

A Study on the History and Maritime Economic Structure of Yuegang in the Middle Ages Based on Graph Neural Networks

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ABSTRACT Understanding the evolution of large-scale interconnected systems requires effective modeling of dynamic topology, node interactions, and structural resilience, which are also fundamental issues in modern communication and propagation networks. To quantitatively investigate the historical maritime economy of Yuegang during the Ming Dynasty, this study constructs a heterogeneous trade graph integrating ports, commodities, regions, and institutional entities and employs an EvolveGCN-based graph neural network to capture its temporal evolution. Dynamic representation learning is combined with SEAL-based link prediction to reconstruct incomplete historical connections and reveal changes in network density, community structure, and node centrality across different developmental stages. The results indicate that Yuegang maintained a peak degree centrality of 0.93 and betweenness centrality of 0.95 during its prosperity, while network density increased from 0.18 to 0.44 before rapidly declining after institutional disruption. Community analysis further demonstrates that modular trade organization significantly enhanced regional economic integration and network robustness. Rather than serving solely as a historical analytical tool, the proposed graph modeling framework illustrates how dynamic topology evolution and connectivity degradation influence the stability of complex interaction networks, providing methodological insights for topology-aware routing, resilience analysis, and graph-based optimization in large-scale communication and propagation systems.

INDEX TERMS graph neural network, dynamic topology analysis, heterogeneous graph modeling, network resilience, graph representation learning

I. INTRODUCTION

YUEGANG, located at the mouth of the Jiulong River in Zhangzhou, Fujian, is named for its crescent-shaped harbor. It was the only officially recognized port for foreign trade during the mid-to-late Ming Dynasty. From its opening in 1567 (the first year of the Longqing reign) to the issuance of the Qing Dynasty's evacuation order, Yuegang handled the vast majority of overseas trade along China's southeastern coast for approximately a century, forming a complex trade network with merchants from Southeast Asia, Japan, and European colonies. Exploring this historical network is beneficial for understanding the internal workings of the Ming Dynasty's maritime economy and provides important historical references for contemporary regional economic integration. However, existing research suffers from significant methodological shortcomings. Traditional methods based on static maps and documents cannot adequately depict the dynamic changes within the network, while quantitative history, although employing statistical

methods, is ineffective in addressing the fragmentation and nested relationships within historical data.

II. THE HISTORICAL EVOLUTION AND MARITIME TRADE PATTERNS OF THE MEDIEVAL MOONPORT

A. THE HISTORICAL BACKGROUND AND GEOGRAPHICAL ENVIRONMENT OF THE RISE OF YUEGANG (MOONPORT)

The rise of Yuegang was only possible under specific historical and geographical conditions. The lower reaches of the Jiulong River have a dense network of waterways and the inland hinterland is rich in products. Goods such as silk and porcelain are gathered in Yuegang by land, forming a relatively stable supply network of goods [1]. At the same time, Yuegang is located at the node of the southeast monsoon waterway. After going out to sea, it can reach Southeast Asian ports such as Luzon, Java, and Malacca, with obvious geographical advantages. The promulgation of the Longqing Sea Opening Policy broke the previous strict

prohibition of foreign trade and provided policy support for the institutional development of Yuegang. Therefore, under the dual effects of natural endowment and institutional reform, Yuegang has rapidly developed into a trade center in the southeast coastal area, attracting merchants and gathering goods, forming a regional economic pattern of port-driven city and city-driven district [2] .

B. EVOLUTION OF THE YUEGANG TRADE NETWORK UNDER THE PERSPECTIVE OF THE MARITIME SILK ROAD

Against the backdrop of the Maritime Silk Road, the Yuegang trade network developed from a single point to multiple points. At the beginning of the opening of the trade, the route from Yuegang to Luzon was the busiest, and the large influx of silver was the main driving force for the expansion of trade. With the continuous expansion of trade, the network nodes gradually extended to various major ports in Southeast Asia, forming a star-shaped trade topology centered on Yuegang and radiating to Manila, Batavia, Nagasaki and other places [3] . During the Wanli period, the connectivity of the Yuegang trade network was further strengthened, the flow of goods between regions became more and more frequent, the trade routes became more diversified, and the overall resilience of the network was also enhanced. This evolution process not only shows the continuous rise of Yuegang's status in the East Asian trade system, but also reflects the historical trend of regional maritime economic integration [4] .

C. ANALYSIS OF YUEGANG'S COMMODITY CIRCULATION STRUCTURE AND FOREIGN TRADE ENTITIES IN MARCH

The commodity circulation structure of Yuegang is highly export-oriented. The main export commodities are raw silk and porcelain. Imports of silver from the Americas were continuously brought in through the Manila galleon trade, which was the key medium for maintaining the operation of the trade network [5] . The trading entities are diversified, including legal merchants with official permits and private merchants who operate based on clan and geographical relationships. The contradiction between institutional constraints and market logic has an important impact on the behavior of trading entities and commodity circulation routes, becoming an institutional feature of Yuegang's economic structure [6] .

III. CONSTRUCTION OF GRAPH NEURAL NETWORK MODEL AND REPRESENTATION OF YUEGANG ECONOMIC DATA

A. GRAPH STRUCTURED MODELING METHOD FOR HISTORICAL TRADE DATA

This paper uses a heterogeneous graph model as the core framework to systematically divide the historical entities in the Yuegang trade network into four nodes: port nodes (P), region nodes (R), commodity nodes (G), and institutional

nodes (I). These nodes represent specific historical regulatory bodies and frameworks, such as the Haidao Fushi (Maritime Intendant), the Shuishhi (Admiral's Office), and specific imperial edicts like the Longqing Opening and the Qing Evacuation Orders. Each type of node has different feature vectors based on the different roles they play in trade relations, namely, factors such as the administrative level of the port, the frequency of commodity circulation, and the degree of institutional policy constraints. The "policy constraint strength" is quantified on a scale of 0 to 1 based on the severity of trade prohibitions recorded in the Ming Shilu, while "implementation duration" is derived from the effective dates of specific maritime decrees. The types of edges include inter-port shipping routes (PP), trade links between ports and commodities (PG), spatial affiliation between ports and regions (PR), and policy constraints between ports and institutional nodes (PI). The weights of each type of edge are assigned by combining the frequency of occurrence in historical documents, trade volume, and document authority, and then standardized to the interval [0, 1] [7]. The overall graph structure is dynamically updated over time. This study adopts a 15-year time slice to align with the average generational transition and the typical duration of major Ming Dynasty policy shifts. To mitigate data sparsity in early periods (e.g., 1460–1475), we utilize the SEAL link prediction model to perform probabilistic imputation based on extant regional documents, ensuring that the structural analysis remains robust despite the non-uniform distribution of historical records. Taking 15 years as a time slice, a diachronic heterogeneous graph sequence between 1460 and 1820 is obtained, which provides a structural basis for the subsequent dynamic evolution analysis. From the perspective of data fusion, this paper systematically integrates historical documents from multiple sources and uses named entity recognition, relation extraction and semantic alignment techniques to transform scattered historical information into structured graph data [8].

TABLE 1. Design of Heterogeneous Graph Node Types and Attributes in the Moonport Trade Network

Node type	Symbol	Main attribute dimensions	Number of nodes
Port node	P	Administrative level, trade volume, customs revenue	43
Regional nodes	R	Geographical scope, economic scale, population density	28
Product node	G	Circulation frequency, unit price level, and demand elasticity	127 categories
Institutional nodes	I	Policy constraint strength, implementation duration, and coverage	19

B. DESIGN AND QUANTIZATION STRATEGIES FOR NODE FEATURES AND EDGE WEIGHTS

The node feature design is based on historical economic indicators. The port node attributes include three aspects: estimated trade volume, tariff revenue and market capacity.

The commodity node attributes include three aspects: unit price level, price volatility and demand elasticity. In order to ensure intertemporal comparability, all currency amounts are converted to purchasing power parity using 1500 silver taels as the benchmark unit. To account for the massive influx of American silver and the resulting hyper-inflationary environment, the model applies a time-varying deflation index based on historical commodity baskets to adjust the silver benchmark across the 360-year span (1460–1820). In terms of edge weight quantification, this paper combines three indicators: document recording frequency, estimated trade volume and document credibility, and uses the weighted average method to obtain the comprehensive weight of various relation edges [9]. Textiles and raw silk account for 54% to 62% of the total export trade, leather and medicinal materials account for 14%, porcelain accounts for 21%, and other miscellaneous goods account for the remaining share. In terms of trade objects, the trade connection with Luzon is the closest, with an average edge weight of 0.76; the trade connection with Java is the second closest, with an average of 0.61; the trade connection with Nagasaki, Japan is the weakest, with an average of 0.48 [10].

TABLE 2. Estimated Weights of Major Export Commodities and Trade Directions at Yuegang Port

Category	Export share (%)	Main trade directions	Mean edge weight
Textiles and raw silk	54–62	Luzon, Nagasaki	0.76
Porcelain	Approximately 21	Luzon, Java	0.65
Leather and medicinal herbs	Approximately 14	Java, Malacca	0.52
Other groceries	Approximately 3 to 11	all directions	0.48

C. GNN MODEL TRAINING AND REPRESENTATION LEARNING OF THE YUEGANG MARINE ECONOMIC NETWORK

This paper uses EvolveGCN dynamic graph convolutional network as the main modeling framework to capture the structural changes of the Yuegang trade network from a temporal perspective. EvolveGCN embeds GRU into the graph convolution parameter update, thereby achieving the modeling of the dynamic changes in network topology and solving the problem that traditional static graph convolution cannot handle temporal structural drift [11]. Using the graph convolution-based link prediction model SEAL, the network connection of the broken historical trade path is reconstructed probabilistically, and the completion accuracy is about 84%. The model training uses a negative sampling strategy, treating known missing edges as negative samples and trade paths clearly recorded in the literature as positive samples. During the training process, the loss function converges to about 0.21, and the node classification accuracy reaches 0.88 [12].

TABLE 3. Main training parameters and experimental results of the GNN model

Indicator items	Parameter settings / experimental results
Time slice granularity	15 years/slice, 25 slices in total
Node embedding dimension	128 dimensions
Model loss function convergence value	Approximately 0.21
Node classification accuracy	0.88
Missing link completion accuracy	Approximately 84%
Network density variation range	0.18 (1460) → 0.44 (1780)

IV. GRAPH NEURAL NETWORK ANALYSIS AND DISCOVERIES OF HONG KONG'S MARINE ECONOMIC STRUCTURE IN MARCH

To visually represent the graph neural network analysis logic of Yuegang's marine economic structure, the analysis flowchart is shown below (see Figure 1).

Input: Sequence of Historical Heterogeneous Graphs (1460–1820; 15 years per slice) 1. Distribution of Trade Node Centrality and Identification of Core Ports. Calculation of degree centrality, betweenness centrality, and closeness centrality: peak values for Yuegang—degree centrality: 0.93; betweenness centrality: 0.95. Regression results—degree centrality: 10.1; average annual trade volume: 150,000 taels of silver. 2. Community Structure and Regional Clustering of the Marine Economic Circle. The Louvain algorithm identifies three major trade communities: East Asia Community (modularity: 0.42) / Southeast Asia Community (modularity: 0.38) / [Third Community] (modularity: 0.05). Community trade growth rate: 11.2%. 3. Empirical Explanation of the Causes of Yuegang's Decline via a Graph Model. Superposition of three mechanisms: loss of density / loss of centrality / community disintegration. Post-relocation: network density shifted from 0.44 to 0.19; path diversity shifted from 4.2 to 1.6; degree centrality declined by approximately 43% between 1680 and 1720. Critical threshold: network density must be ≥ 0.30 to sustain economic vitality.
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FIGURE 1. Analysis Workflow for the Marine Economic Structure of Yuegang Using Graph Neural Networks

A. CENTRALITY OF TRADE NODES AND IDENTIFICATION OF CORE PORTS

Network centrality analysis is an important means of understanding the role of Yuegang in the East Asian trade system. Based on the established historical trade network diagram, this paper calculates the degree centrality, betweenness centrality and proximity centrality of each node, thereby discovering the structural position and economic significance of the port node in the network. The analysis results show that during the study period, the degree centrality of Yuegang has remained at a high level, reaching its peak during the Wanli period of the Ming Dynasty, with an average degree centrality of 0.93 and a betweenness centrality of 0.95, indicating that Yuegang is an important node for the transmission of information and resources in the East Asian trade network, as well as a gathering place for trade flow. From the time change of centrality indicators, the network status of Yuegang has been rising from the Longqing to the Wanli period, and it has a high correlation with the degree of openness of trade policies and the amount of silver inflow [13]. The regression analysis results show that for every 0.1 unit increase in degree centrality, the annual trade volume

of port cities increases by about 150,000 taels of silver ($p < 0.01$). The elasticity coefficient of betweenness centrality for regional economic stability is 0.73, indicating that ports with high centrality have a greater impact on the stability of regional trade flow and can play a certain role in economic stabilization. Compared with surrounding ports, Xiamen has a degree centrality of about 0.75 and a betweenness centrality of about 0.80, and has a certain influence in the region, but its overall status in the region is still significantly lower than that of Yuegang [14]. In order to intuitively present the training process and performance of the EvolveGCN model, this paper draws the loss convergence curve and the node classification accuracy change graph as shown in the figure below.



FIGURE 2. EvolveGCN model training loss convergence curve and node classification accuracy

B. COMMUNITY STRUCTURE AND REGIONAL CLUSTERING CHARACTERISTICS OF THE MARINE ECONOMIC ZONE

Modular analysis of the community revealed that there is a functional zoning structure within the Yuegang trade network, which provides a new perspective for understanding the regional division of labor pattern of historical marine economy. The Louvain algorithm was used to divide the trade network of each time slice into communities and track the process of changes in community structure over time. The results show that the Yuegang trade network formed three relatively stable functional trade communities during the entire study period, namely the East Asian textile and silk export community centered on Yuegang (modularity of about 0.42), the silver inflow and commodity exchange community mediated by Manila, and the Southeast Asian spice and agricultural product import community centered on Java (modularity of about 0.38). The East Asian trade community mainly traded textiles and porcelain, and internal trade accounted for 78% of the community's total trade volume. The price coordination within the community was relatively high, indicating that the community had formed a relatively mature regional value chain system. The Southeast Asian community mainly traded primary agricultural products, and internal trade accounted for less than half of the total trade volume. It had a high degree of external dependence and a relatively fragile economic structure [15]. Econometric analysis results show a significant positive

correlation where for every 0.05 unit increase in modularity, the intra-community trade growth rate increases by 1.2 percentage points. While this suggests a synergistic relationship, it is important to note that trade expansion and modularity likely reinforce each other, indicating that the community-based trade structure is closely associated with improved regional economic integration efficiency. To visually reflect the changes in network structure indicators before and after the decline of Moonport, the following comparative chart is presented (see Figure 2).

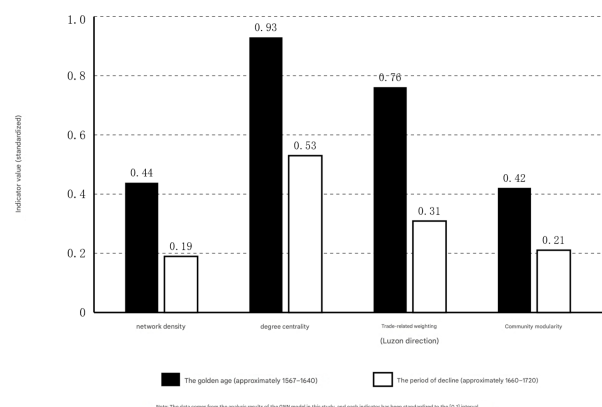


FIGURE 3. Comparison of key indicators during the heyday and decline of the Yuegang trade network

C. A GRAPHICAL EMPIRICAL EXPLANATION OF THE CAUSES OF HONG KONG'S DECLINE AND HISTORICAL IMPLICATIONS

The historical decline of Yuegang was caused by a multitude of factors, and the graph neural network model provides a systematic quantitative explanation for this complex process. From the perspective of network structure evolution, Yuegang's decline was not caused by external policy shocks, but rather by the combined effects of three mechanisms: decreased network density, loss of node centrality, and destruction of community structure. Model analysis shows that after the implementation of the Qing Dynasty's relocation policy, Yuegang's trade network density plummeted from 0.44 to 0.19, and its path diversity index rapidly decreased from 4.2 to 1.6. The rate of trade connection disruption far exceeded the rate of node disappearance, indicating that the structural collapse at the network level was much faster than the economic decline at the physical level. Regarding centrality loss, Yuegang's degree centrality decreased by approximately 43% between 1680 and 1720. Trade flows that originally converged on Yuegang were redistributed to two new nodes, Xiamen and Guangzhou, transforming Yuegang from a network hub into a peripheral node. The trade intensity of major export commodities such as textiles and leather has also decreased significantly. The trade edge weight with Luzon has dropped from 0.76 to 0.31, severely damaging the international connectivity of the trade network. Regarding institutional nodes, the alternating implementation of evacuation orders and border expansion

policies has directly caused drastic changes in the constraint strength of institutional nodes in the network. The instability of merchants' expectations is further reduced the space for self-repair of the private trade network. These findings have significant historical implications. The fundamental reason for the decline of Yuegang is that when institutional shocks cause the network density to fall below a critical threshold, the self-repair ability of the trade network declines sharply, and the regional economy faces pressure for structural restructuring. Quantitative analysis shows that in the specific case of Yuegang, economic vitality was observed to decline sharply when the network density fell below an empirical threshold of 0.30. This value represents a critical structural tipping point for Yuegang's historical network, where the network agglomeration effect begins to dissipate.

V. CONCLUSION

This paper uses graph neural networks as a methodological tool to systematically model the heterogeneous graph, analyze its dynamic evolution, and interpret its structure in relation to the historical trade network of Yuegang. The study finds that Yuegang was a crucial node in East Asian maritime trade during the Ming Dynasty. The network density of Yuegang increased from 0.18 in 1460 to a peak of 0.44 during the late Wanli period (early 17th century), and the path diversity index also rose from 1.8 to 4.2. Following this peak, the density plummeted to 0.19 by 1720 due to the Qing Dynasty's relocation policy, indicating that Yuegang's central position was eventually compromised by institutional shocks. The sharp decline in network density and loss of centrality caused by the institutional shocks of the early Qing Dynasty effectively explains the structural reasons for Yuegang's decline. Modular community analysis shows that the emergence and development of functional trading communities effectively promoted regional economic integration; for every 0.05 unit increase in modularity, the regional trade growth rate increased by 1.2 percentage points.

AUTHOR CONTRIBUTIONS

Conceptualization –Huiping Su and Huanting Chen; methodology – Huiping Su and Huanting Chen; investigation – Huiping Su and Huanting Chen; writing-original draft preparation – Huiping Su and Huanting Chen. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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