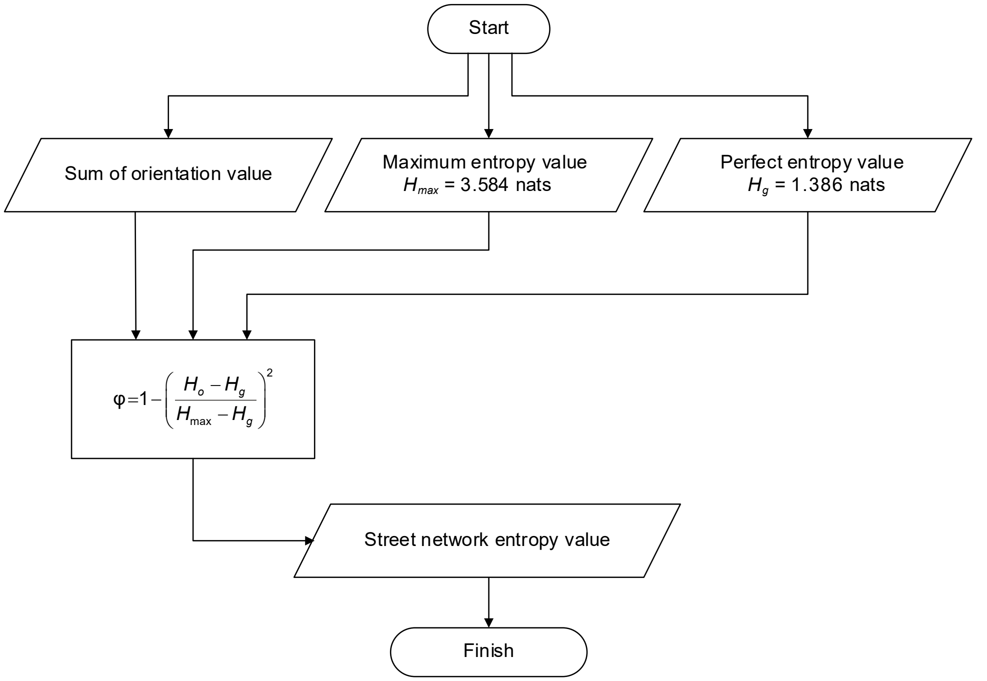

Fig. 3. Flowchart of entropy analysis

The effectiveness of a street network is evaluated by its circuity, which compares the distance of a typical journey along the network to the straight-line (or geodesic) distance between origin and destination.

Equation (3) is used to calculate the average circuity of the street network:

$$\varsigma=\frac{L_{net}}{L_{gc}} \tag{3}$$

where ς represents the average circuity, L_{net} denotes total street length, and L_{gc} refers to the sum of all great-circle distances between pairs of adjacent nodes.

The process of the circuity analysis can be seen in Figure 4.

Cluster analysis is a multivariate technique used to group variables based on their characteristics. The primary objective of cluster analysis is to classify cases or variables into relatively homogeneous groups. A good cluster exhibits high similarity among the cases within the same cluster and significant differences between clusters [17]. Cluster analysis is used to classify cities based on similarities in street network structural indicators derived from OSMnx.

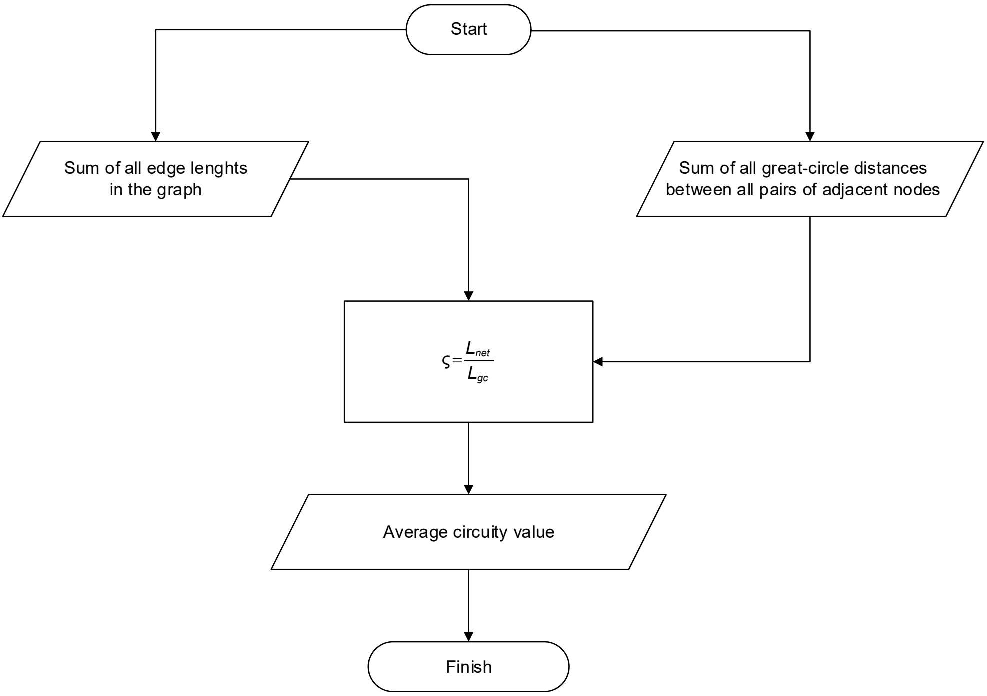

Fig. 4. Flowchart of circuity analysis

To achieve this goal of grouping similar cases, a measure is required to determine the degree of similarity or dissimilarity between cases. In cluster analysis, three measures are commonly used to assess similarity among objects or cases: association strength, correlation size, and proximity size [18]. Similarity between cases can be determined based on the correlation coefficient between pairs of cases, which is measured using multiple variables.

The hierarchical method is a technique that groups cases based on their similarities, starting with the most similar pairs and progressively merging other cases that share similarities with the preceding cases. This process continues until a hierarchy or level of relationships is formed among the cases [19]. In conducting cluster analysis using SPSS software, the data obtained through network analysis are organized in tables according to their respective cities. The hierarchical method was used to classify the street network along a continuum from more ordered to less ordered configurations.

3. Results and Discussion

The research findings revealed a diversity of street network patterns across Indonesia, combining grid-like configurations with multi-oriented street networks. Below are the indicator values for each city studied, listed in alphabetical order (Table 2).

Table 2. Result indicator for each city

No.	City	Orientation (*H*)	Entropy (φ)	Circuity (ς)
1	Bandar Lampung	3.510	0.066	1.065
2	Bandung	3.380	0.177	1.063
3	DKI Jakarta*	3.399	0.161	1.067
4	Makassar	3.444	0.123	1.068
5	Medan	2.921	0.512	1.049
6	Palembang	3.575	0.008	1.068
7	Semarang	3.441	0.126	1.069
8	Surabaya	3.277	0.260	1.053

* DKI Jakarta (Daerah Khusus Ibukota Jakarta) – Special Capital Region of Jakarta.

Source: elaboration using OSMnx

To better visualize the results for each indicator, we use bar charts to compare the values of each indicator across the metropolitan cities in Figure 5.

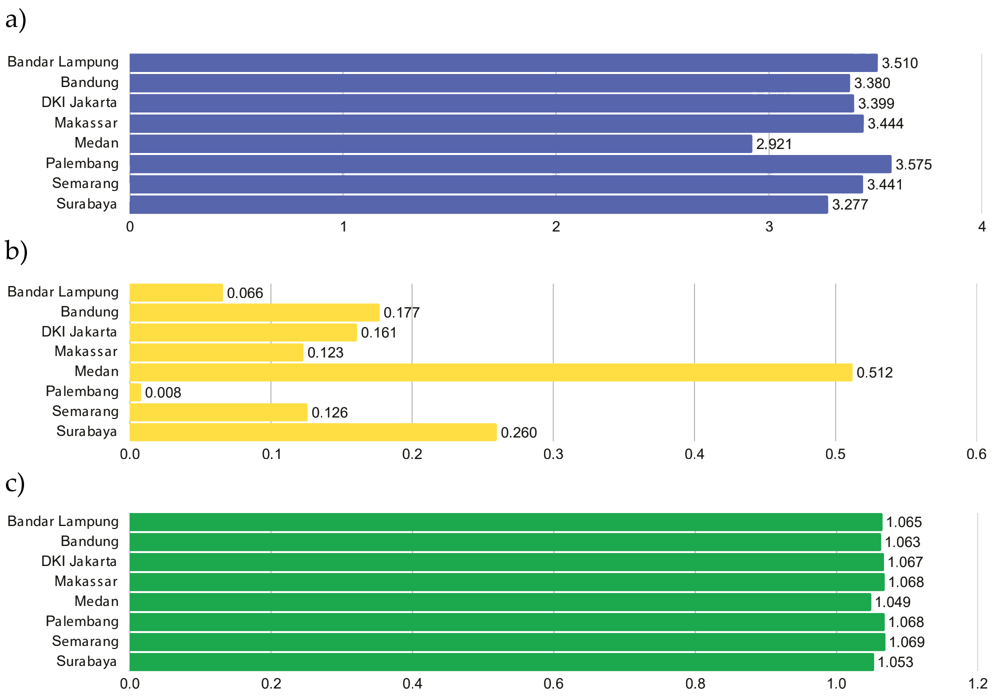

Fig. 5 Indicator values for each metropolitan city:
a) orientation value; b) entropy value; c) circuity value

Source: elaboration using OSMnx

3.1. Street Network Orientation

The research findings revealed a diversity of street network orientation across Indonesia, combining both more varied and less varied street networks. As shown in Table 2, among the metropolitan cities, Medan has the lowest orientation distribution value at 2.921 nats. In contrast, Bandar Lampung and Palembang have the highest orientation distribution values, with 3.510 nats and 3.575 nats, respectively, compared to the maximum possible value of 3.584 nats. This indicates a variation in street-network patterns across metropolitan cities in Indonesia.

Based on historical factors, Bandar Lampung's strategic location plays a significant role in shaping its street network and city layout. As a transit point connecting areas such as Bengkulu Province and Palembang City, these routes facilitate trade and transport, supporting economic activity in the region. Bandar Lampung's street network follows a dispersed pattern, and the city's hilly topography has contributed to a circular and winding street network design [19].

Jakarta's street network has evolved since the Dutch colonial period, with construction aimed at connecting the centers of government and trade. The resulting street network follows a grid or regular pattern. After Indonesia's independence, the government began constructing inner and outer ring roads to alleviate congestion in the city. The Jakarta city government continues to optimize the street network by developing new roads and implementing a system of arterial, collector, and local roads to enhance traffic efficiency and connect various areas within and around the city [20]. The orientation distribution values for each city are visualized using polar histograms in Figure 6.

Figure 6 illustrates the diversity of street network orientations, represented by the orientation distribution values of metropolitan cities. Medan's street network is primarily directional, with its streets concentrated in four polar diagram bins, showing minimal distribution in other bins. In contrast, Palembang's street network is spread across all directions. In the polar diagram, each bin is nearly fully filled, indicating that the orientation of Palembang's street network extends in all directions. Bandar Lampung exhibits a diverse street network orientation, with four fully filled bins and others partially filled, suggesting that the street network spreads throughout the city.

Figure 6 shows that Jakarta and Surabaya have street networks with diverse orientations, as all four bins (representing north, south, east, and west) are fully filled. Meanwhile, Bandung, Semarang, and Makassar exhibit diverse street network orientations, with each bin filled and the street network spreading in all directions.

Cities with higher orientation distribution values exhibit more diverse street network directions compared to cities with lower orientation distribution values. This is because a city with a higher distribution value has a more varied street network, offering more directional options for road users.

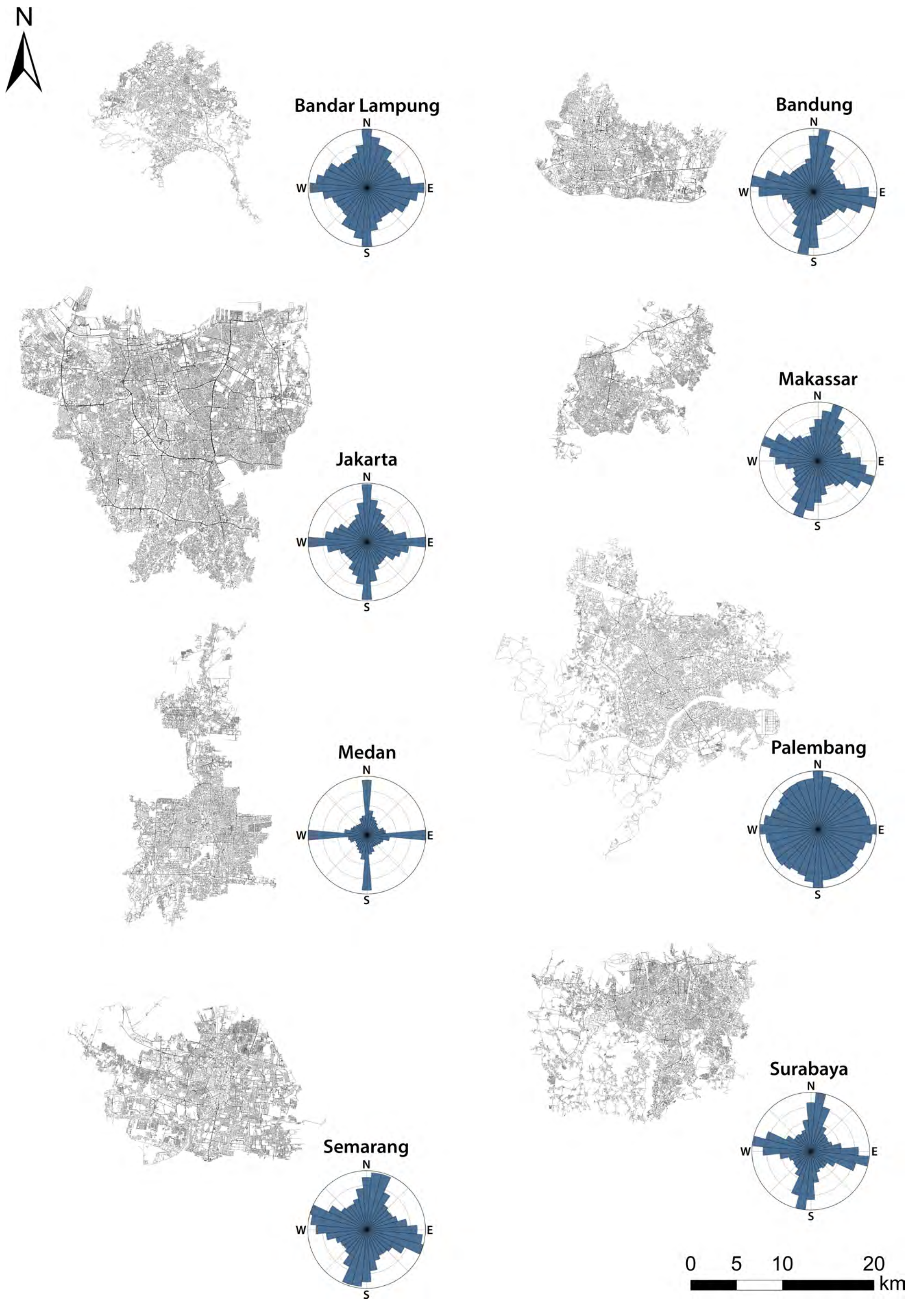

Fig. 6. Street network and its polar diagram

Source: elaboration using OSMnx

3.2. Street Network Entropy

Street network entropy measures the level of regularity within a street network. The research findings revealed a diversity of street network patterns across Indonesia, combining both grid-like and multi-oriented street networks.

From Figure 5, it is evident that Medan has the highest entropy value at 0.512 (out of a maximum of 1), while Palembang has the lowest entropy value at 0.008. The polar histograms for the corresponding cities are sorted from the least-oriented (most grid-like) city to the most-oriented (least grid-like) city based on their entropy values. Figure 6 further illustrates that metropolitan cities in Indonesia exhibit a mix of street patterns throughout the city. Medan is the most ordered city, followed by Surabaya. Jakarta, Bandung, Semarang, and Makassar show similar street network patterns, combining both uniform and grid-like elements. Meanwhile, Bandar Lampung and Palembang are the least ordered cities, with entropy values of 0.066 and 0.008, respectively.

Several factors influence the level of regularity in a street network, including geographical and historical conditions. Palembang's street network originally developed along the Musi River during the Srivijaya period (7th–13th century), and this river-oriented structure persisted for centuries, shaping the city's present-day layout. As one of Southeast Asia's oldest cities, Palembang has undergone significant changes in its street network and urban morphology. In the 17th century, the street network continued to follow the Musi River, serving as a transportation route reflecting its long-standing function as a major trading hub. By the early 19th century, colonial influences and growing urbanization contributed to the development of a more concentric street network. Post-independence, Palembang evolved into a polycentric city, as urban expansion and diversified land uses produced a more complex street network to accommodate various functions [21].

There is a clear correlation between street network orientation and its entropy value. Cities with higher entropy values, closer to 1 (like Medan), tend to exhibit grid-like street network patterns, while cities with lower entropy values tend to have more uniform or circular street networks. Palembang's extremely low entropy value (0.008) quantitatively confirms its organic historical development. For example, Figures 6 shows two cities with the highest and lowest entropy values, respectively.

In Figure 5, Medan has the lowest orientation value, while Palembang has the highest orientation value, nearly reaching the maximum of 3.584 nats. In terms of entropy, however, their results are opposite: Medan has the highest entropy value, while Palembang has the lowest. Historical factors have also influenced city planning; for instance, in 1863, Medan began to transform into a plantation town, influenced by European entrepreneurs and farmers. This period marked the beginning of structured urban planning in Medan, as the city grew to accommodate agricultural and trade activities [22].

3.3. Street Network Average Circuity

Average circuity measures the ratio of the actual travel distance to the straight-line distance between the starting point and the destination of a trip. Circuity helps assess the efficiency of a street network by indicating how much further ordinary travel is when following the street network compared to traveling in a straight line.

Figure 5 shows that Medan and Surabaya have the least circuitous street networks, with 4.9–5.3% greater circuity than the straight-line distances, owing to their straight, gridded streets. In contrast, Bandar Lampung, Palembang, and Semarang have the most circuitous street networks, with 6.5–6.9% greater circuity than the straight-line distances, influenced by topographic conditions and historical development.

The development of Surabaya's street network has been shaped by various factors, including historical, economic, social, and urban development processes. In the 18th century, development focused on the port area, and a network of roads was built to connect the port with the trading center, forming a linear street network pattern running north-south. Infrastructure development, including railroads and highways in the late 19th century, supported the mobility of goods and people and facilitated economic growth [23]. After Indonesia's independence, Surabaya experienced significant growth as its street network expanded to accommodate population growth and support economic activity. The street network became more scattered, with a dominant north-south orientation and inadequate access to the city's west-east areas [24]. Over time, the city's development became more organic and irregular, with many areas built without careful planning, resulting in a more fragmented network pattern [25].

Semarang's street network pattern was influenced by its geographical location as a major port. Initially, the street network formed a radial pattern, connecting the city center with the port. Other streets leading to the Central Square became centers of economic and social activity for various ethnic communities, such as the Chinese, Arabs, and Malays. During the colonial period, the street network in Semarang was systematically planned to support trade activities. The central commercial corridor emerged organically alongside the economic growth of the area [26].

3.4. Street Network Cluster

Next, we use cluster analysis to classify the street networks of cities by examining the characteristics of each network, which were analyzed using OSMnx software. Hierarchical cluster analysis was conducted to group cities with similar characteristics into one cluster [19]. From the cluster analysis, the results can be interpreted through the dendrogram in Figure 7, which illustrates the similarity between the street networks of metropolitan cities.

The structure of the dendrogram shows that two main clusters emerge: the first cluster contains Medan, while the second cluster includes all other cities. For a more detailed insight, an alternative clustering approach can be applied, resulting in four clusters. Cluster I consists solely of Medan; Cluster II includes Surabaya; Cluster III includes Makassar, Semarang, Bandung, and Jakarta; and Cluster IV consists of Palembang and Bandar Lampung.

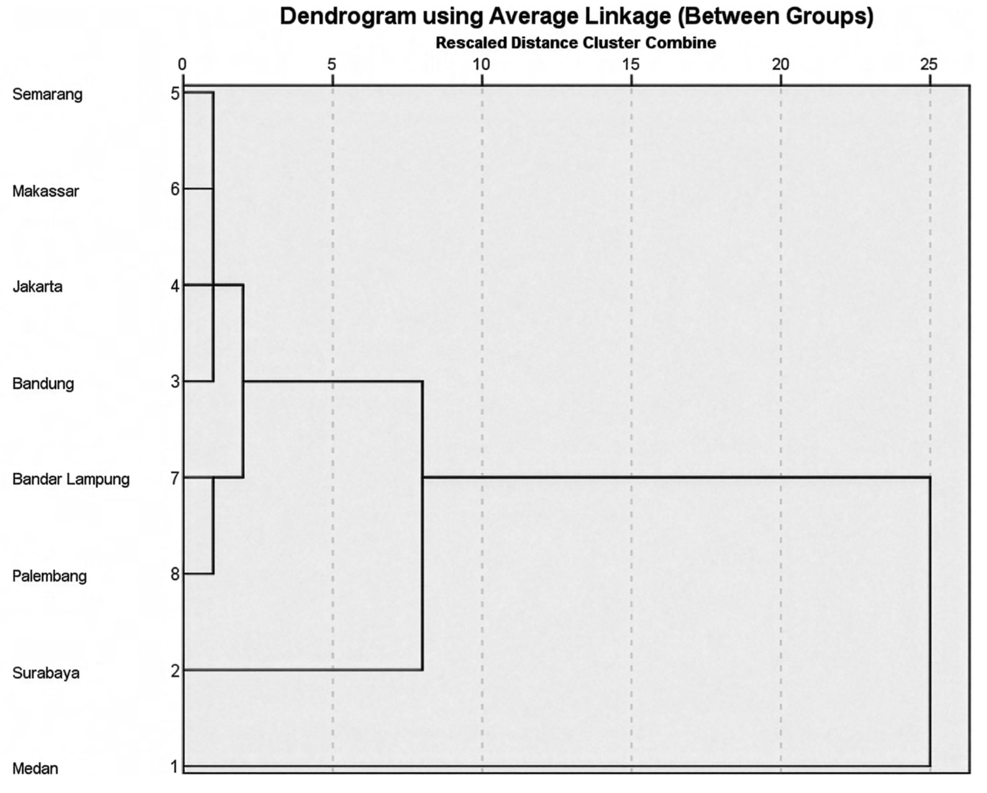

Fig. 7. Cluster analysis dendrogram

Source: elaboration using SPSS

4. Conclusion

Based on the results, we can conclude that Medan is the most ordered city among the metropolitan cities, with the lowest orientation value due to its straight, grid-like street networks. This indicates that Medan lacks variation in its street network directions. On the other hand, Palembang is the most disordered city in the sample. It also has the highest orientation value, reflecting the greater variation in its street network, which can be attributed to historical factors.

In terms of circuity, Medan has the lowest value, with an average value of 1.049, indicating that 4.9% of the street network is more winding than the straight-line distance. Conversely, Semarang has the highest average street network circuity, at 1.069, indicating that 6.9% of its street network deviates from the straight-line distance.

The clustering analysis, based on shared characteristics of the street networks, revealed two alternative groupings. In the first grouping, Medan forms its own cluster, while the other cities cluster together. In the second grouping, the cities are divided into four clusters: Group I consists of Medan, Group II consists of Surabaya, Group III includes Makassar, Semarang, Bandung, and Jakarta, and Group IV contains Palembang and Bandar Lampung.

Orientation, entropy, and circuity serve as quantitative morphological metrics that allow planners to move beyond qualitative descriptions to operationally assess the organization, efficiency, and functionality of urban street networks. **Orientation** serves as a measure of directional connectivity and quantifies the diversity of street directions within a city. In assessing street-network connectivity, this metric identifies whether a network offers varied directional options or follows a rigid alignment. A higher orientation value indicates a network distributed across all directions, often found in organically developed cities. A lower orientation value indicates a network concentrated in specific directions (e.g., the cardinal directions of a grid), which can signal a planned, directional connectivity structure. In a historical context, planned cities often utilize orthogonal grids to maximize specific connectivities (e.g., sunlight exposure or connecting government centers), whereas organic networks develop based on population dynamics and topography, resulting in less defined spatial orientations.

Entropy is a measure of network regularity and captures the degree of order and regularity within a street network. It functions as an order-disorder metric. Higher entropy values (closer to 1) indicate a high level of regularity and a grid-like structure, which is associated with planned urban forms. High entropy (high order) often correlates with better connectivity and reduced circuity. For instance, cities with grid-like structures (high entropy), like Medan, tend to have lower circuity compared to disordered cities like Palembang. Meanwhile, lower entropy values reflect disordered, organic, or diffuse development.

Circuity is the primary indicator for network efficiency. Cities with higher circuity signify winding, organic, or disconnected roads, which contribute to fuel consumption, travel delays, and mobility constraints. Conversely, lower circuity values (e.g., 1.049 in Medan) indicate straighter, more direct routes, typical of grid-like patterns that facilitate efficient movement.

These indicators transform the study of urban form from qualitative observation to quantitative classification, enabling planners to benchmark cities against one another using computational tools like OSMnx. Benchmarking allows policymakers to tailor interventions based on specific morphological deficits. For cities in the disordered cluster, planning should focus on improving connectivity between organic, winding arterial roads to reduce travel distances. For cities in the ordered cluster, planning can focus on maintaining the efficiency of the existing grid.

These indicators also allow planners to benchmark current performance against historical or geographical contexts. For example, a high circuity benchmark in Bandar Lampung can be quantitatively linked to its hilly topography and sprawling urban form, whereas low circuity in Surabaya reflects its historical development around port-connected rail and highway infrastructure.

While these specific metrics focus on the road network, broader morphological benchmarking can also integrate building and region-level metrics (such as building density, road length, and fractal dimensions) to classify functional areas (e.g., commercial vs. residential) and assess their relationship with environmental factors like land surface temperature [27]. However, for street network efficiency specifically, the combination of orientation, entropy, and circuity provides the critical set of morphological metrics required to guide national transportation infrastructure planning.

The implications of this study for national policy highlight the importance of efficient street network planning, particularly in metropolitan cities. Such morphological metrics provide a data-driven foundation for urban policy. The findings suggest that cities with better orientation patterns and more efficient street circuity tend to have higher connectivity. For cities in the "disordered' clusters (e.g. Bandar Lampung and Palembang), planning interventions should focus on improving connectivity between organic, winding arterial roads to reduce the high circuity (>1.065) that likely contributes to fuel consumption and travel delays. In contrast, cities with lower entropy values face mobility constraints. Therefore, urban street network planning should aim to reduce irregularities and improve traffic efficiency. This research can serve as a foundation for planning strategies to reduce traffic congestion, pollution, and regional inequality, while also enhancing the quality of life for urban residents. To further understand Indonesia's street networks, additional research into street patterns, entropy, and circuity is recommended across different scales.

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CRediT Author Contribution

Z. A. M.: conceptualization, data curation, formal analysis, investigation, methodology, resources, software, visualization, writing – original draft preparation, writing – review and editing.

S. A.: conceptualization, supervision, validation, visualization.

F. A.: conceptualization, supervision, validation, writing – review and editing.

Declaration of Competing Interests

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

All data used in this study are publicly available from https://www.openstreetmap.org/.

Use of Generative AI and AI-Assisted Technologies

An AI-assisted technologies were employed in the preparing the alt texts description.

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