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Enhancing Regional Resilience through Entropy Analysis of Road Networks: A Case Study of West Kalimantan Province

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***Abstract*— This research provides insights into the complexity of the road network layout in the regencies and cities of West Kalimantan Province through an analysis of entropy levels in the road networks across various cities in the province. This study aims to analyze the entropy levels of the road networks in the regencies and cities of West Kalimantan Province. In this context, entropy analysis provides insights into urban structure and the role of road networks in shaping city characteristics and understanding resilience and vulnerability. The results indicate that the entropy values of the road networks in West Kalimantan Province range between 3.4 and 3.5. Based on the entropy analysis, there are three groups of road networks in West Kalimantan Province: low, medium, and high. Regencies and cities with low entropy values (between 3.46 and 3.48) include Pontianak City and Singkawang City. Regencies and cities in the medium category (entropy values between 3.49 and 3.56) include Kayong Utara Regency, Ketapang Regency, Kubu Raya Regency, Sintang Regency, and Mempawah Regency. Regencies and cities with high entropy values (above 3.56) include Sambas Regency, Melawi Regency, Kapuas Hulu Regency, Bengkayang Regency, Sekadau Regency, Sanggau Regency, and Landak Regency. Several factors contribute to the entropy values of the road networks in the regencies and cities of West Kalimantan Province, including topography and geography, population density, infrastructure development, economic and social factors, urban planning, and traffic management.**

***Keywords*— Resilience; entropy; West Kalimantan.**

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I. INTRODUCTION

Cities are complex systems that evolve spatially [1]. Each city possesses unique characteristics reflected in its physical form, road network systems, and spatial layout. The development of modern cities goes hand in hand with the increasing complexity of road networks [2]. The transition of metropolitan areas, cities, or villages from past to present conditions illustrates the process of urban growth, impacting the form and structure of cities [2], [3]. Uncontrolled urban growth is known as urban sprawl [4]. Refers to the rapid expansion of a city's geographical area, often characterized by low-density settlements, single-use zones, and increased reliance on private automobiles for transportation [5], [6].

Urban road networks play a crucial role in shaping the characteristics of a city [7], [8], [9]. They constitute the fundamental infrastructure of urban areas or regions and provide valuable information that helps to characterize the dynamics of human activity space [10], [11]. The Network structure analysis is to understand resilience and vulnerability[12]. The factors that influence the vulnerability of urban road network factors are the layout of internal road networks, the structural strength of the networks, and external events, which have high uncertainty and complexity [13]. The concept of entropy in urban systems and the key aspects are crucial [14], [15]. Studies on entropy and regularity in urban road networks play a central role in understanding urban dynamics and their impact on population mobility, transportation patterns, and sustainable urban development [2], [7]. Urban planners have started using contemporary digital technology to measure and control urban sprawl [16]. Urban sprawl requires spatially based solutions from urban policymakers to analyze utilities, transportation, and other infrastructure [4] Transportation connectivity can also serve as a basis for spatial analysis approaches [17], [18].

This study provides insights into the complexity of the road network layout in Districts and Cities in West Kalimantan

Province based on entropy analysis of the road networks. In the context of West Kalimantan Province, entropy analysis offers insights into urban structure and the role of road networks in shaping city characteristics. West Kalimantan Province has several cities experiencing rapid growth and significant urban development. This study employs the concept of entropy to analyze the complexity levels of road networks in Districts and Cities in West Kalimantan Province. The role of the Entropy study is to monitor and manage urban sprawl, which impacts the lives and the future of residents and our civilization [4]. Entropy is a level of randomness or disorder in a system, while regularity refers to the level of structure or organized patterns within that system [2].

This research utilizes road network data from Districts and Cities in West Kalimantan Province to analyze the relationship between entropy and regularity in the context of urbanization. The integration of digital technology into urban planning and development processes not only mitigates the negative impacts of urban sprawl but also fosters cities that are more sustainable and livable [16]. Entropy analysis provides valuable insights into the complexity and regularity of the distribution of road networks in West Kalimantan Province.

Urban traffic networks are closely linked to traffic flow and infrastructure [19]. Road networks are crucial elements in urban morphology that influence human dynamics and urban transportation systems. In West Kalimantan, the unique configuration and orientation of road networks form the logic and spatial order of cities in this region. These conclusions could be a foundation for developing more effective and sustainable urban planning strategies in West Kalimantan Province. This study provides a deeper understanding of entropy levels in urban road networks in West Kalimantan Province. By understanding the hierarchical structure and connectivity of cities, the research effects can assist urban planners in making better decisions regarding infrastructure development, mobility, and urban space [2] [20]. Adaptive and resilient infrastructure makes transportation systems more robust in supporting development and economic growth [18], [21], [22].

II. Materials and Method

This study examines the road network structure of West Kalimantan Province using the analysis of street network models based on entropy values of the road networks in Districts and Cities. Street network models are used to depict the structure and connectivity of cities [20]. The research employs entropy measures to quantify information contained in each network representation based on spatial scale [20].

The study area includes the road networks of 14 Districts and Cities in West Kalimantan Province: Pontianak City, Kubu Raya Regency, Singkawang City, Mempawah Regency, Sekadau Regency, Sintang Regency, Ketapang Regency, Kayong Utara Regency, Bengkayang Regency, Landak Regency, Melawi Regency, Sambas Regency, Sanggau Regency, and Kapuas Hulu Regency. Data taken from Open Street Map network data modelled using the open-source software OSMnx. Open Street Map data enables the analysis and visualization of urban forms and configurations [23], [24]. The analytical steps include entropy and network resilience analyses. Entropy analysis employs Shannon's entropy formula to measure the level of disorder in road network orientations [20]. Resilience and vulnerability analysis assess the network's ability to withstand and be vulnerable to disruptions [19].

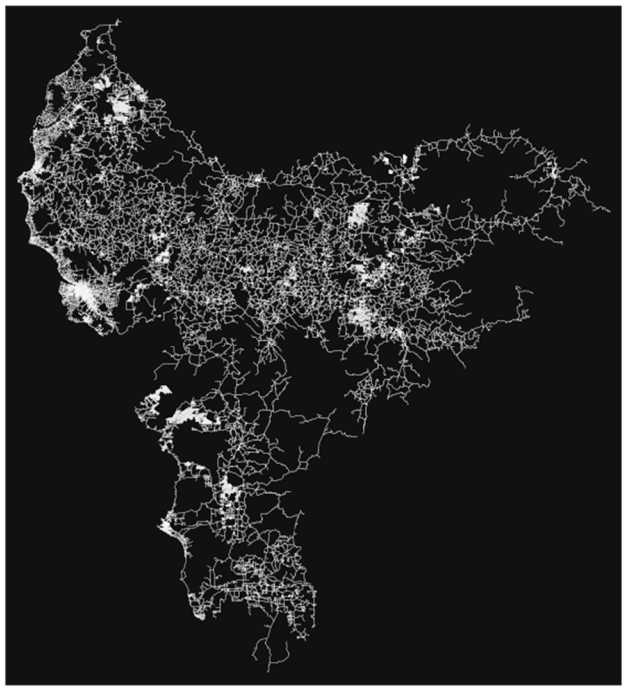

Fig. 1 The Road Network of West Kalimantan Province Based on OSM Data

Entropy is measured based on the distribution of road segment lengths in each city, while regularity is assessed by analyzing the connection patterns between road nodes in the network [2]. Entropy influences spatial distribution in cities. If there is an equal distribution of land use, population density, or accessibility, then the entropy is low. However, significant imbalance results in high entropy [2]. Entropy identification involves:

1) Direction Identification: Identifying sectors showing specific directions. For instance, a sector indicating a northern direction implies a data-oriented north.

2) Frequency: Noting the length of lines in each sector. Longer lines indicate more data in that direction.

3) Entropy: Within entropy contexts, describing data direction variations. Similar line lengths in each sector indicate low entropy (more regular). Contrasting lengths suggest high entropy (more random).

4) Interpretation: Understanding direction and frequency clarifies data directional patterns. Entropy helps grasp data direction variability.

Sustainable planning involves urban planning that prioritizes the sustainability of residents' welfare and must consider entropy. This research measures the vulnerability of the road networks in the Districts/Cities of West Kalimantan Province and models the relationship between vulnerability and the characteristics of road network design. The road network depends significantly on both the distribution of geometry, as described by fractal geometry dimensions, and the level of structural complexity [25].

III. Results and Discussion

West Kalimantan Province covers an area of 147,037 km² [26] and comprises 14 Districts and Cities. Become one of Indonesia's provinces that shares a direct border with a foreign country, namely the State of Sarawak, East Malaysia, West Kalimantan now has a land road access for entry and exit to and from foreign countries between Pontianak - Entikong - Kuching (Sarawak, Malaysia), spanning approximately 400 km and taking about six to eight hours of travel time. Analysis of road networks becomes crucial in urban planning and infrastructure development context for understanding the complexity and diversity of transportation systems in West Kalimantan Province.

Calculating the distribution of road segment lengths (or segments between nodes) within a region is an entropy measurement in road networks. The greater the diversity in road segment lengths, the higher the entropy value. Entropy and regularity in urban road networks are interconnected and have significant implications in urban contexts [2]. Table 1 shows the entropy values of the road networks in West Kalimantan Province. The level of entropy in urban road networks has significant implications for population mobility, transportation patterns, and urban development. The entropy values of the road networks in West Kalimantan Province range from 3.4 to 3.5. The analysis results indicate no significant variation in entropy levels among the cities in West Kalimantan Province.

TABLE I
ENTROPY VALUE OF DISTRICTS/CITIES IN WEST KALIMANTAN

No.	District/City	Entropy Value
1.	Pontianak City	3.465
2.	Singkawang City	3.477
3.	Kayong Utara Regency	3.523
4.	Ketapang Regency	3.533
5.	Kubu Raya Regency	3.539
6.	Sintang Regency	3.552
7.	Mempawah Regency	3.557
8.	Sambas Regency	3.565
9.	Melawi Regency	3.566
10.	Kapuas Hulu Regency	3.568
11.	Bengkayang Regency	3.572
12.	Sekadau Regency	3.574
13.	Sanggau Regency	3.575
14.	Landak Regency	3.576

Entropy is measured based on the distribution of road segment lengths in each city, while regularity is assessed by analyzing the connectivity patterns between road nodes within the network [2]. In addition, the frequency of entropy needs to be identified and interpreted from directions using a mathematical model known as a graph [27]. Graphs can represent the geometry and topology of real-world road networks [27]. They are used to elucidate urban structures through road connectivity [28]. Figure 1 illustrates a radial entropy diagram with a circular grid and blue bars radiating from the center. The following is the basis for identification:

1) Circular Grid: This grid spans angles from 0° to 315°, resembling a compass. Each angle represents a specific direction within the road network.

2) Blue Bars: These bars indicate road density in the corresponding direction. The longer the bar, the denser the roads in that direction.

3) Entropy: The entropy value describes the level of irregularity or diversity in the layout of the road network. A higher entropy value indicates a more complex and diverse road network.

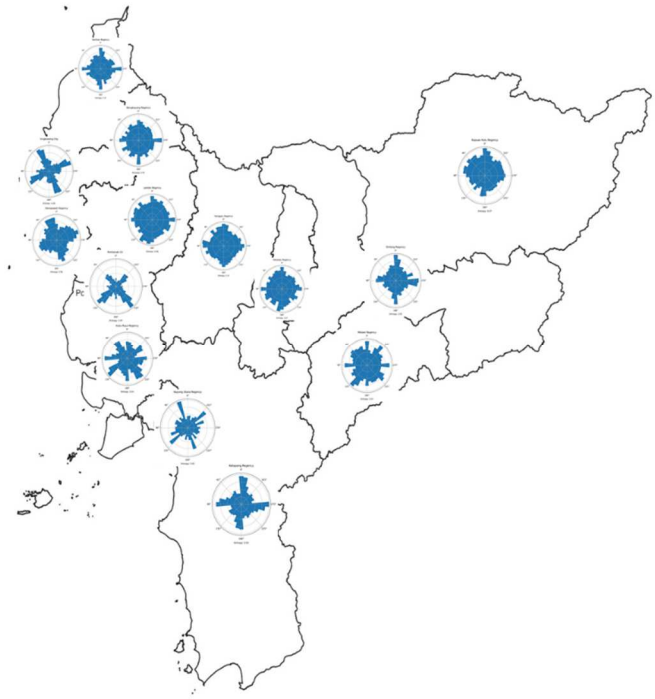

Fig. 2 Provincial Rose Diagram of West Kalimantan Province Road Network

Entropy maps of the road networks are placed at various locations on the map. The figure includes a circular grid covering angles from 0° to 315°, resembling a compass. Each angle represents a specific direction within the road network. The blue bar diagram shows road density in the direction corresponding to its angle. The longer the bar, the denser the road in that direction. Entropy: 3.47. The entropy value of 3.47 depicts the level of irregularity or diversity in the layout of the road network. A higher entropy value indicates a more complex and diverse road network.

Figure 2 shows that the road network in Pontianak City exhibits significant directional variation. This indicates diversity in road layout, including arterial, collector, and local roads. The entropy value of 3.47 indicate that the road network in Pontianak City has a relatively high level of complexity. Topography, population density, and development policies factors influence these road patterns. Figure 1 shows the entropy analysis results of road networks in various regions of West Kalimantan. Entropy in this context likely refers to several measures of irregularity or variability within the road network system. The spider diagram provides a visual representation that helps identify patterns, uniformity, or dissimilarities in structure and organization of road networks in each location. Entropy describes the variation in direction data.

If the lines in each sector are nearly the same length, the directional distribution of the data exhibits low entropy (more orderly). Conversely, if the lines vary significantly in line

length, the directional distribution demonstrates high entropy (more random). The direction of the polar histogram bars represents compass directions, and the line length of the bars signifies the proportion of urban road segments in those directions [29]. Based on the analysis, certain Regencies/Cities exhibit high orientation because nearly all roads align in four distinct directions. These areas include Pontianak City, Singkawang City, Kayong Utara Regency, Ketapang Regency, Kubu Raya Regency, Sintang Regency, Mempawah Regency, and Sambas Regency. In contrast, low orientation comes about where roads are more evenly distributed across all directions and are of nearly equal length. Regencies with low orientation include Sekadau Regency, Sanggau Regency, and Landak Regency.

Pontianak City and Singkawang City exhibit the lowest entropy values, 3.47. The entropy value reflects the extent of diversity in a city's layout, land use, and mobility [2]. The cities in West Kalimantan Province exhibit the lowest entropy values. On the other hand, areas with district characteristics, especially Landak Regency and Sanggau Regency, have the highest entropy values. Cities with high entropy levels tend to have more complex road network patterns, which may necessitate more advanced transportation planning strategies. On the other hand, cities with low entropy levels may be easier to manage and possess more structured road network [7]. Based on the analysis of road network entropy in West Kalimantan Province, there are three categories: low, medium, and high.

A. Low Group (Regular)

Regencies/Cities in West Kalimantan Province with low entropy values range from 3.46 to 3.48. These areas include Pontianak City and Singkawang City. Pontianak City has an entropy value of 3.47, indicating a high level of diversity in its road network. This diversity stems from the category of road types (e.g., arterial, collector, and local roads) and the area's topography. As the capital of West Kalimantan Province, Pontianak City plays a strategic role in regional development and infrastructure. Analyzing road network entropy helps us understand the complexity and diversity of the transportation system in this city. The radial entropy diagram you provided allows us to explore the distribution of the road network and its implications in greater detail. The Radial Entropy Diagram features circular grids and blue bars emitted from the center. Singkawang City, with an entropy value of 3.48, also shows significant diversity in its road network. Population growth and development policies contribute to the complexity of this network.

The radial entropy diagram for Pontianak City's Road network, with an entropy value of 3.47, measures the irregularity or randomness in its layout. This value indicates a certain level of complexity or irregularity in the structure of the road network, suggesting that Pontianak City has diverse road orientations contributing to its overall layout. This measure is relevant for urban planning, traffic management, and understanding the efficiency and ease of the city's transportation infrastructure.

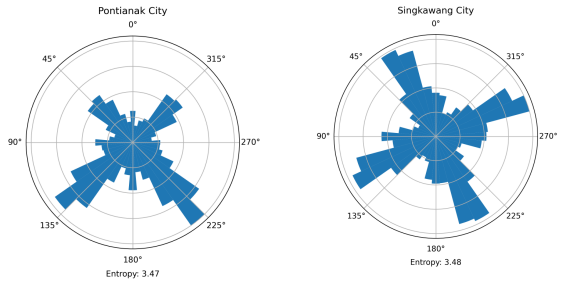

Fig. 3 Results of Low Entropy Analysis Rose Diagram of the Road Network in West Kalimantan Province

A higher entropy value (3.47) indicates greater complexity in the road network of Pontianak City. The implications of this entropy value include:

1) Mobility: The possibility of various alternative routes affects the mobility of residents and goods.

2) Connectivity: A complex road network enables good interregional connectivity but can lead to congestion and navigation challenges.

B. Medium Group (Complex)

Regencies and cities classified in the medium group in West Kalimantan Province have entropy values ranging from 3.49 to 3.56. These areas include Kayong Utara Regency, Ketapang Regency, Kubu Raya Regency, Sintang Regency, and Mempawah Regency.

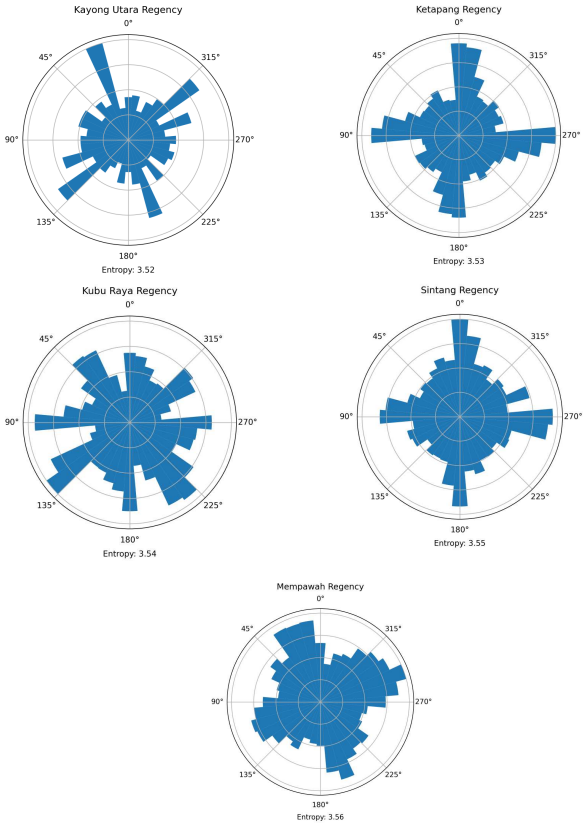

Fig. 4 Results of Medium Group Entropy Analysis, Provincial Rose Diagram, West Kalimantan Province Road Network

1) Kayong Utara Regency: An entropy value of 3.52 indicates that the road network in Kayong Utara Regency exhibits higher diversity than several regions. This diversity may be due to variations in topography and different transportation needs in the area.

2) Ketapang Regency: With an entropy value of 3.53, Ketapang Regency also displays significant diversity in its road network. Economic and social factors play crucial roles in influencing transportation patterns in this region.

3) Kubu Raya Regency: An entropy value of 3.54 suggests that Kubu Raya Regency has significant diversity in its road network. Numerous important nodes, such as city centers, ports, and industries, influence the distribution of roads.

4) Sintang Regency: With an entropy value of 3.55, Sintang Regency also exhibits considerable diversity in its road network. Geographic factors and local transportation needs contribute to this network pattern.

5) Mempawah Regency: An entropy value of 3.56 indicates that Mempawah Regency also has significant diversity in its road network. Two factors of concern in this area are population density and accessibility.

C. High Complexity Group

Regencies and cities in West Kalimantan Province that fall into the High Complexity Group have entropy values above 3.56. The regencies/cities included in this group are Sambas Regency, Melawi Regency, Kapuas Hulu Regency, Bengkayang Regency, Sekadau Regency, Sanggau Regency, and Landak Regency.

1) Sambas Regency: With an entropy value of 3.57, Sambas Regency demonstrates a significant diversity in its road network. There may be numerous transportation hubs connecting this region with other areas.

2) Melawi Regency: The entropy value of 3.57 in Melawi Regency indicates a high level of diversity in its road network. Environmental factors and development policies also play crucial roles.

3) Kapuas Hulu Regency: Having an entropy value of 3.57, Kapuas Hulu Regency exhibits significant diversity in its road network. There may be numerous rural roads and forests. The calculated entropy value for the road network in Kapuas Hulu Regency shows a high level of diversity in road orientation and distribution. It reflects the complexity of the road network layout in this regency. Road orientation in Kapuas Hulu Regency contributes to the overall road network layout. This consistency or variability is crucial in urban planning and traffic management as it can affect navigation, transport efficiency, and future infrastructure development. Kapuas Hulu Regency covers a vast area of 31,318.25 km², approximately 21.3% of the total area of West Kalimantan Province. With such a large area, there are challenges in managing an efficient and effective road network to meet the transportation needs, population, and economic activities.

4) Bengkayang Regency: Bengkayang Regency also exhibits significant diversity in its road network with an entropy value of 3.57.

5) Sekadau Regency: The entropy value of 3.57 in Sekadau Regency indicates a high level of diversity in its road network.

6) Sanggau Regency: Sanggau Regency also shows significant diversity in its road network with an entropy value of 3.57.

7) Landak Regency: The entropy value of 3.58 in Landak Regency indicates a high level of diversity in its road network. Based on the image you uploaded, the entropy value of 3.58 for the road network in Landak Regency shows a high level of diversity in road orientation and distribution. This diagram displays various lengths of blue bars extending from the center to the edges at different angles, representing the entropy measure for each direction in the road network of Landak Regency. The high entropy value indicates that there are various directions of roads in Landak Regency, which may be due to geographic conditions such as forests, mountains, and rivers that influence road development. A higher entropy value indicates greater complexity in the road network structure, which can pose challenges in traffic planning and management. This information is valuable in infrastructure development planning, ensuring the road network supports population mobility and economic growth. Influence of Area Size: The Landak Regency has a significant land area, and this entropy value reflects how the road network is adjusted to the size of the area to meet transportation needs.

The analysis results reveal a correlation between entropy and the regularity of urban road networks. Cities with higher entropy tend to feature more random and complex road network patterns, whereas cities with lower entropy tend to boast structured and organized road networks [1]. The application of entropy in various disciplines and its relevance to urban studies, particularly concerning city sustainability and architecture, have been thoroughly examined [14]. Connectivity between locations is crucial as it significantly impacts human mobility and activity within urban spaces, which serve diverse functional purposes [20]. A resilient transportation system reflects its capability to facilitate movement despite major disruptions with minimal disturbance or to quickly recover with minimal economic loss and cost reduction [22]. The results of the entropy analysis are outlined based on the identification of directions, frequency, entropy, and interpretation of the following outcomes:

a. Diversity of Road Directions: Diverse geographical conditions, such as forests, mountains, and large rivers, influence the development of roads in various directions.
b. Transportation Management: Effective transportation management strategies are necessary to optimize connectivity between regions within this extensive regency.
c. Urban Planning: Entropy information is utilized in urban planning to enhance integrated infrastructure development and improve the efficiency of existing transportation systems.
d. Economic Development: A well-organized road network supports economic growth, especially in areas with significant natural resource potential, such as Kapuas Hulu.
e. Density and Complexity of Road Networks: the City of Pontianak, as the provincial capital, may have a more

dense and complex road network set side by side with the wider Kapuas Hulu Regency and may have a more dispersed and less congested road network.

f. Road Orientation: The entropy diagram for Pontianak City might exhibit wider variation in road orientation due to the need to accommodate diverse urban activities, whereas Kapuas Hulu Regency may feature more orderly road orientations tailored to local topography and needs.

g. Area Size: With a larger area, Kapuas Hulu Regency may boast a broader road network with entropy reflecting greater geographic diversity.

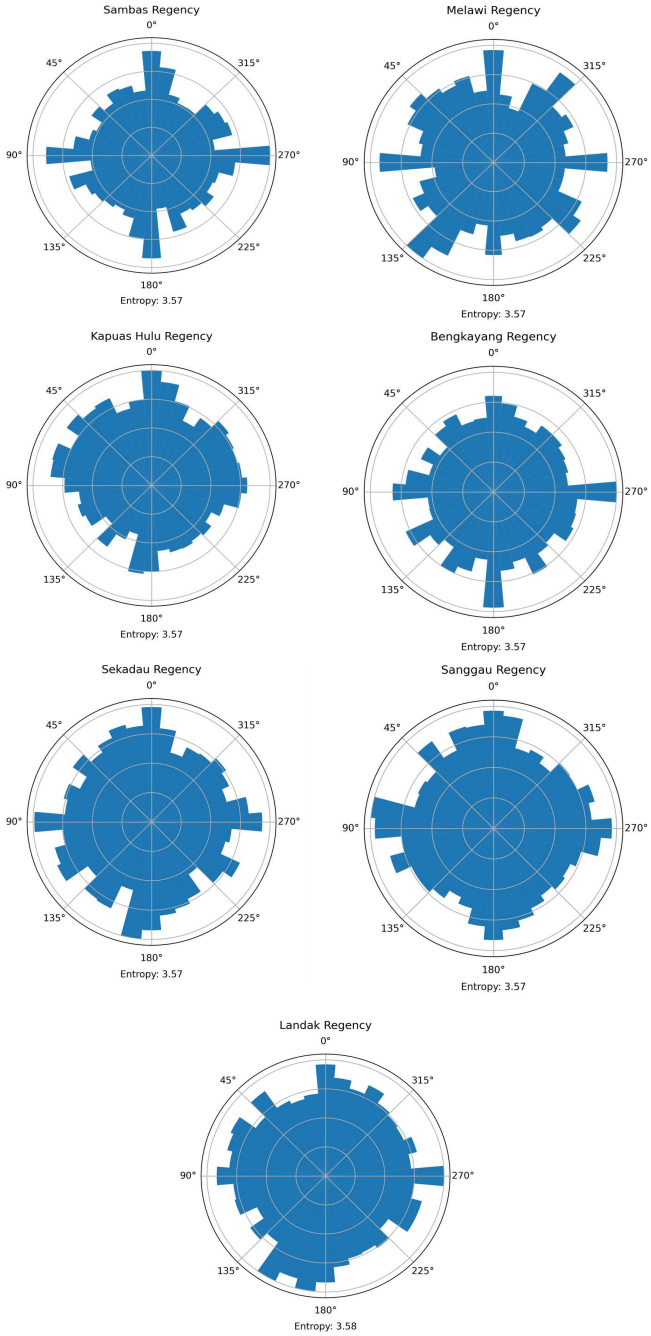

Fig. 5 Results of Medium Group Entropy Analysis, Provincial Rose Diagram, West Kalimantan Province Road Network

High entropy values indicate greater diversity and complexity in road orientation. The implications of entropy values include:

a. Mobility: Diverse transportation needs affect population mobility and economic activities. Various road directions impact population mobility and the distribution of goods.

b. Connectivity: Diverse road networks ensure connectivity across extensive regions. Efficient planning of road networks is required to ensure good connectivity in these vast areas.

Entropy analysis of road networks is crucial for identifying areas needing infrastructure improvements or changes in road planning to enhance efficiency and connectivity across the entire region. Entropy methods in this study measure uncertainty or variability in the distribution of urban traffic networks, aiding in identifying their attributes of topology, geography, and mining traffic network communities. Entropy allows researchers to assess traffic network organization and flow efficiency, which is critical for network planning and optimization [19].

Efforts to increase regularity can foster more sustainable cities [2]. Road networks facilitate the movement of people and goods within cities but are susceptible to disasters such as floods, earthquakes, and terrorist attacks [30]. Effective network design and planning can enhance a city's resilience and ability to withstand disruptions [30]. There are empirical relationships globally between specific design characteristics and resilience [30]. The development space in the central and densely populated network is limited, whereas the edge zones and less densely connected network areas rarely demonstrate a phenomenon of irregular evolution [31]. Based on the analysis of Network Resilience and Vulnerability: How traffic networks can survive and be vulnerable to disturbances [19].

IV. Conclusion

Entropy values influence how road networks adapt to local needs and characteristics in each region. Infrastructure planning and traffic management must consider this complexity to ensure optimal mobility and connectivity. Based on the entropy analysis of road networks in West Kalimantan Province, there are three categories: low, medium, and high entropy. Municipalities with low entropy values ranging from 3.46 to 3.48 are Pontianak City and Singkawang City. In the medium entropy group, municipalities with values ranging from 3.49 to 3.56 include Kayong Utara Regency, Ketapang Regency, Kubu Raya Regency, Sintang Regency, and Mempawah Regency. Municipalities in the high entropy group have values exceeding 3.56, including Sambas Regency, Melawi Regency, Kapuas Hulu Regency, Bengkayang Regency, Sekadau Regency, Sanggau Regency, and Landak Regency.

Based on the analysis, we can conclude that the differences in road network entropy results in West Kalimantan Province may be due to several factors:

a. Topography and Geographic Area: Each region has different topographic and geographic characteristics. For instance, Pontianak City may have more roads connecting urban areas, whereas Kapuas Hulu and Landak Regencies may have more rural roads following

river flows. Different topographies can affect road distribution and network complexity.

b. Population Density: Pontianak City tends to have a higher population density than other regencies. Population density affects the need for road networks and their complexity. Kapuas Hulu and Landak Regencies may have fewer roads due to lower population density.
c. Infrastructure Development: Road infrastructure planning and development may differ in each region. Development priorities, budget allocations, and local government policies play a role in shaping the road network.
d. Economic and social: Factors such as transportation demands, primary economic sectors, and social activities influence the development and utilization of road networks.
e. Urban Planning and Traffic Management: Different urban planning strategies can result in road networks with varying orientations. Traffic management and traffic policies also influence network complexity.

Considering these factors, the variations in road network entropy among these three regions can be attributed. Higher entropy values indicate more complex and diverse road networks in those areas.

REFERENCES

[1] H. Zhang, T. Lan, and Z. Li, "Fractal evolution of urban street networks in form and structure: a case study of Hong Kong," *International Journal of Geographical Information Science*, vol. 36, no. 6, pp. 1100–1118, 2022, doi: 10.1080/13658816.2021.1974451.

[2] A. Gudmundsson and N. Mohajeri, "Entropy and order in urban street networks," *Sci Rep*, vol. 3, 2013, doi: 10.1038/srep03324.

[3] F. Afrianto and A. D. Hariyanto, "Clustering Dan Visualisasi Bentuk Kota Di Jawa Timur," *Jurnal Plano Buana*, vol. 2, no. 2, pp. 57–67, Apr. 2022, doi: 10.36456/jpb.v2i2.5303.

[4] P. Cabral, G. Augusto, M. Tewolde, and Y. Araya, "Entropy in urban systems," 2013, *MDPI AG*. doi: 10.3390/e15125223.

[5] I. A. Festus, I. F. Omoboye, and O. B. Andrew, "Urban Sprawl: Environmental Consequence of Rapid Urban Expansion," *Malaysian Journal of Social Sciences and Humanities (MJSSH)*, vol. 5, no. 6, pp. 110–118, Jun. 2020, doi: 10.47405/mjssh.v5i6.411.

[6] S. Angel, "Urban expansion: theory, evidence and practice," 2023, *Web Portal Ubiquity Press*. doi: 10.5334/bc.348.

[7] G. Boeing, "Urban spatial order: street network orientation, configuration, and entropy," *Appl Netw Sci*, vol. 4, no. 1, Dec. 2019, doi: 10.1007/s41109-019-0189-1.

[8] T. Viderman, I. Geddes, and C. Psathiti, "Lived Urban Form," *The Journal of Public Space*, vol. 8, no. 3, pp. 79–92, Dec. 2023, doi:10.32891/jps.v8i3.1410.

[9] D. Ma, R. Guo, Y. Zheng, Z. Zhao, F. He, and W. Zhu, "Understanding chinese urban form: The universal fractal pattern of street networks over 298 cities," *ISPRS Int J Geoinf*, vol. 9, no. 4, 2020, doi:10.3390/ijgi9040192.

[10] Y. Kaoru, K. Yusuke, and Y. Yuji, "Local Betweenness Centrality Analysis of 30 European Cities," in *Urban Book Series*, 2021, pp. 527–547. doi: 10.1007/978-3-030-76059-5_26.

[11] C. Wu, J. Wang, M. Wang, and M. J. Kraak, "Machine learning-based characterization of urban morphology with the street pattern," *Comput Environ Urban Syst*, vol. 109, Apr. 2024, doi:10.1016/j.compenvurbsys.2024.102078.

[12] G. Boeing, "Measuring the complexity of urban form and design," *Urban Design International*, vol. 23, no. 4, pp. 281–292, Nov. 2018, doi: 10.1057/s41289-018-0072-1.

[13] H. Xiang, "Urban Road Network Emergency: An Integrative Vulnerability Identification Method," *Complexity*, vol. 2021, 2021, doi: 10.1155/2021/6325578.

[14] D. R. Rondinel-Oviedo and N. Keena, "Entropy and Cities: A Bibliographic Analysis towards More Circular and Sustainable Urban Environments," Mar. 01, 2023, *MDPI*. doi: 10.3390/e25030532.

[15] G. Boeing, "Street Network Models and Indicators for Every Urban Area in the World," in *Geographical Analysis*, John Wiley and Sons Inc, Jul. 2022, pp. 519–535. doi: 10.1111/gean.12281.

[16] M. Geshkov, "Application of Digital Technologies in Controlling Urban Sprawl," *SHS Web of Conferences*, vol. 176, 2023, doi:10.1051/shsconf/202317601010.

[17] D. R. Sedubun, N. S. Laamena, R. Salhuteru, and P. Studi Statistika, "Development of Spatial Weighted Matrix based on Transportation Connectivity for Archipelago Provinces in Indonesia," *Parameter (Matematika dan Terapan)*, vol. 02, no. 02, pp. 101–114, 2023, doi:10.30598/parameterv2i02pp101-114.

[18] O. Soelistyo Pribadi, K. Risma, D. Kartika, D. W. Hidayat, and D. R. Navianti, "Analysis of National Road Network Connectivy in Bali Province," *Jurnal Teknologi Transportasi dan Logistik*, vol. 4, no. 2, 2023, doi: 10.52920/jttl.v4i2.208.

[19] R. Ding *et al.*, "Application of Complex Networks Theory in Urban Traffic Network Researches," *Netw Spat Econ*, vol. 19, no. 4, pp. 1281–1317, Dec. 2019, doi: 10.1007/s11067-019-09466-5.

[20] H. N. Huynh and M. A. Bin Ramli, "Urban Landscape from the Structure of Road Network: A Complexity Perspective," Jan. 2022, doi: 10.48550/arXiv.2201.10949.

[21] S. Liu *et al.*, "A Generalized Framework for Measuring Pedestrian Accessibility around the World Using Open Data," May 2021, doi:10.1111/gean.12290.

[22] Z. R. Peng, W. Zhai, and K. Lu, "Smart, Sustainable, and Resilient Transportation System," in *New Thinking in GIScience*, Springer Nature, 2022, pp. 319–328. doi: 10.1007/978-981-19-3816-0_34.

[23] G. Boeing, "Exploring Urban Form through OpenStreetMap Data: A Visual Introduction," in *Urban Experience and Design: Contemporary Perspectives on Improving the Public Realm*, 2020, pp. 167–184. doi: 10.31235/osf.io/rnwgv.

[24] G. Boeing *et al.*, "Using open data and open-source software to develop spatial indicators of urban design and transport features for achieving healthy and sustainable cities," Jun. 01, 2022, *Elsevier Ltd*. doi: 10.1016/S2214-109X(22)00072-9.

[25] H. Zhang, P. Gao, T. Lan, and C. Liu, "Exploring the Structural Fractality of Urban Road Networks by Different Representations," *Professional Geographer*, vol. 73, no. 2, pp. 348–362, 2021, doi:10.1080/00330124.2021.1871765.

[26] BPS-Statistics of Kalimantan Barat Province, *Provinsi Kalimantan Barat Dalam Angka 2024*, vol. 41. 2024.

[27] G. Boeing, "Street Network Models and Indicators for Every Urban Area in the World," in *Geographical Analysis*, Blackwell Publishing Inc., 2021. doi: 10.1111/gean.12281.

[28] D. Ma, F. He, Y. Yue, R. Guo, T. Zhao, and M. Wang, "Graph convolutional networks for street network analysis with a case study of urban polycentricity in Chinese cities," *International Journal of Geographical Information Science*, 2024, doi:10.1080/13658816.2024.2321229.

[29] G. Boeing, "The right tools for the job: The case for spatial science tool-building," *Transactions in GIS*, vol. 24, no. 5, pp. 1299–1314, Oct. 2020, doi: 10.1111/tgis.12678.

[30] G. Boeing and J. Ha, "Resilient by design: Simulating street network disruptions across every urban area in the world," *Transp Res Part A Policy Pract*, vol. 182, Apr. 2024, doi: 10.1016/j.tra.2024.104016.

[31] Y. Long and Y. Chen, "Multifractal scaling analyses of urban street network structure: The cases of twelve megacities in China," *PLoS One*, vol. 16, no. 2 February, Feb. 2021, doi:10.1371/journal.pone.0246925.