Clustering Dynamic Proximity Graphs to Profile Vessel Traffic Density over Time in a Baltic Sea Case Study

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ABSTRACT

Maritime traffic in the Baltic Sea consists of continuously changing vessel-to-vessel interactions. To characterise these interactions at the network level, we construct time-indexed proximity graphs, where vessels are connected when they are within a defined encounter range. Each graph is decomposed into connected components representing local traffic formations. For every component, we compute structural descriptors such as size, density, degree statistics, clustering, path efficiency, and centrality. These feature vectors are clustered using unsupervised learning to identify recurring traffic regimes. The resulting clusters reveal interpretable maritime traffic states ranging from sparse dyadic encounters to dense, highly connected formations. A full-day Baltic Sea AIS case study demonstrates clear diurnal patterns in traffic structure and shows that graph-based clustering provides a scalable and data-driven approach to profiling traffic density and maritime interaction complexity.

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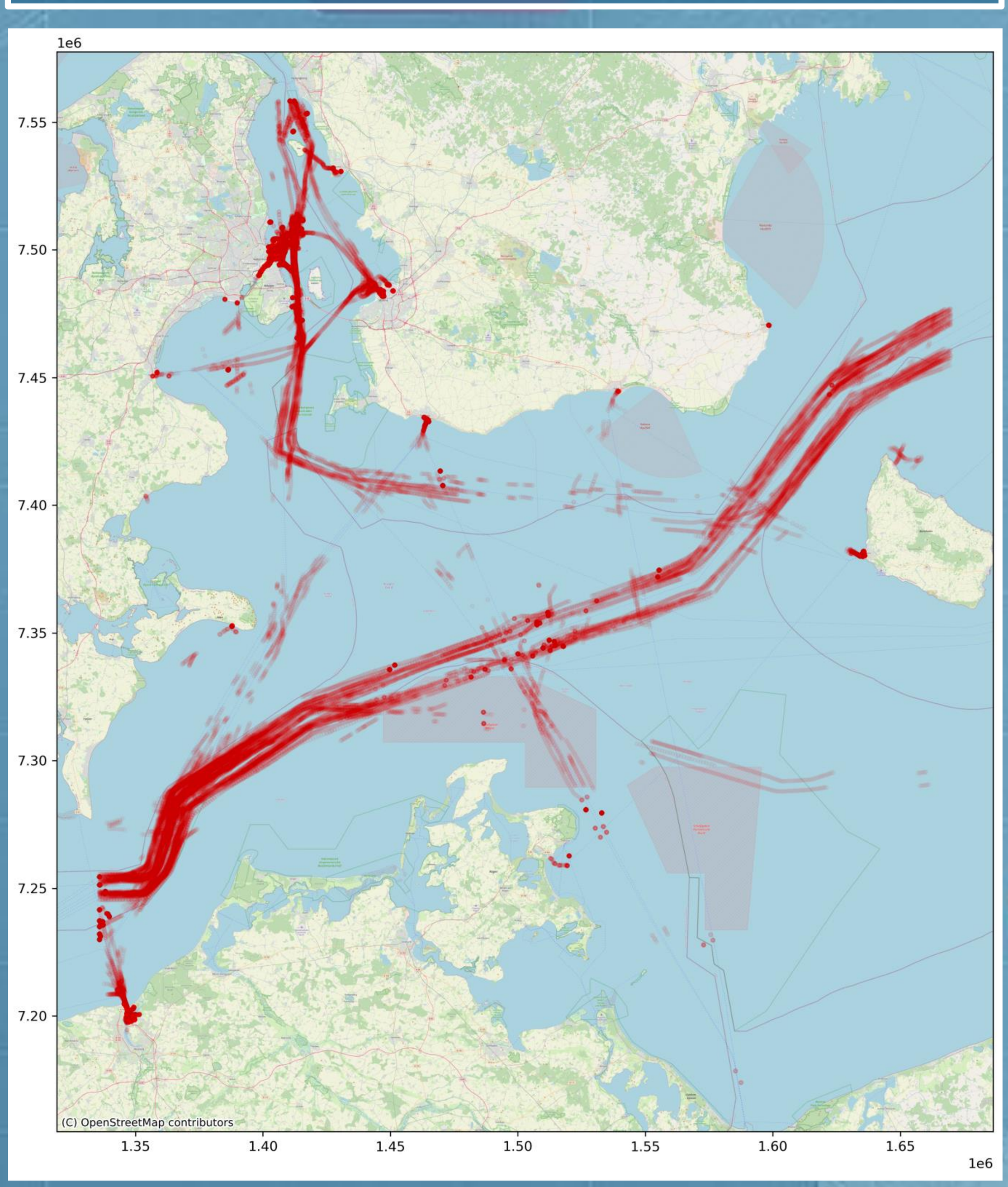


Fig. 1. Baltic Sea region with filtered AIS daytime data

DATASET

Automatic identification system (AIS)

Region: Baltic Sea
Time period: 2024-01-11
Data sources: AIS observations (positions, speed, heading, distances)

Preprocessing steps:

- 1-minute resampling
- Proximity threshold: 2 NM
- Vessel pairs filtered:
- Distance < 2 NM
- SOG1 > 0 and SOG2 > 0
- MMSI1 != MMSI2

METHODS

Dynamic Proximity Graphs

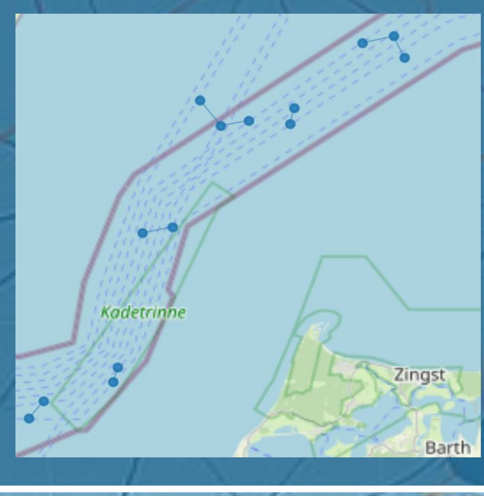
- Each minute, vessels are represented as nodes.
- Edges link vessel pairs within a 2 NM threshold.
- Each snapshot is a separate proximity graph; connected components represent local interaction groups.

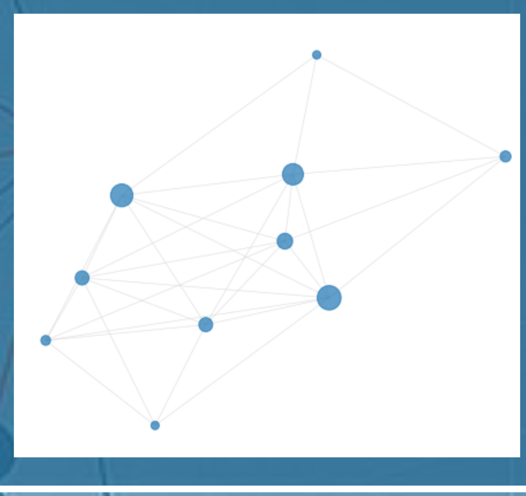
Graph Feature Extraction

- Size & structure: nodes, edges, density
- Degree statistics: mean, median, std, max
- Connectivity: clustering coefficient, transitivity
- Distance structure: shortest path, diameter approximation
- Centrality measures: closeness, betweenness
- Edge statistics: mean/median proximity distance
- Metadata: timestamp, component ID

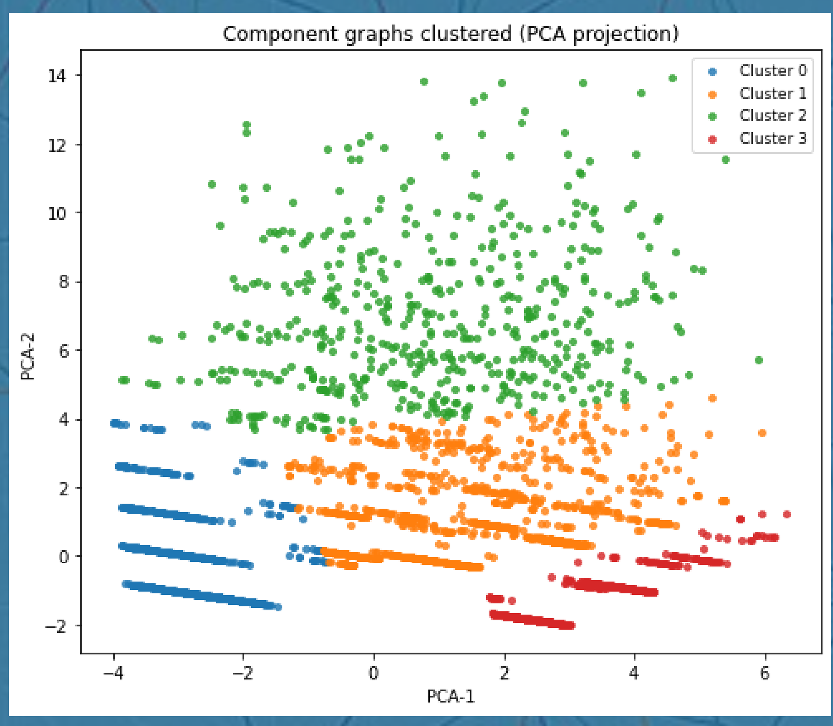
Unsupervised Clustering

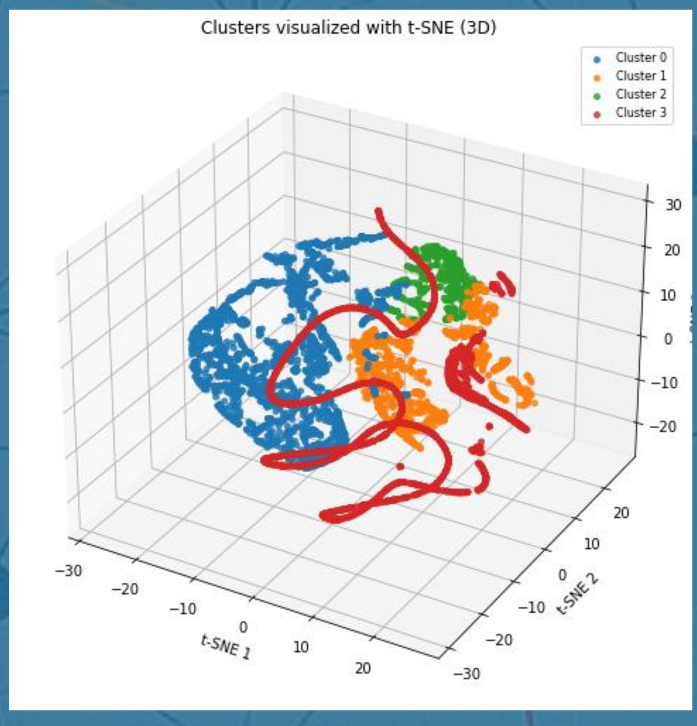
- Feature vectors are standardized using StandardScaler.
- Components are grouped via unsupervised clustering (e.g., K-Means, DBSCAN).
- Dimensionality reduction (PCA, t-SNE) is used to visualize cluster separation.

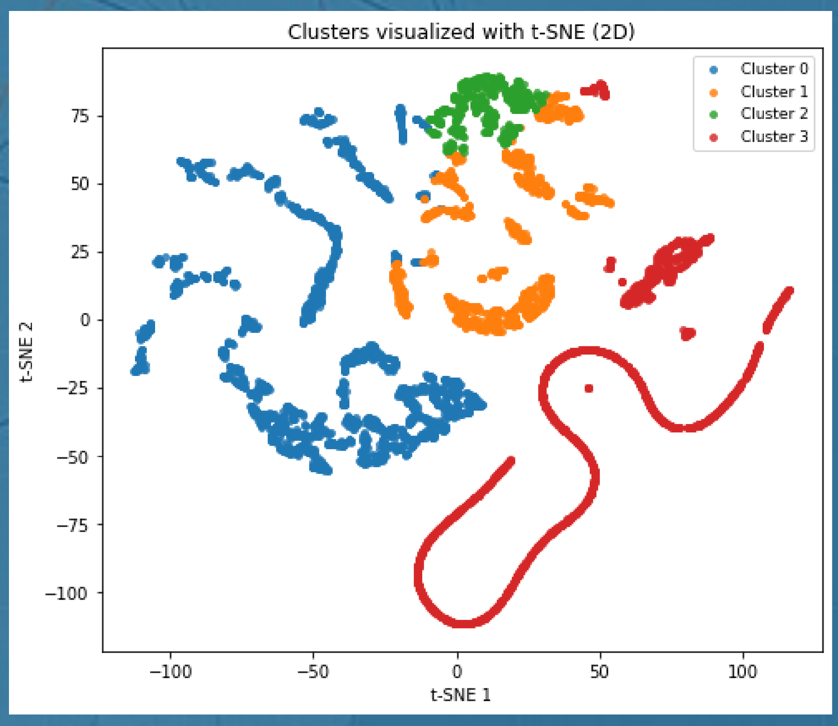


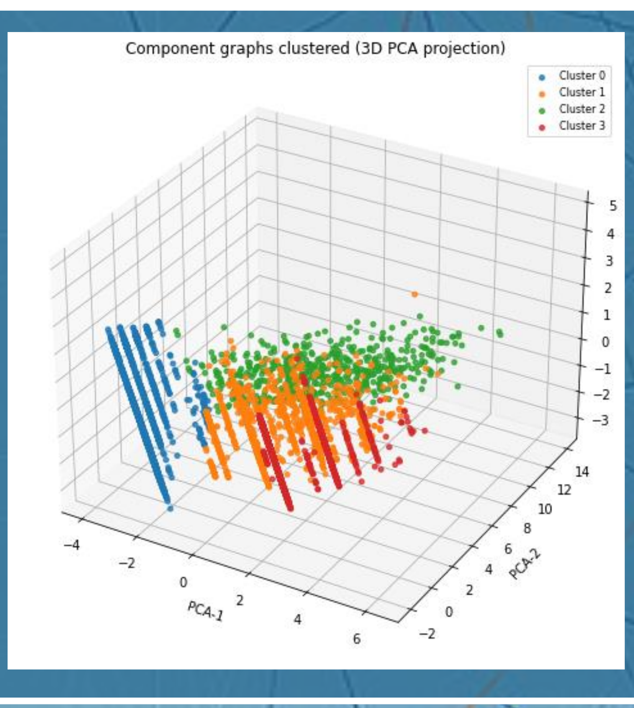


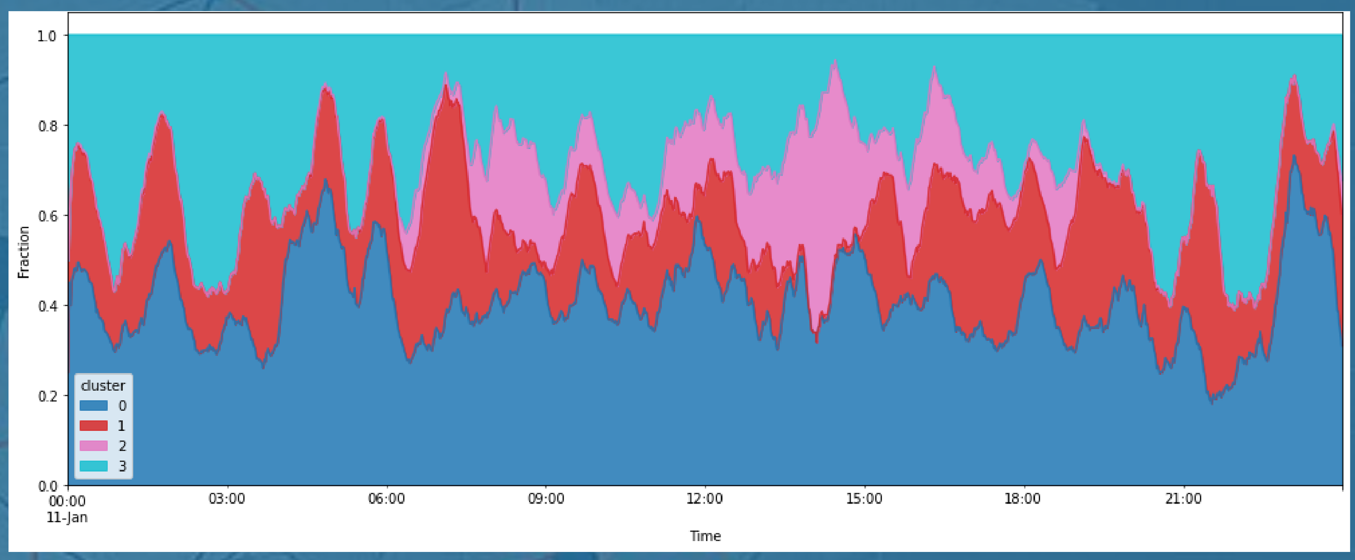
RESULTS











DISCUSSION

The analysis reveals that maritime traffic in the Baltic Sea naturally organizes into a small number of recurring structural regimes. Dense clusters correspond to high-complexity navigational periods, while sparse clusters indicate reduced interaction intensity. The temporal analysis highlights diurnal fluctuations in traffic structure, with daytime peaks and nighttime reductions. The method provides scalable and interpretable macro-level traffic characterization.

CONCLUSIONS & FUTURE WORK

Dynamic proximity graphs combined with graph-based feature extraction and unsupervised clustering form an effective framework to profile maritime traffic density over time. The identified clusters correspond to meaningful structural regimes and reveal temporal patterns useful for maritime monitoring and situational awareness. This approach supports macroscopic interpretation of vessel interactions and provides a foundation for traffic-state forecasting, anomaly detection, and integration with vessel-type or environmental data.

Integrate vessel type information
Evaluate weather influence on cluster transitions
Apply time-series clustering (e.g., HMM or sequence mining)
Explore Leiden/louvain community detection as additional graph descriptors
Predict traffic regime transitions