

Optimized AIS-Derived Indicators through Application of Port Administrative Boundaries

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Abstract

Defining port boundaries for Automatic Identification System (AIS) data processing is challenging, since docks and berthing facilities are relatively easy to define, while anchorage zones in open waters are often less clearly delineated. This study uses administrative boundaries, known as Daerah Lingkungan Kerja Pelabuhan (Port Working Area, DLKr), to represent port areas as the Area of Interest (AoI) in AIS data processing. With DLKr, port boundaries can be clearly outlined and divided into several zones, enabling more accurate calculation of AIS-derived indicators. The research estimates port calls and port stay durations using the Stationary Marine Broadcast Method (SMBM), focusing on cargo, tanker, and passenger vessels at the Port of Tanjung Priok during 2024. The AIS-derived indicators generated with DLKr as the AoI show good performance, with an RMSE of 55.94 and a MAPE of 5.27%. In addition, the results are supported by the similarity in patterns and distribution of port call values when compared with the official maritime statistics provided by the Ministry of Transportation.

Keywords: Area of interest, automatic identification system, port call, port stay, port working area.

Abstrak

Optimisasi Indikator Turunan Data AIS melalui Penerapan Batas Administratif Pelabuhan: Penentuan batas pelabuhan untuk pemrosesan data Automatic Identification System (AIS) merupakan tantangan karena dermaga dan fasilitas sandar relatif mudah didefinisikan, sedangkan zona tambat di perairan terbuka sering kali kurang memiliki batas yang jelas. Penelitian ini menggunakan batas administratif yang dikenal sebagai Daerah Lingkungan Kerja Pelabuhan (DLKr) untuk merepresentasikan area pelabuhan sebagai Area of Interest (AoI) dalam pemrosesan data AIS. Dengan DLKr, batas pelabuhan dapat digambarkan dengan jelas dan dibagi menjadi beberapa zona, sehingga memungkinkan perhitungan indikator turunan AIS yang lebih akurat. Penelitian ini memperkirakan jumlah kunjungan kapal dan durasi singgah kapal menggunakan Stationary Marine Broadcast Method (SMBM), dengan fokus pada kapal kargo, tanker, dan penumpang di Pelabuhan Tanjung Priok pada tahun 2024. Indikator turunan AIS yang dihasilkan dengan DLKr sebagai AoI menunjukkan kinerja yang baik, dengan RMSE sebesar 55,94 dan MAPE sebesar 5,27%. Selain itu, hasil tersebut diperkuat oleh kesesuaian pola dan distribusi nilai port call dengan data statistik resmi yang disediakan oleh Kementerian Perhubungan sebagai otoritas data kemaritiman.

Kata Kunci: Bidang minat, daerah lingkungan kerja pelabuhan, kunjungan dan keberangkatan kapal, sistem identifikasi otomatis, waktu tunggu kapal.

1. Pendahuluan

The use of big data from the Automatic Identification System (AIS) offers high temporal resolution, as vessel signals are continuously updated in real time [1]. AIS generates billions of daily records and provides detailed information on vessel characteristics and movements [2]. Recent studies have shown that AIS data can be transformed into derived indicators for monitoring maritime activities, including port calls as exemplified by those developed by MarineTraffic [3].

Indonesia is an archipelagic country made up of islands that are linked by the waters surrounding and connecting them, providing substantial potential to strengthen social welfare, national defense, political stability, and economic development [4][5]. Within this maritime setting, ports serve as key nodes between land and sea, and their role has shifted from handling loading and unloading activities to functioning as crucial links in wider logistics networks within global distribution systems [6]. Indonesia has 636 seaports that support its maritime transport system [7]. Among them, four ports hold major significance: Belawan (Medan), Makassar (South Sulawesi), Tanjung Priok (Jakarta), and Tanjung Perak (Surabaya) [8].

With the large number of ports situated near one another, defining port boundaries for calculating AIS-derived indicators requires careful consideration. This task is inherently complex. While physical areas such as docks and berthing facilities can usually be identified clearly, anchorage zones in open waters often lack clearly defined boundaries [2]. In AIS-based studies, port areas are commonly defined using bounding boxes that encompass berths, anchorage locations, and their surroundings [9]. However, this approach may unintentionally include areas outside the actual port scope, such as nearby terminals or passing shipping lanes [2]. Consequently, there remains a lack of standardized methods for defining port boundaries in AIS data analysis. Existing methods struggle to accurately represent the true operational boundaries of ports, particularly in regions with adjacent ports and ambiguous anchorage areas. For instance, large and busy maritime hubs, such as Shanghai, with coastlines extending approximately 100 km, fail to capture important information on port calls, including vessel origin-destination data. In contrast, at smaller hubs, vessels are incorrectly recorded as making a port call while simply passing near the port. Another challenge that can occur due to inaccurate definition of port boundaries is the misidentification of small movements of vessels between berths within the same port, movements after short stops, and minor shifts caused by sea currents [9][10].

Considering these challenges, this study aims to optimize the calculation of AIS-derived indicators by applying the administrative boundaries defined by the Ministry of Transportation, namely the *Daerah Lingkungan Kerja Pelabuhan* (Port Working Area, DLKr). The DLKr refers to areas directly designated for port operations, both on land and in waters [11]. The land-based DLKr includes primary facilities such as docks, terminals, warehouses, and stacking yards, as well as supporting facilities like office areas, utilities, vehicle waiting zones, and public services. The water-based DLKr covers shipping lanes, anchorage zones, ship-to-ship transfer areas, harbor basins, turning basins, and pilotage zones [12].

With clearly defined DLKr boundaries, AIS-derived indicators are expected to more accurately capture actual activities within ports. One port of particular interest in this context is Tanjung Priok, the largest international port and the busiest hub in Indonesia [13][14]. In addition to passenger services, Tanjung Priok is heavily engaged in international trade and logistics, encompassing export and import operations, cargo handling, and the movement of goods across both maritime and land-based transport networks [15]. Accordingly, this study addresses the following research question: How can the incorporation of administrative port boundaries (DLKr) improve the accuracy and policy relevance of AIS-derived indicators in measuring port activities? By integrating AIS-based indicators with officially designated administrative boundaries, this study introduces a more standardized and policy-relevant approach compared to prior research in Indonesia, which often relied on heuristic or data-driven definitions of port areas.

2. Methodology

To maximize the use of AIS data in producing complementary data for official statistics, the definition of port boundaries as an Area of Interest (AoI) must be carried out carefully. This process requires systematic and specific steps to ensure that port boundaries are clearly defined. One approach that can be applied is utilizing the administrative boundaries established by the Ministry of Transportation. Figure 1 presents the research framework, outlining the flow from problem identification to indicator evaluation.

Based on the identified problems, this study explores the use of administrative boundaries as the AoI in AIS data processing. The research begins with data acquisition, including AIS data, DLKr, and port call data provided by the official maritime statistics authority, namely the Ministry of Transportation. The next step is defining port boundaries using two methods, depending on data availability. Once established, the boundaries serve as the AoI for producing AIS-derived indicators. These indicators are calculated using the Stationary Marine Broadcast Method (SMBM). The results of this study are demonstrated through descriptive statistics and chart visualizations, followed by an evaluation based on Root Mean Squared Error (RMSE) and Mean Absolute Percentage Error (MAPE) by comparison with official maritime statistics provided by the Ministry of Transportation.

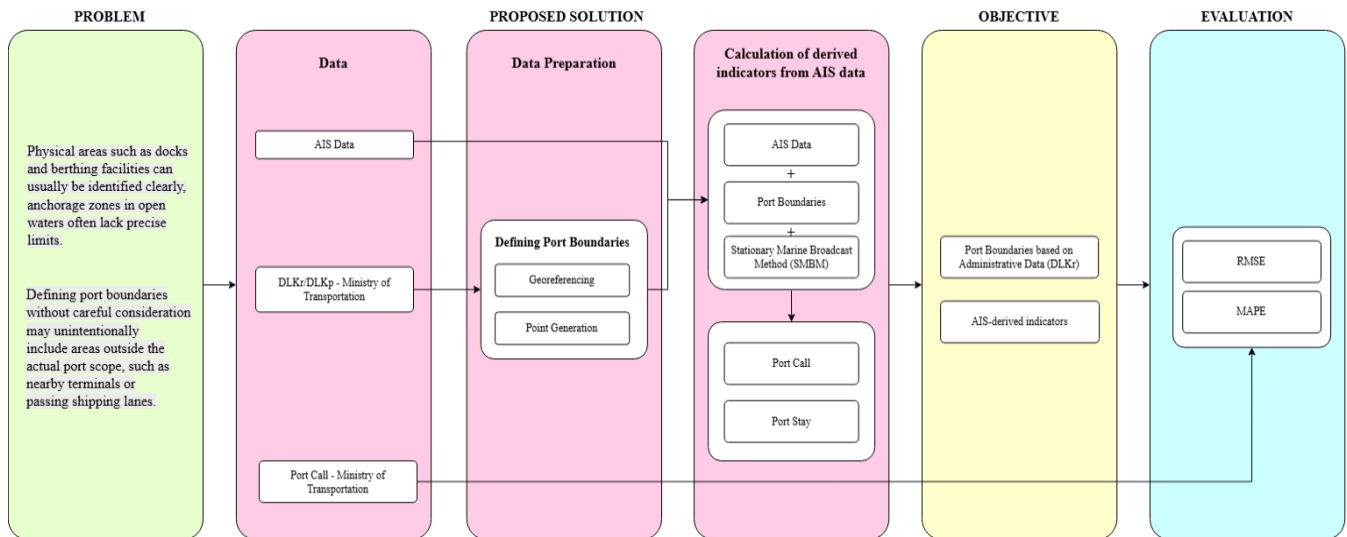


Figure 1. Research framework.

2.1. Study Area

This study calculates AIS-derived indicators, namely port calls and port stays, to monitor vessel activities at the Port of Tanjung Priok throughout 2024. The analysis focuses on three vessel types: cargo, tanker, and passenger. To generate these indicators, the study applies the SMBM in combination with the port's official administrative boundaries (DLKr). The SMBM detects vessel arrivals and departures by analyzing AIS signals from ships that remain stationary within the port area [16], while the DLKr provides the formally designated operational boundaries covering both land and waters [11].

2.2. Data Acquisition

The data acquisition process involves three main sources: AIS, DLKr, and official port call statistics. AIS data are obtained through the Spot Console platform provided by the United Nations Global Platform (UNGP). The port boundaries are defined based on the DLKr document obtained from the Directorate of Ports, Ministry of Transportation. Moreover, official port call data are collected from the Ministry of Transportation's dashboard, Inaportnet, an internet-based network and web service system designed to monitor and administer ship movements and cargo operations [17][18].

AIS is a system based on VHF radio transmitters that enables the automatic exchange of vessel position and identity data. It operates using transponders that continuously transmit signals, which can be received by other vessels, shore stations, or satellites equipped with AIS receivers. AIS is used globally in the maritime industry. For example, international regulations require vessels of at least 300 GT, as well as all passenger ships to be equipped with AIS transponders [19].

The AIS data used in this study consist of signals detected within a 10-kilometer buffer around the administrative boundaries of the Port of Tanjung Priok throughout 2024. AIS data are acquired using the platform provided by the United Nations Global Platform (UNGP), specifically the AWS Spot Console, which is part of the AWS Management Console. The UNGP-AIS historical dataset is available from December 2018 and is updated every four hours. By May 2023, it contains about 4 terabytes of data, with an annual average of roughly 33.5 million records [20]. Table 1 presents the attributes of AIS data and vessel registry data used in this research [2].

Table 1. Attribute used in this research

No	Attribute	Description
1	MMSI	<i>Maritime Mobile Service Identity</i> , a unique vessel identifier
2	IMO	<i>International Maritime Organization</i> , a unique vessel identifier
3	vessel_name	Vessel name
4	vessel_type	Vessel type
5	longitude	Vessel longitude in decimal degrees (DD)
6	latitude	Vessel latitude in decimal degrees (DD)
7	Speed over Ground	Vessel speed in knots
8	nav_status	Vessel navigation status
9	dt_pos_utc	Date and time of AIS message transmission (UTC)
10	H3_int_index_10	H3 index resolution 10

2.3. Data Analysis

The data analysis process consists of two stages: defining port boundaries and calculating AIS-derived indicators. The port boundaries are defined based on the DLKr document using georeferencing and point-generation methods. After the boundaries are established, the SMBM method is applied to calculate the AIS-derived indicators. These indicators include port calls (number of vessel arrivals and departures) and port stays (vessel waiting times).

2.3.1. Defining Port Boundaries

DLKr refers to the area designated for port activities, encompassing both land and water zones. The DLKr land area consists of primary and supporting facilities. Primary facilities include berths, terminals, line-1 warehouses, line-1 container yards, firefighting stations, and other essential infrastructure. Supporting facilities encompass office areas, clean water supply, electricity, vehicle waiting areas, and various public facilities such as recreational spaces, places of worship, and healthcare services. Meanwhile, the DLKr water area includes navigation channels, anchorage zones, ship-to-ship transfer areas, harbor basins, turning basins, pilotage areas, and other activities related to port operations [12].

The DLKr document presents its content in one or both formats: a map image or coordinate points defining the boundaries. For map images, the port boundaries are defined through georeferencing and digitizing, whereas for coordinate data, the boundaries are constructed by generating points and connecting them to form a polygon, as illustrated in Figure 2.

Figure 2 illustrates the stages of defining port boundaries based on DLKr. In this approach, the DLKr document serves as the reference for delineating port boundaries, which function as the AoI. The document may contain either map images or coordinate lists. When the DLKr consists of map images, the boundaries are defined through georeferencing and digitizing, a process that assigns fixed surface coordinates to geographic features within a defined spatial reference system [21]. Conversely, DLKr documents containing coordinate lists are processed by converting the listed coordinates into points within a Geographic Information System (GIS), which are then connected to form a polygon. The resulting polygons are subsequently stored in shapefile format.

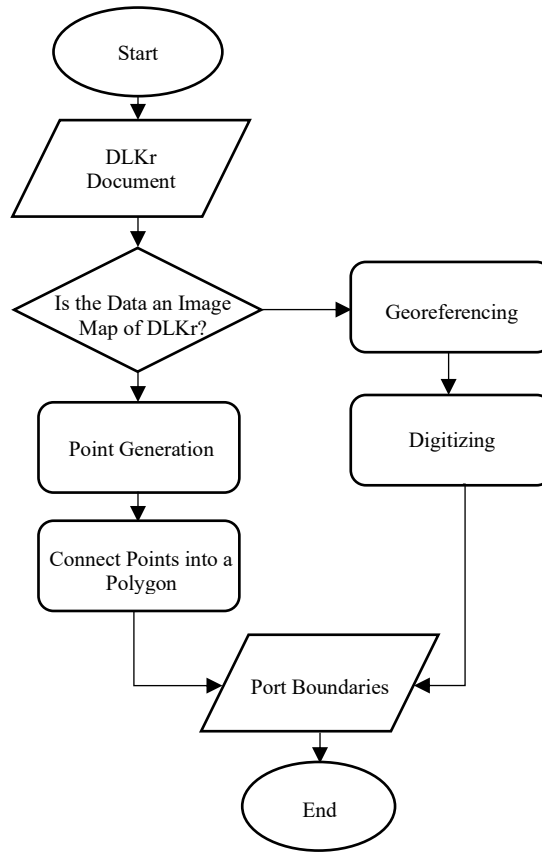


Figure 2. Port boundaries definition using DLKr.

2.3.2. Calculation of AIS-Derived Indicators

The Stationary Marine Broadcast Method (SMBM) defines a vessel's port visit as occurring when the vessel remains stationary within the port area to conduct cargo operations or other port-related activities. If a vessel stays stationary in the port area and transmits multiple AIS messages from the same zone, this is most likely considered a port call. In simple terms, SMBM estimates port visits based on stopped ship events that occur within the port boundaries. A stopped ship event is determined when a vessel's speed drops to zero within the port and is followed by subsequent AIS messages detected around the initial stopping position [16].

The method employs the H3 indexing system to define the neighborhood surrounding a stationary vessel. This neighborhood is used to identify when the vessel leaves the area. Once a vessel is detected as stationary (trigger event), subsequent AIS messages are evaluated to determine whether the vessel remains within the neighborhood or has left it (escape event). A vessel is considered to have left the neighborhood (escape condition met) if the H3 index of the next AIS message no longer belongs to the set of H3 indices forming the initial stopping neighborhood [16].

To define the neighborhood of a stationary vessel, the method uses the H3 k-ring (griddisk) function, which returns a set of H3 indices surrounding the vessel's current H3 index. The method introduces two main hyperparameters [16]: The k-depth of the k-ring, which determines the extent of the neighborhood considered, and the H3 resolution used in the k-ring to define the vessel's neighborhood.

Furthermore, the calculation of port stay using the SMBM method is performed by measuring the differences among the stop-event flags in the dataset, namely prior, previous, reference, and escape. This study applies the Lower Time Estimate, which is calculated as the difference between the timestamps of the previous and reference flags, as shown in the following formula.

$$LT = L_{Previous} - L_{Reference} \quad (1)$$

where $L_{Previous}$ represents the last moment the signal remains stationary, while $L_{Reference}$ denotes the first moment the signal becomes stationary [16].

To address overcoverage, stationary vessels with multiple stopped-ship events within the same part of the DLKr and within closely spaced time periods are merged. In addition, a vessel that first remains stationary in the anchorage area and subsequently records stopped-ship events in the shipping lanes and docks has these events merged, with shorter durations aggregated across both periods.

The results of this study are presented using descriptive statistics, which provide an overview and summary of the collected data. The analysis also employs various visualization techniques, including bar charts for categorical variables [22], box plots that visually represent the distribution of a dataset [23], and line charts to illustrate changes in values over time [24].

2.4. Evaluation

To evaluate the accuracy of AIS-derived indicators, this study uses official maritime statistics as a reference. The dataset applied is the 2024 port call statistics at the Port of Tanjung Priok published by the Ministry of Transportation. The accuracy is measured using two metrics, namely RMSE and MAPE, as defined in the following formula.

$$RMSE = \left(\frac{1}{n} \sum_{k=1}^n (X'_k - X_k)^2 \right)^{\frac{1}{2}} \quad (2)$$

$$MAPE = \frac{1}{n} \sum_{k=1}^n \frac{X'_k - X_k}{X_k} \times 100\% \quad (3)$$

where X_k denotes the actual value, X'_k denotes the predicted value, and n is the total number of data points used in the calculation [25].

3. Results and Discussions

3.1. Results

The main results of AIS data processing and analysis, along with the use of DLKr as an AoI, illustrate its role in monitoring vessel activity at the Port of Tanjung Priok. Port boundaries are defined, vessel operational indicators are calculated, and the results are evaluated to ensure the accuracy and reliability of the analysis. This approach provides a comprehensive view of DLKr usage and shows how the resulting AIS-derived indicators capture vessel movement patterns recorded by AIS.

3.1.1. Port Boundaries using DLKr

The port boundaries are defined through georeferencing and digitizing of the DLKr document provided by the Ministry of Transportation. The defined area includes shipping lanes, docks, and navigation areas, as well as eleven designated anchorage zones, with a total coverage of approximately 7,137.11 hectares, as illustrated in Figure 3. The anchorage zones are represented by symbols A to K, each characterized by distinct sizes and functions. Table 2 presents the area and specific function of each anchorage zone within the Port of Tanjung Priok [26].

Table 2. Anchorage zone in Port of Tanjung Priok.

No	Zone	Area Coverage (Ha)	Usage
1	A	75.23	Anchorage Area for Small Tanker Vessels
2	B	40.48	Anchorage Area for Tugboats and Barges
3	C	73.72	Anchorage Area for General Cargo Vessels LOA $\leq$ 140 m
4	D	77.03	Anchorage Area for Container Vessels LOA $\leq$ 140 m
5	E	450.79	Anchorage Area for General Cargo Vessels LOA $>$ 140 m
6	F	170.70	Anchorage Area for Container Vessels LOA $>$ 140 m
7	G	238.17	Anchorage Area for Large Tanker/Liquid Bulk Vessels
8	H	103.77	Anchorage Area for Quarantine
9	I	52.28	Anchorage Area for Vessels Loading/Unloading B3 Cargo
10	J	35.26	Anchorage Area for State Vessels
11	K	518.83	Transshipment Area

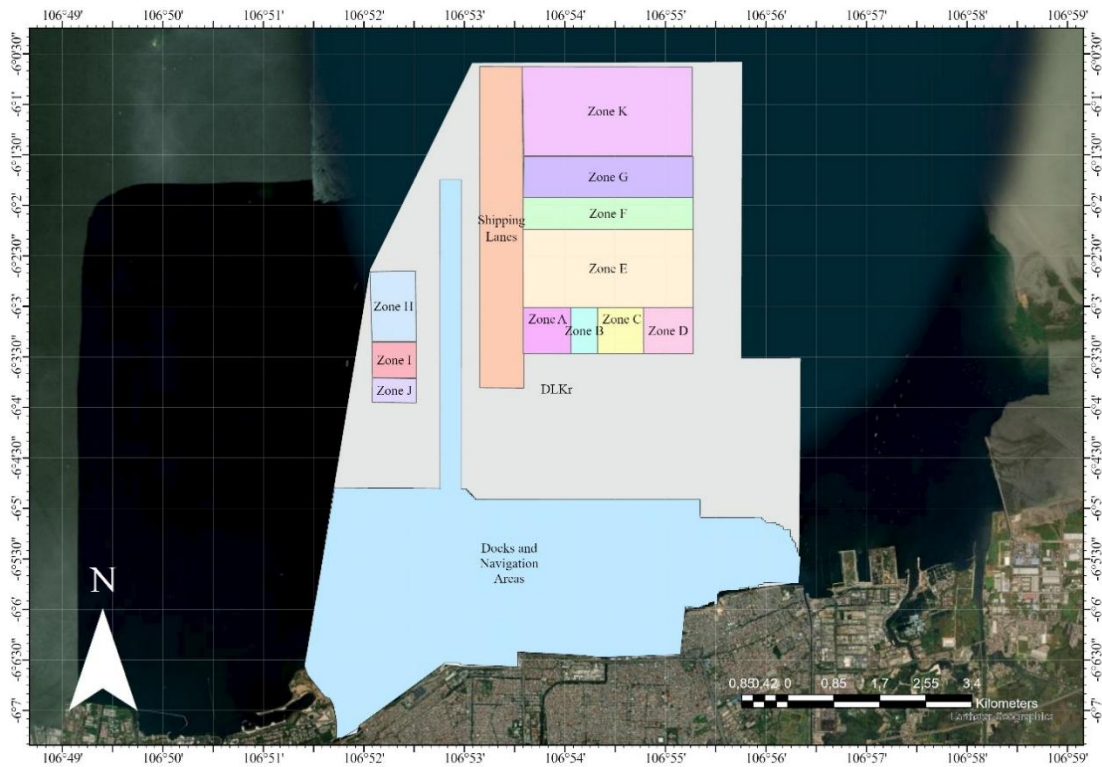


Figure 3. Port boundaries of Tanjung Priok.

Based on Table 2, each zone has a distinct area and function, with size corresponding to the designated operational role. Zone K is the largest, covering 518.83 hectares, followed by Zone E at 450.79 hectares. The extensive coverage of these zones reflects their critical roles in ship-to-ship transfer and in accommodating large cargo vessels with a length overall exceeding 140 meters. These functions require wider spaces to ensure navigational safety and operational efficiency. In contrast, Zone J at 35.26 hectares and Zone B at 40.48 hectares represent the smallest anchorage areas, allocated for the berthing of state vessels and the operation of relatively small tugboats. The variation in size across zones indicates a functional differentiation in the allocation of anchorage space within the port, where spatial distribution depends on the scale and operational requirements of the vessels utilizing the zones.

3.1.2. AIS-Derived Indicators

Based on the data presented in Figure 4, the port call values at the Port of Tanjung Priok throughout 2024 show notable fluctuations. The number of vessel arrivals and departures varies from month to month, with a clear peak in March and a low point in April. This trend is characterized by a notable increase in both arrivals and departures in March, reaching 935 arrivals and 933 departures, respectively. In contrast, April records the lowest figures for the year, with 718 arrivals and 717 departures.

Throughout the year, the number of vessel arrivals consistently remains slightly higher than or equal to the number of departures, with a minimal difference observed in any given month. For example, in May, there are 851 arrivals and 850 departures, a difference of just one vessel. This consistent pattern of a very small disparity between arrivals and departures suggests an efficient and balanced vessel traffic management system at the port. This stability points to smooth operational flow, as the port effectively manages the simultaneous entry and exit of vessels without notable backlogs or delays, reinforcing the interpretation of efficient port operations.

Figure 5 provides a detailed breakdown of port call values at the Port of Tanjung Priok by vessel type for 2024. The data show that cargo vessels consistently accounted for the highest number of port calls, followed by tankers and then passenger vessels. This pattern highlights the port's primary role as a key hub for logistics and commodity trade, particularly for cargo and energy goods.

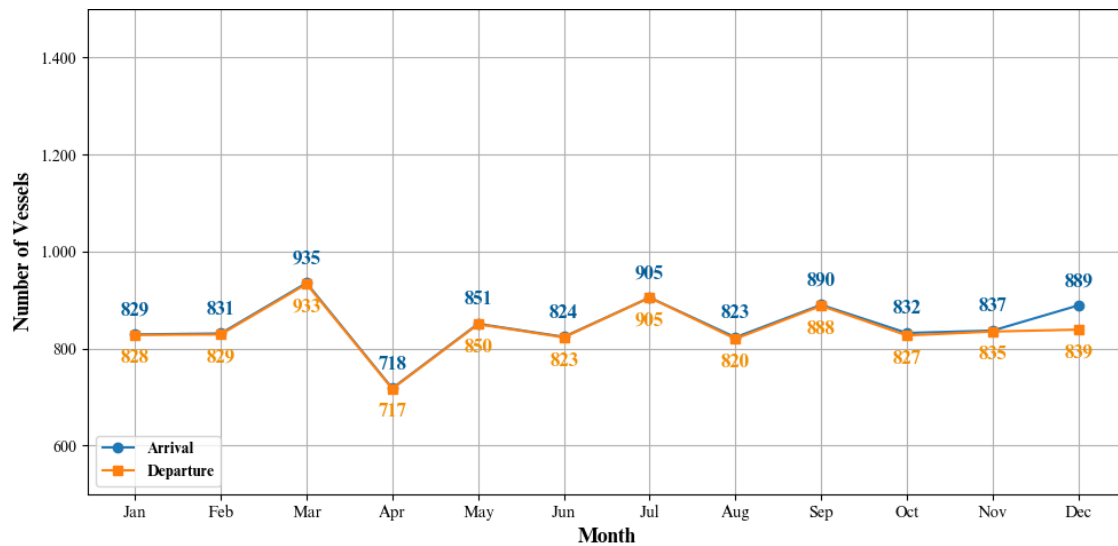


Figure 4. Port calls at Port of Tanjung Priok, 2024.

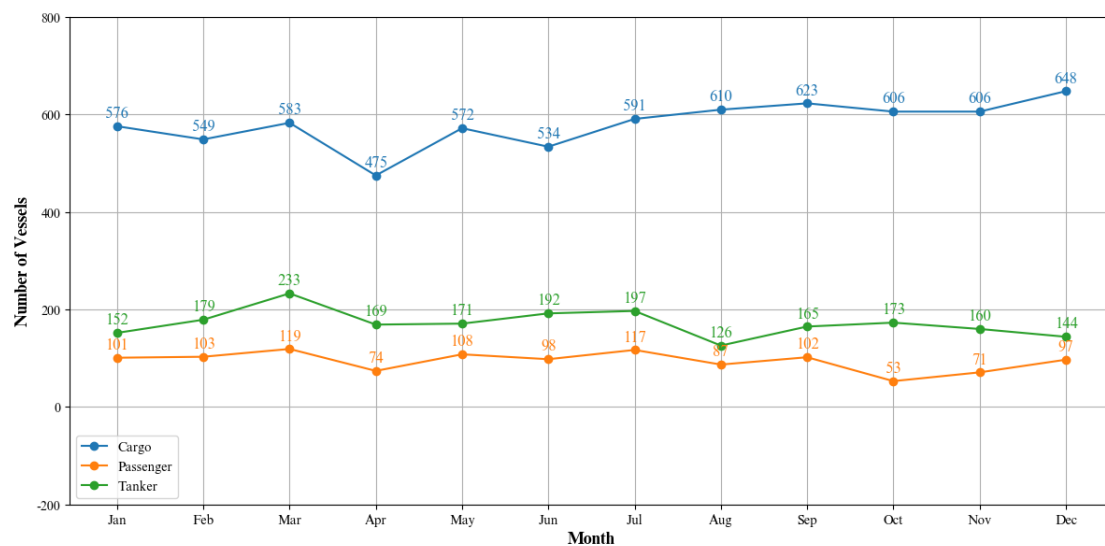


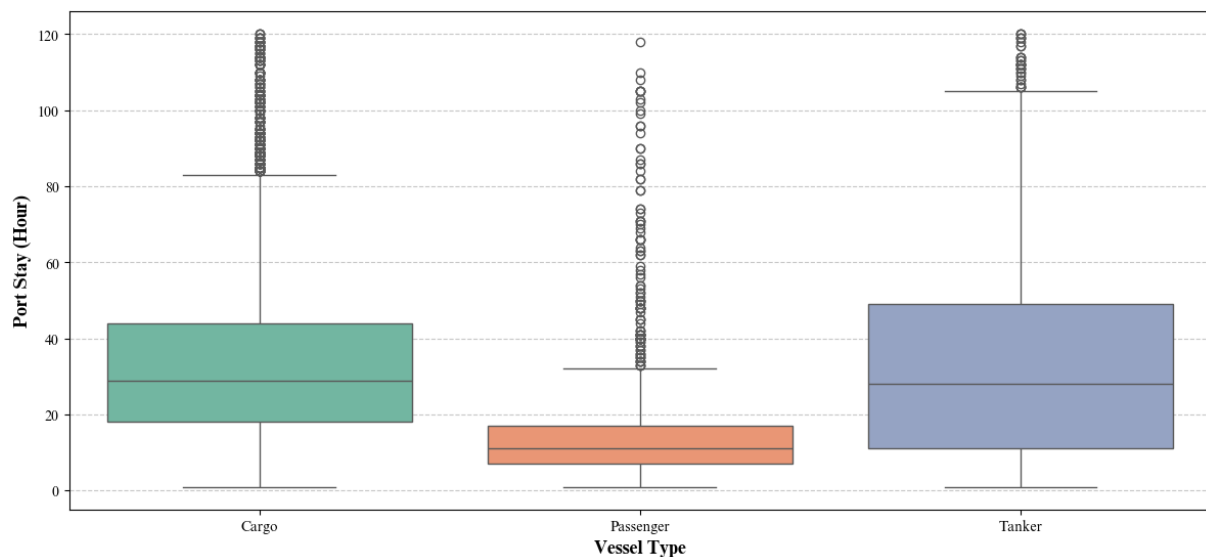
Figure 5. Port calls at Port of Tanjung Priok by vessel type, 2024.

The observed increase in port calls during March, especially for cargo vessels, corresponds with the elevated transportation and logistics activity of the high season. Ramadan in 2024 begins on March 11 and ends on April 9, with Eid al-Fitr occurring on April 10. The increase in vessel traffic in March is likely linked to the pre-Idul Fitri period, which is typically associated with improved financial performance in the transportation and logistics sector [27].

Based on the data in Table 3, the Port of Tanjung Priok has an overall average port stay of 32 hours and a median of 27 hours. However, port stay duration differs across the zones. The longest port stay occurs in Zone C, an anchorage area for general cargo vessels, with an average duration of 54.75 hours and a median of 59.50 hours. In contrast, Zone D, which serves as an anchorage for container vessels, has the shortest port stay, with both the average and median at just 6 hours. This difference highlights the varying operational efficiencies for different cargo types, where the fast-paced and standardized handling of containerized goods leads to quicker turnaround times compared to the more time-consuming processes for general cargo.

Table 3. Port stay at Port of Tanjung Priok, 2024.

No	Zone	Port Stay (Hour)	
		Median	Average
1	Shipping Lanes and Dock	25.00	29.61
2	A	32.00	39.14
3	B	29.50	38.60
4	C	59.50	54.75
5	D	6.00	6.00
6	E	23.00	32.51
7	F	16.00	27.67
8	G	20.00	29.17
9	H	21.00	28.57
10	I	20.00	28.74
11	J	25.00	31.24
12	K	19.00	26.46
13	Port of Tanjung Priok	27.00	32.02

**Figure 6.** Port stay at Port of Tanjung Priok by vessel type, 2024.

Passenger ships generally have the shortest and consistent port stay durations, with a median of 17.79 hours. This suggests a regular, scheduled pattern for passenger movements. In contrast, cargo ships and tankers have relatively longer port stay durations. Cargo ships have a median of 22.22 hours, while tankers have a slightly longer median duration of 25.99 hours. This pattern is consistent with [28], which highlights differences in port stay characteristics between cargo and tanker vessels. Figure 6 reveals greater variability in port stays for cargo vessels and tankers compared to passenger vessels. Both cargo and tanker vessels show numerous outliers, represented by individual points, indicating a number of instances with very long port stays. This can occur due to the complexity of the loading and unloading processes for large cargoes, which for tankers also involves strict safety procedures as well as external factors such as adverse weather.

3.1.3. Evaluation

The indicator evaluated in comparison with the official statistics is the number of port visits at the Port of Tanjung Priok throughout 2024. Based on Table 4, the RMSE and MAPE values are 55.94 and 5.27%, respectively. An RMSE of 55.94 indicates that the estimated number of port visits derived from AIS data differs from the actual data by an average of about 55 to 56 vessels per month. Meanwhile, a MAPE of 5.27% shows that the estimation has an average error rate of only 5.27% compared to the actual data.

Table 4. Evaluation result

Metric	Value
RMSE	55.94
MAPE (%)	5.27

Figure 7 presents a comparison of vessel arrivals at the Port of Tanjung Priok in 2024. Overall, both datasets exhibit similar movement patterns throughout the year, reflecting seasonal trends and the dynamics of port activities. The similarity in patterns indicates that AIS data has strong potential to represent vessel activity at the port temporally, although some quantitative discrepancies remain compared to the official data. The smallest difference occurs in January, with a gap of six vessels, whereas the largest difference appears in October, with a gap of 103 vessels.

Alongside the similar monthly patterns, the distribution of vessel arrivals by type also shows consistent proportions, reflecting stability in the operational characteristics of the port. As shown in Figure 8, cargo vessels are the most dominant type, making up 68.6% of visits in AIS data and 71.6% in official statistics. Following cargo vessels, tankers represent 20.3% of visits in AIS data and 18.9% in official statistics. Passenger vessels show the lowest proportion, with 11.1% in AIS data and 9.5% in official statistics.

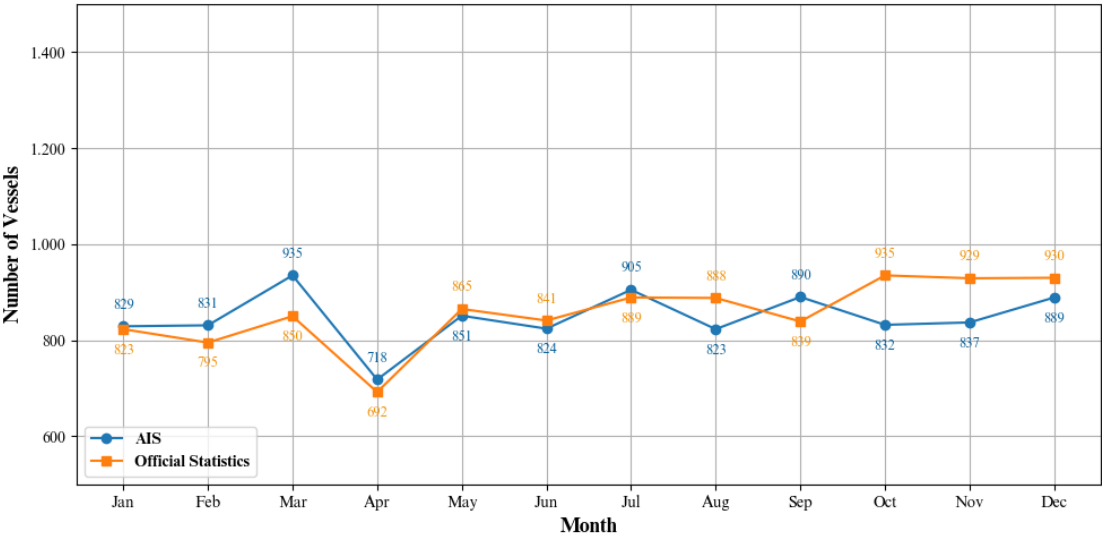


Figure 7. Comparison of AIS-based and official statistics on vessel arrivals at the Port of Tanjung Priok, 2024.

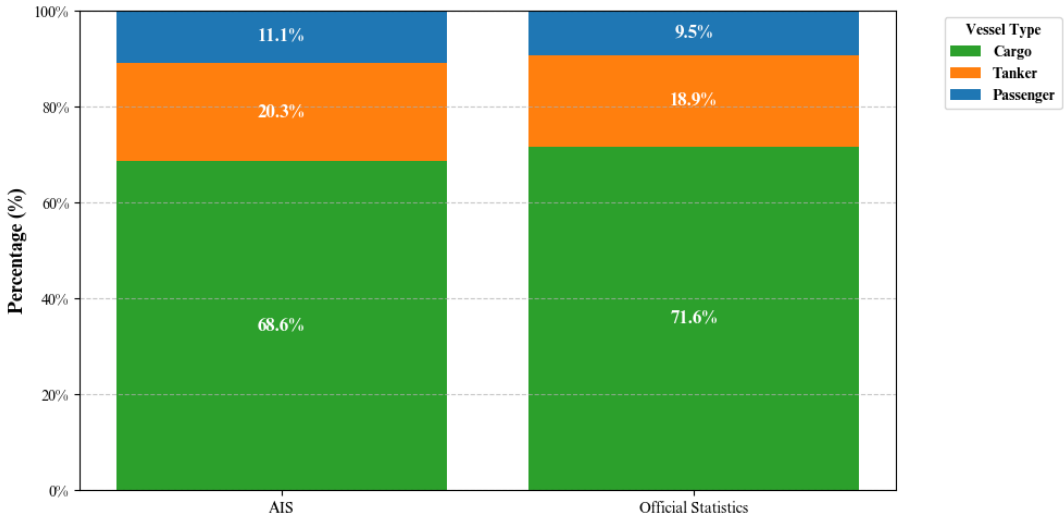


Figure 8. Comparison of AIS-based and official statistics on the distribution of vessel arrivals by type at the Port of Tanjung Priok, 2024.

3.2. Discussions

The use of administrative port boundaries as the AoI in AIS data processing shows promising results. This can be seen from the clearly defined port boundaries that successfully distinguish different parts of the port area. This approach addresses previous challenges by resolving the issue of overlapping areas in adjacent ports. Furthermore, with well-defined boundaries, deeper analysis can be conducted, enabling the identification of vessel conditions both in anchorage areas and at the berth. Using these boundaries, the calculation of AIS-derived indicators can produce more representative and accurate values.

The AIS-derived indicators also demonstrate strong performance, as reflected in the alignment of the patterns. The evaluation results show an RMSE of 55.94 and a MAPE of 5.27%, indicating a close match with official statistics. Moreover, the monthly trends and distribution of port calls for cargo, tanker, and passenger ships show consistent values and trends compared with official statistics. This indicates the potential use of AIS data as a complementary source to official statistics, offering more timely and granular insights.

Previous studies have extensively discussed the potential of AIS as a complement to official statistics. One key factor in obtaining reliable results lies in the definition of port boundaries. Clearly defined boundaries are required to produce more representative outcomes. The use of administrative boundaries, or DLKr, proves effective as the AoI in AIS data processing. This finding aligns with [2], which argues that manually defined AoI can produce reliable results when based on expert input or high-quality ground-level data.

By clearly defining port boundaries and reducing spatial overlap between adjacent ports, the use of DLKr has the potential to generate AIS-derived indicators that are more representative of actual port conditions. This finding addresses the limitations of commonly used boundary definition approaches, such as square or bounding box methods, which are prone to errors and inadequately represent real port activities [9]. However, this approach is limited by the availability of DLKr data. This limitation highlights a lack of scalability when research requires broader coverage.

Alternatively, several approaches have been proposed to define port boundaries using data-driven decisions. One such approach is the application of cluster-based and heatmap-based methods, as demonstrated by [2][20]. Under this approach, port boundaries are dynamically derived from AIS signal activity observed during a reference year. In other words, each port can be assigned its own boundaries; however, this comes at the cost of additional computational requirements.

However, no study has systematically compared the performance of AIS-derived indicators generated using DLKr-based AoI with other approaches, such as data-driven AoI. A comparative assessment between these methods would be essential to evaluate the ability of each approach to capture actual port activities, particularly within the diverse operational and data availability contexts of Indonesian ports. This comparative evaluation could provide empirical evidence to identify the most suitable AoI definition for large-scale maritime monitoring in Indonesia.

4. Conclusions

DLKr provides a clear division of port areas based on their respective functions, resulting in variations in the size of each zone. The largest zone is designated for transshipment and ship-to-ship operations, while the smallest zone serves as anchorage for state vessels. This functional definition is expected to enhance the representativeness and accuracy of AIS-derived indicators. The AIS-derived port call indicators for the Port of Tanjung Priok show reasonable consistency with official statistics from the Ministry of Transportation, as reflected in RMSE and MAPE values. This consistency confirms that DLKr-based AoI can reliably represent port traffic dynamics while maintaining coherence between arrivals and departures. Vessel activity is predominantly driven by cargo ships, followed by tankers and passenger vessels, reflecting the operational characteristics of the port. Analysis of port stay indicates that vessel duration varies across DLKr zones and vessel types. Tankers tend to exhibit longer and more variable stays compared to other vessels. In contrast, passenger vessels generally have shorter port stays. These patterns align with operational practices observed in previous studies. These findings provide a scientific contribution by demonstrating that the use of administrative boundaries as the AoI in AIS data

processing can produce more robust AIS-derived indicators. The use of DLK_r improves the validity of AIS-based indicators for monitoring port vessel activities and complements official statistical data. This result confirms that administratively defined port boundaries offer a more representative spatial framework for capturing actual port-related vessel behavior. Furthermore, these findings can serve as a basis for the development of real-time, big data-driven monitoring systems to support continuous observation of vessel activities in port areas. To strengthen this application, future research should systematically compare the performance of DLK_r-based AoI with alternative data-driven AoI approaches. Additionally, the results of this study can also serve as a foundation for the development of additional AIS-derived indicators, such as estimates of cargo volume, emissions, and other maritime indicators.

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