**The evolution of the port network along the Maritime Silk Road: from a sustainable development perspective**

**Abstract:** This paper explores the evolution of the port network along the Maritime Silk Road (MSR) motivated by the need for sustainable development. First, considering the influence of sustainable development on the attraction of ports, we optimize the AB model, a generator based on connectivity. After this the evolution simulation is carried out based on the data of 55 major ports along the MSR. The results of evolution simulation show that, due to sustainable development, ports in Southeast Asia and South Asia are expected to become the core nodes in the network while the status of China's ports in the network will decline significantly. The results further show that the frequency of nodes close to the mid-value increases significantly and that ports currently under construction, such as Melaka Gateway, Hambantota and Gwadar, will have an important impact on the network structure. This study serves as a useful reference for port development along the MSR from a sustainable development perspective.

**Keywords:** Sustainable development; Maritime Silk Road; Port network; Evolutionary simulation

1. **Introduction**

In the context of the global energy crisis and environmental degradation, sustainable development has become the main strategic direction for the port industry. Sustainable development impacts port production, construction and operations management from three aspects of economic prosperity, environmental quality and social welfare (Lam and Li, 2019). In terms of the economy, ports are required to continuously improve production efficiency, technical capacity and management level to enhance their sustainable competitiveness. In terms of the environment, the ports are required to save energy and reduce emissions, and ensure that natural resources and the environment are not damaged. In social terms, it is necessary to strengthen resource integration and any complementary advantages with surrounding ports to achieve regional development (Marzantowicz and Dembinska, 2018). Therefore, in order to adapt to these requirements, many world-famous ports and shipping companies, such as those found in Shanghai and the Mediterranean, have begun to make efforts in sustainable development (Mediterranean Shanghai. Co [MSC], 2019; Shanghai International Port (Group) Co [SIPG], 2019). Thus, considering the requirements for sustainable development, it is an important task for the realization of the long-term development strategy for ports to investigate the development trends and propose countermeasures for their future development.

Sustainable development will also significantly influence the evolution of the port network along the Maritime Silk Road (MSR). The 21stCentury MSR Initiative, proposed by China, is an important regional cooperation project for the world. At present, countries along the MSR have carried out extensive cooperation with China in the fields of investment, trade and security (Tim, 2016; Lam *et al*., 2018; Tekdal, 2018). Under the guidance of sustainable development, the breadth and depth of cooperation will be further strengthened. In terms of economic and social sustainable development, China has invested in, and constructed, many ports along the MSR including the Melaka Gateway, Kyaukpyu, Gwadar, Hambantota, Kuantan and Haifa (Chung, 2018), further deepening infrastructure interconnection. The construction and use of these ports will change the number of nodes in the MSR port network, thus affecting the evolution of port networks. In the context of environmental sustainable development, the Chinese Ministry of Environmental Protection issued the “Ecological and Environmental Protection Cooperation Plan of the ‘Belt and Road.” This comprehensively improved the following: safety standards; pollution control; scientific and technological innovation; information services; and other key cooperation areas of the MSR, which will change the status of some nodes in the MSR port network and also affect the evolution of port networks. In addition, the global COVID-19 pandemic has restricted the movement of people and logistics (Liu *et al*., 2020), which has brought new requirements for the sustainable development of ports. Thus, safe ports and smart ports have become the new trends in port development. Against the backdrop of this complex situation, this research addresses the following question: *How will the sustainable development concept affect the evolution of the port network along the MSR?*

Currently, the BA model is widely used in the evolution research of ports and other networks. In order to explain the mechanism of power-law distribution, Barabasi and Albert (1999) proposed the BA scale-free model, which has two characteristics: growth and preferential attachment. The AB model is an extension of the BA model proposed by Albert and Barabasi (2000), which was applied to the topological modeling of the Internet. The network will grow and expand by adding node, edge, and re-configuring edge. Compared with the BA model, the AB model is more consistent with the characteristics of port network evolution. The probability of connection between ports in the evolution of the port network is related to the degree of the port, in the BA scale-free network, and the older the node, the higher the degree (Sun and Si, 2015). In the AB model, the connection probability between ports is not only proportional to the degree of nodes but also to the product of degree and attractiveness of nodes. Thus, this paper applies the AB model to construct the port network along the MSR and explores the influence of a sustainable development concept.

There are two main aspects in this paper. First, it discusses the role of sustainable development within the process of port development. Second, based on the complex network method, it forecasts the evolution of the port network and individual ports along the MSR as a result of the drive toward of sustainable development. The contribution of this paper is that the simulation results reveal the evolution trend of the port network along the MSR under the requirements of sustainable development, and therefore provide an important reference for each port in order to adjust its own development strategy and further improve its position in the network.

The remaining sections of this paper are organized as follows: in section two, we review the literature on the MSR port network from the aspects of network construction and priority connectivity determination; section three describes the data and methodology we use to investigate the influence of sustainable development on the evolution of the MSR port network; section four presents the evolution results based on the collected data and conducts a discussion of the MSR port network; finally, the implications of the research findings and conclusions are drawn in section five.

1. **Literature review**

The fifth generation ports (5GP) consist of five aspects: service, technology, sustainable development, cluster and hub (Lee *et al*., 2018). From these, sustainable development and clustering are contemporary aspects that are newly evolved in the 5GP concept. Contemporary port development is facing multiple pressures in order to address sustainable development issues, such as blind expansion of port scale, inefficient utilization of resources, and increasingly serious environmental pollution (Wiegmans and Louw, 2011). The increasingly prominent issue of sustainable development in recent years has become an essential consideration in determining competition and cooperation between ports (Homsombat *et al*., 2013). However, the evaluation standard of port sustainability is a controversial issue, and many scholars have proposed their own frameworks.

From the perspective of port operations, Kang and Kim (2017) integrated environmental technology, process and quality improvement, monitoring and upgrading, communication and cooperation, active participation and other related issues. Furthermore, they constructed a five-factor model of port sustainable development. Lu *et al*. (2016a) focused on port sustainable supply chain management and concluded that the external sustainable cooperation and internal sustainable management of ports can have a positive impact on the performance of port sustainable development. Schipper *et al*. (2017) reviewed various long-term port plans and port improvement documents. They evaluated the sustainable development planning of ports and port cities, and concluded that the formulation of comprehensive plans, measures and regulations is helpful to promote the sustainable development of ports. Based on the survey of Taiwan's major international ports, Lu *et al*. (2016b) found that the social issues of employees' job security and safety are the most important assessment criteria for sustainable development. Hua *et al*. (2020) paid more attention to the environment, and proposed that the sustainable development of ports should focus on energy consumption, pollutant emission monitoring, scientific research, technological innovation and green port construction. In summary, although scholars put forward the evaluation framework of port sustainable development from differing angles, the core aspects are economic prosperity, social welfare and environmental quality.

From an environmental perspective, the most vulnerable ecosystem at the interface between sea and land is air pollution which seriously limits the sustainable development of ports, particularly the large emissions of CO2 (Bailey and Solomon, 2004). From the perspective of social development, the quality of port infrastructure determines the efficiency of port operation. Efficient port operation not only brings about greater economic benefits, but can also improve the utilization rate of resources, which in turn brings higher environmental benefits. In addition, the quality of the environmental protection infrastructure will also affect the sustainable development of ports (Li *et al*., 2004). From the perspective of economic development, the logistics performance, such as the efficiency of the customs clearance processes will have a long-term effect on the trade volume of the port (Portugal-Perez and Wilson, 2009). Higher customs clearance efficiency means better port logistics performance, which is conducive to the increase of port trade volume, and thus improves the sustainable development capacity of the port. Therefore, this paper takes CO2 emission per unit of GDP, port infrastructure quality, and customs clearance efficiency as three indicators to measure the sustainable development of ports within the port network evolution model, in order to investigate the impact of sustainable development on port network evolution.

Regionalization represents a new phase in the development of port systems (Notteboom and Rodrigue, 2005), which means the Complex Network Theory is increasingly used in port system research. The typical complex network is composed of a large number of nodes and edge-connecting nodes, which coincides with the port network composed of ports and shipping routes. Increasingly, scholars are analyzing and simulating the port network using the idea and method of the complex network by regarding the port as the node of the network and the connection between ports as the connection between nodes in the network (Jiang *et al*., 2015; Wang *et al*., 2016; Zhao *et al*., 2020).

At present, the research on the port network based on Complex Network Theory mainly focusses on the following aspects: the first is to study the structural characteristics of the shipping network, analyze and demonstrate the vulnerability (Ducruet *et al*., 2010), the robustness (Ducruet and Notteboom, 2012) and the small-world property (Zhang and Zeng, 2019) of the global shipping network and the spatial heterogeneity of ports (Liu *et al*., 2018). The second is to study the evolution process of the shipping network, which not only discusses the centralized or decentralized development of global shipping routes and ports as a whole (Fremont, 2007), but also analyzes the unequal development of regional status in the process of port evolution from a regional perspective (Xu *et al*., 2015). Third, the status of ports in the maritime transport network is assessed. Most of these are analyzed by the centrality index (Li *et al*., 2015; Sik *et al*., 2017) and connectivity index (Jiang *et al*., 2015). Table 1 summarizes the major research on the port network based on Complex Network Theory. However, it is worth noting that these analyzes only focus on the changes to the current status of the port compared with the past, and do not carry on empirical prediction analysis on the evolution of the future status. Therefore, there is a research gap to propose an appropriate model to predict the future evolution of port status.

**Table 1 Major research on the port network based on Complex Network Theory**

|  |  |  |
| --- | --- | --- |
| **Aspects** | **Main findings** | **Author** |
| **Structural characteristics** | This article reveals the strong relationship between local port policies and the evolution of shipping network design. | Ducruet *et al*. (2010) |
| The paper reveals a certain level of robustness in the global shipping network. | Ducruet and Notteboom (2012) |
| This article finds that the values of the degree of ports follow power-law distribution, which indicates that the global marine network is scale-free; that is, there are a few well-connected ports, while the majority are less connected ports. | Liu *et al*. (2018) |
| Based on complex networks, the statistical characteristics of the MSR are investigated, and numerical analysis shows its small-world effects and scale-free properties. Additionally, the MSR highly depends on its hubs, which is likely to lead to network vulnerability. | Zhang and Zeng (2019) |
| **Evolution process** | This paper demonstrates that there is no contradiction between the two models of approaches to the provision of maritime services, one based on direct port to port services, the other characterized by a hub and spoke network. In fact they are complementary.  | Fremont (2007) |
| This paper investigates the evolution of regional inequality in the global shipping network and finds that the East Asian, Northwest European and European (including the Mediterranean) regions have consistently held the highest positions, while East African and North African regions have held the lowest positions. | Xu *et al*. (2015) |
| **Port Status** | The results show that the average path length of the sea transportation network decreases after the Arctic route is open to traffic, the port degree value increases obviously in some Northeast Asia and Northwest Europe ports, and the port nuclear degree tends to be more polarized. | Li *et al*. (2015)  |
| This paper introduces an analysis framework for port connectivity from a global container liner shipping network perspective: it is defined in terms of the impact on the transportation network when the transshipment service is not available at the evaluated port. | Jiang *et al*. (2015) |
| The results first indicate that the degree centrality in the throughput flow is changing from the Busan port in Korea to the Shanghai or Qingdao ports in China. Second, the export volume of Korea is decreasing. Third, as for the major ports in Korea and China, China may be in a more favorable position compared to Korea.  | Sik *et al*. (2017) |

In the construction of the port evolutionary network, most of the network models adopt the BA scale-free model. Even if some improvements are made, the weights of the characteristic indicators are changed only on the basis of the BA model (Xiong *et al*., 2008; Jian *et al*., 2016). The BA model has two important characteristics. One is scale growth; that is, the number of ports keeps increasing. The other is preferential attachment, which means that newly emerged ports are more likely to connect with those ports with higher connectivity (Sun and Si, 2015). However, with the rapid development of global shipping and the full exploitation of geographical and natural resources, the total number of ports has become saturated and this makes it very difficult for new ports to emerge. In fact, there is no contradiction between the development of large ports and the survival of smaller ports because, alongside the development of large ports, smaller ports will exist in the form of feeder or feeding ports (Mohamedcherif and Ducruet, 2016; Svindland *et al*., 2019). As a result, ports are connected not by old and new ports, but by changes in existing ports, or by new connections resulting from existing port strategies or political diplomacy, or by reconfigured ports resulting from resource allocation or the development of environmental protection initiatives. Therefore, it can be seen that the basic characteristics of the BA model are not suitable for today's global shipping network. However, the AB model, an expansion of the BA model, assumes that the growth and expansion of the network are mainly realized through the addition and reconfiguration of edges, and that overcoming the weakness of the BA model in simulating network growth can explain and predict the evolution process of the port network more objectively (Albert and Barabasi, 2000).

As a topological modeling model, the AB model is widely used in the evolution of the railway express consolidation network (Zhao *et al*., 2019b), novel email network (Zhang *et al*., 2018), overlapping community networks (Karan and Biswal, 2017), and other aspects. The attractiveness of ports is composed of many factors affecting the connection of port nodes. Before containerization, location factors profoundly affected the evolution of port systems. In the development stage of containerization, shipping market factors and technological progress factors had a more obvious impact on the evolution of port systems. For example, Yap and Lam (2006) attributed the evolution and development of ports in Hong Kong, Busan and Kaohsiung to the development of the regional economy. Lee *et al*. (2008) postulated that traffic congestion and land restrictions are important factors affecting the ranking of both the Singapore and Hong Kong ports in the port system. Based on the above views, some scholars take the container throughput of ports, GDP of the cities where ports are located, and the sea distance between ports as the determinants affecting the connection of port nodes in the network. After weighting and quantifying, the attractiveness formula of port nodes can be formed (Wang *et al*., 2013; Li *et al*., 2015).

Finally, in terms of the research scope, the vast majority of current literature on the evolution of port networks focusses on the discussion of the global shipping network or regional port networks based on the division of countries and continents, while little attention is paid to the emerging sub-regional network. The MSR is a new regional cooperation initiative introduced by China in 2013. Only very limited literature focused on the description of the overall structure and pattern of the network. For example, Jiang *et al*. (2019) determined the network type by constructing the network feature set, demonstrated that the shipping network of the MSR belongs to the scale network, and analyzed its topological characteristics. Mou *et al.* (2018) explored the spatial pattern and current situation of regional trade associations of the MSR shipping network.

To conclude, there are three obvious gaps in the research that we aim to address in this paper. First, we explore the development trend of ports under the influence of the sustainable development concept. Second, we analyze the evolution characteristics of the port network along the MSR. Third, we reveal the evolution law of port network under the new situation of the global economy and trade with the AB model.

1. **Methodology and data description**

*3.1. Data description*

According to the geographical scope of the Maritime Silk Road (MSR) (Zhao *et al*., 2019a) and the ranking of the world's top 100 container ports in 2018 published by Lloyd's Daily (2019), we selected 49 major ports along the MSR. As the proponent and important participant of the MSR initiative, China's overseas ports invested in and constructed along the route have a great impact on the MSR port network, we included another six major ports along the MSR, which are Melaka Gateway, Kuantan, Gwadar, Hambantota, Kyaukpyu and Haifa (Belt and Road Portal, 2017). Table 2 lists the 55 ports from 21 countries (regions) along the MSR.

**Table 2 Major ports in the Maritime Silk Road area in 2018**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **No.** | **Port** | **Country/Region** | **No.** | **Port** | **Country/Region** |
| 1 | Shanghai | China | 29 | Tanjung Perak | Indonesia |
| 2 | Singapore | Singapore | 30 | Cai Mep | Vietnam |
| 3 | Ningbo-Zhoushan | China | 31 | Dongguan | China |
| 4 | Shenzhen | China | 32 | Fuzhou | China |
| 5 | Guangzhou | China | 33 | Salalah | Oman |
| 6 | Hong Kong | Hong Kong | 34 | Nanjing | China |
| 7 | Qingdao | China | 35 | Ambarli | Turkey |
| 8 | Tianjin | China | 36 | Port Said | Egypt |
| 9 | Dubai | United Arab Emirates | 37 | Yantai | China |
| 10 | Hambantota | Sir Lanka | 38 | Tangshan | China |
| 11 | Port Klang | Malaysia | 39 | Chittagong | Bangladesh |
| 12 | Xiamen | China | 40 | Quanzhou | China |
| 13 | Kaohsiung | Taiwan | 41 | Zhuhai | China |
| 14 | Dalian | China | 42 | King Abdullah | Saudi Arabia |
| 15 | Tanjung Pelepas | Malaysia | 43 | Karachi | Pakistan |
| 16 | Laem Chabang | Thailand | 44 | Bandar Abbas | Iran |
| 17 | Tanjung Priok | Indonesia | 45 | Khorfakkan | United Arab Emirates |
| 18 | Colombo | Sir Lanka | 46 | Haikou | China |
| 19 | Ho Chi Minh City | Vietnam | 47 | Taichung | Taiwan |
| 20 | Yingkou | China | 48 | Abu Dhabi | United Arab Emirates |
| 21 | Jawaharlal Nehru | India | 49 | Jiaxing | China |
| 22 | Manila | Philippines | 50 | Mersin | Turkey |
| 23 | Taicang | China | 51 | Taipei | Taiwan |
| 24 | Kyaukpyu | Myanmar | 52 | Haifa | Israel |
| 25 | Lianyungang | China | 53 | Melaka Gateway | Malaysia |
| 26 | Mundra | India | 54 | Kuantan | Malaysia |
| 27 | Jeddah | Saudi Arabia | 55 | Gwadar | Pakistan |
| 28 | Rizhao | China |  |  |  |

The impacts on each port are influenced by the economic growth rate, export and import trade volume, port location and cost, and economic development policy (Sik *et al*., 2017). Consequently, we calculated the container throughput of each port, the distance between ports, and the economic growth trend of port hinterland, which is calculated by the growth rate of GDP and total international trade volume (see Appendix A). We also collected the quality of port infrastructure, the CO2 emission per unit GDP, and the clearance efficiency. It should be noted that the data for these were mainly from Lloyd's Daily (2019), World Bank Open Data (World Bank, 2019), United Nations Conference on Trade and Development Statistics (UNCTDSTAT, 2020), [World Economic Forum](http://www.baidu.com/link?url=cBGkJeCtOUk0pNy-wwamnLC1DoVXai2JNQLnndX8wnMdazb-GDVAC2ElQYuaH63S) (2017), and Marine Circle (2019). Table 3 provides the definition and data source of each factor.

**Table 3 Definition and data source of factors**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Aspects** | **Features** | **Factors** | **Definition** | **Data source** |
| Conventional factors | Capacity | Throughput  | Annual container throughput of the port | Lloyd's Daily (2019) |
| Potential | Economic growth trend | The economic growth trend of port hinterland | World Bank (2019) and UNCTDSTAT (2020) |
| Cost | Distance | The transport distance between two ports calculated according to the opened route | Marine Circle (2019) |
| Sustainable development factors | Social | Quality of port infrastructure | The infrastructure’s quality of the liner shipping connectivity and efficiency of seaport services of ports | [World Economic Forum](http://www.baidu.com/link?url=cBGkJeCtOUk0pNy-wwamnLC1DoVXai2JNQLnndX8wnMdazb-GDVAC2ElQYuaH63S) (2017) |
| Economy | Efficiency of customs clearance process | The efficiency of customs clearance processes (i.e. speed, simplicity and predictability of formalities) of the country where the port is located | World Bank (2019) |
| Environment | Reciprocal of CO2 emissions | The carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring of the country where the port is located | World Bank (2019) |

The significance of liner shipping to global trade can be inferred from the fact that over 70% of seaborne trade, in terms of value, is transported by container ships (Xu *et al*., 2015). Therefore, it is reasonable to construct the port network with the global container liner data. We constructed the actual MSR port network based on the global route network announced by the top 10 liner companies, whose total capacity published by Alphaliner (2019) account for more than 80% of the world market share (as in Table 4). The actual network takes the port as the node and the route between ports as the edge and establishes a 0-1 adjacency matrix of 55 × 55. UCINET software is used to generate a simple indirect and unauthorized network and calculate the node degree, that is, number of nodes connected to the node, of each port in the network.

**Table 4 Transport capacity and market share of top 10 liner companies**

|  |  |  |  |
| --- | --- | --- | --- |
| **Ranking** | **Operator** | **TEU** | **Share** |
| 1 | APM-Maersk | 4,180,805 | 17.8% |
| 2 | Mediterranean Shg Co | 3,670,049 | 15.6% |
| 3 | COSCO Group | 2,959,346 | 12.6% |
| 4 | CMA CGM Group | 2,660,149 | 11.3% |
| 5 | Hapag-Lloyd | 1,694,463 | 7.2% |
| 6 | ONE (Ocean Network Express) | 1,586,978 | 6.8% |
| 7 | Evergreen Line | 1,299,033 | 5.5% |
| 8 | Yang Ming Marine Transport Crop. | 649,165 | 2.8% |
| 9 | PIL (Pacific Int. Line) | 393,498 | 1.7% |
| 10 | Hyundai M.M. | 367,317 | 1.6% |

Data sources: Alphaliner (2019)

According to the number of shipping companies operating on each route (the standard is three or more shipping companies) we obtained the simplified actual maritime network of the MSR as shown in Figure. 1.



**Figure.1.** Simplified actual shipping network

*3.2. Methodology*

Considering that the development of the existing ports of the MSR is relatively mature, we removed the step of adding new port nodes from the optimized AB model and adopted two evolution types for the MSR port network – these were *adding edge* and *re-configuring edge.* Specifically, adding edge refers to adding several new connections between existing port nodes in the network. Edge reconfiguration requires deleting the existing connection between two nodes, then adding a new connection between the third node and the initial first node. According to the actual situation, the route adjustment between ports will occur over a long period of time. Therefore, we use the AB model to predict the evolution of port network along MSR based on a long period of time in the future. In addition, the evolution process, connection-deleting-connection, is not only in line with the actual port network evolution law in theory, but the rationality has also been empirically tested (Karan and Biswal, 2017). The construction process of the model is as follows:

There are initial isolated nodes in the port network . Each evolutionary process performs one of the following two steps with equal probability.

Adding new internal connections with probability , which means adding new edges between existing nodes; randomly selecting a node as the starting point of the new edge, and the other end point of the edge is determined by the probability ,

 , (1)

Where represents the degree of node and is the sum of the degree of all nodes in the network. In order to ensure that the probability of establishing new connections of isolated nodes is non-zero, is used instead of in the formula.

Re-configuring edges with a probability of. Randomly selecting node and an edge which are connected to, deleting the edge and replacing it with a new edge that connects node i and node . The choice of node is determined by the probability .

In the AB model, it is known from equation (1) that nodes with longer existence time have higher degree value. However, in the real MSR port network, due to the competition and cooperation between the nodes, the optimal connection probability will change. The degree value of the final node is not only related to the existence time of the node, but also related to the factors such as politics, economy, transportation, geography, industrial structure and shipping policy. Based on the reality, we express the adaptive functions of the port node and get the attractiveness of node to node.

 (2)

Compared with the AB model, the optimal connection in the optimized model is determined by the overall attractiveness, not only in direct proportion to the degree value of nodes. In the optimized model, if a node has a higher fitness, it may get more edges in the evolution process of the node network. If the fitness of each node is the same, then the probability of adding edges in the network is completely determined by the probability.

In this model, we introduced six indices to measure the attractiveness of port nodes in the network, namely: (i) container throughput (Q), (ii) economic growth trend (Z), (iii) distance between ports (D), (iv) port infrastructure quality (S), (v) customs clearance efficiency of each port country (E), and (vi) CO2 emissions per unit of GDP (C). Among them, the economic growth trend is calculated by the growth rate of GDP and total international trade volume. The faster the development speed of the port hinterland economy is, the stronger the port's external economic connection will be in the future, the more transportation demand will be generated, and the greater the attraction of establishing connection to other ports will be. The container throughput represents the throughput capacity of the port. The larger the port scale, the higher the handling efficiency, and the greater the attraction to other ports to establish connections. The distance between ports is the current shipping distance between ports. Considering the cost of route opening, the greater the distance between ports is, the greater the resistance to the new route opening becomes. The quality of port infrastructure (Li *et al*., 2004), CO2 emissions per unit of GDP (Bailey and Solomon, 2004), and customs clearance efficiency (Portugal-Perez and Wilson, 2009), respectively, measure the economic, environmental and social standards of sustainable port development. The higher the quality of port infrastructure and customs clearance efficiency, the stronger the sustainable development of the economy and social are, and the greater the attraction of the port becomes. Conversely, the higher the CO2 emission per unit of GDP, the weaker the sustainable development is, and the smaller the attraction of the port becomes.

In order to eliminate the dimensional differences between different indicators, each indicator is standardized as:

 . (3)

According to the positive and negative correlations between each index and attractiveness, the attractiveness of each network node can be obtained by using the index construction formula after weighted quantification:

 , (4)

Where are the parameters, which are calculated by the maximum likelihood estimation method.

 . (5)

 . (6)

Equation (6) is the likelihood function. Take a logarithm of it, calculate the partial derivative of, and make it equal to 0.

 . (7)

Finally, calculate the parameter value by MATLAB.

After considering the effect of node degree and node influence factors, we substitute equation (4) into equation (2), and the attractiveness function of nodes in the network is obtained as follows:

 . (8)

Based on the data of 55 ports along the MSR, taking the attractiveness as the decisive factor of the connection between nodes, the evolution simulation process is as follows:

Step 1: Initialize the parameters according to the data. Determine the value of nodes, set the parameter values, set the probability, evolution times and total execution times of the model.

Step 2: The edge-adding operation is performed once at first, and then the edge-adding and re-configuring operations are performed with probability and ( as follows: In the edge-adding operation, selecting a node A1 randomly, and then selecting another node A2 of the edge according to the attractiveness of other nodes to A1. In the reconfiguration operation, selecting a node B1 randomly, finding all nodes connected with it, then deleting the connection between B1 and one of the nodes randomly. According to the attractiveness of other nodes to B1, another node B2 with edge is selected.

Step 3: Reporting results. The average node degree of the final network is calculated according to the total number of execution times of the model.

1. **Results and discussion**

*4.1 Simulation results*

The optimized AB model is used to simulate the evolution of 55 major ports along the MSR. The parameter values obtained by the maximum likelihood estimation method are, , , , , , respectively. The AB model is set to perform the edge-adding and edge reconfiguration operations with equal probability. The total number of execution times is 2,000 (see Appendix B). Finally, in order to show the evolution results and characteristics of the port network more clearly, we take the average value of 1,000 evolution results, and the ranking (RAN) and degrees (DEG) of each node are shown in Table 5.

**Table 5 Evolution results of network of Maritime Silk Road ports**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Port** | **Actual network** | **Evolution network** | **Port** | **Actual network** | **Evolution network** |
|  | **RAN** | **DEG** | **RAN** | **DEG** |  | **RAN** | **DEG** | **RAN** | **DEG** |
| Shanghai | 1 | 31 | 6 | 32 | Manila | 29 | 7 | 14 | 28 |
| Singapore | 2 | 31 | 4 | 34 | Taipei | 30 | 7 | 39 | 20 |
| Ningbo-Zhoushan | 3 | 31 | 42 | 18 | Fuzhou | 31 | 6 | 40 | 19 |
| Shenzhen | 4 | 31 | 17 | 26 | Chittagong | 32 | 3 | 11 | 30 |
| Port Klang | 5 | 25 | 1 | 36 | Taichung | 33 | 3 | 32 | 23 |
| Hong Kong | 6 | 23 | 15 | 27 | Haifa | 34 | 3 | 41 | 19 |
| Qingdao | 7 | 23 | 48 | 8 | Tanjung Perak | 35 | 1 | 21 | 26 |
| Guangzhou | 8 | 22 | 24 | 25 | Salalah | 36 | 1 | 29 | 24 |
| Dubai | 9 | 22 | 30 | 23 | Mersin | 37 | 1 | 43 | 18 |
| Colombo | 10 | 21 | 9 | 30 | Kuantan | 38 | 1 | 5 | 33 |
| Jawaharlal Nehru | 11 | 21 | 19 | 26 | Hambantota | 39 | 0 | 8 | 31 |
| Kaohsiung | 12 | 20 | 28 | 24 | Yingkou | 40 | 0 | 46 | 9 |
| Laem Chabang | 13 | 20 | 18 | 26 | Taicang | 41 | 0 | 54 | 2 |
| Jeddah | 14 | 19 | 33 | 22 | Kyaukpyu | 42 | 0 | 7 | 32 |
| Xiamen | 15 | 18 | 31 | 23 | Rizhao | 43 | 0 | 47 | 9 |
| Tanjung Pelepas | 16 | 18 | 2 | 35 | Dongguan | 44 | 0 | 25 | 25 |
| Tianjin | 17 | 16 | 49 | 8 | Nanjing | 45 | 0 | 55 | 2 |
| Mundra | 18 | 15 | 20 | 26 | Yantai | 46 | 0 | 52 | 8 |
| Cai Mep | 19 | 14 | 34 | 22 | Tangshan | 47 | 0 | 53 | 8 |
| Karachi | 20 | 14 | 22 | 26 | Quanzhou | 48 | 0 | 35 | 22 |
| Tanjung Priok | 21 | 12 | 12 | 29 | Zhuhai | 49 | 0 | 16 | 27 |
| Ho Chi Minh City | 22 | 12 | 10 | 30 | Bandar Abbas | 50 | 0 | 26 | 25 |
| Abu Dhabi | 23 | 12 | 36 | 22 | Khorfakkan | 51 | 0 | 27 | 25 |
| Port Said | 24 | 10 | 38 | 20 | Haikou | 52 | 0 | 13 | 29 |
| King Abdullah | 25 | 10 | 37 | 21 | Jiaxing | 53 | 0 | 45 | 16 |
| Lianyungang | 26 | 9 | 51 | 8 | Melaka Gateway | 54 | 0 | 3 | 35 |
| Ambarli | 27 | 9 | 44 | 17 | Gwadar | 55 | 0 | 23 | 26 |
| Dalian | 28 | 8 | 50 | 8 |  |  |  |  |  |

The degree distribution of nodes in the network can be expressed by degree distribution function. In order to clearly compare the actual network and the evolutionary network, we log the degree distribution of the two networks and obtain the result as shown in Figure. 2.



**Figure.2. Comparison of degree distribution between actual network and evolutionary network**

Compared with the actual MSR port network, the evolution simulation results mainly differ in the following five aspects:

1. The network density has increased and the isolated nodes have disappeared. The average degree of the actual network is 10, and 17 nodes are isolated nodes. The average degree of evolution simulation is 22.24, and the minimum degree is 2.
2. Compared with the actual network, the frequency of nodes with the maximum and minimum degrees decreases in the evolutionary network, while the frequency of nodes close to the mid-value increases significantly. The frequency of nodes with the maximum and minimum degrees of the actual network are 0.07 and 0.31 respectively, while they are only 0.02 and 0.04, respectively, in the evolutionary network. Besides, the frequency of nodes close to the mid-value, 24, are 0.13, 0.07, and 0.05 in the evolutionary network, which are much higher than the actual network. This distribution means that the status gap between ports will narrow, showing a trend of coordinated development.
3. Most of the core nodes in the network are ports in Southeast Asia and South Asia, and the status of ports in China has generally declined. Among the top 10 ports in the evolution result, except for Shanghai port, other ports are located in Southeast Asia and South Asia. China's ports, including Ningbo-Zhoushan, Qingdao and Tianjin, have generally declined in the network in the simulation results.
4. According to the results of evolutionary simulation, the ports under construction that are not yet fully operational will be at the core of the MSR port network in the future. The main ports with obvious performance are Melaka Gateway, Kyaukpyu, Hambantota and Gwadar. At present, these ports are not fully in use, so they are isolated nodes in the actual network. The simulation results suggest that these ports will evolve into important core nodes in the MSR port network in the future.
5. The simulation results show that the central positions of ports in the south and north of China are significantly differentiated in the network. Haikou, Zhuhai, Shenzhen and other southern ports are significantly higher than Dalian, Yantai, Qingdao, Tianjin and other northern ports.

*4.2 Discussion*

Based on the data of 55 major ports along the MSR, the evolutionary simulation results show that the degree distribution of ports is consistent with the research results that ports are developing towards regional integration (Notteboom and Rodrigue, 2005; Mohamedcherif and Ducruet, 2016) and that the development of large ports and the survival of smaller ports are not contradictory. Affected by the adaptive functions, the status of each port node in the MSR port network has changed significantly, and the overall density of the network has increased. When the attractiveness determines the generation of a network connection, the attribute-value of each node is the main factor determining its position in the network. Because of the differences of throughput, economic growth trend, geographical location and level of sustainable development, the status of ports in the evolutionary network undergoes many different changes compared to the actual network. With the continuous progress of the construction of the MSR, it is bound to promote the economic exchanges and growth in this region. The ports in this region will further enhance their own reputation due to an increase in communication with other ports. Additionally, the vision of facility connectivity will be further realized.

Unlike the research of Mou *et al.* (2018), we found that ports in Southeast Asia and South Asia, although having have a higher position in the network, under the influence of sustainable development factors, were lower in the network than those ports in East Asiaer. According to the current indicators of sustainable development, Southeast Asian and South Asian ports are expected to move to the center of the MSR port network, while the status of Chinese ports will gradually decline. This result is mainly attributed to the following two aspects: first, the evolution of port status was only limited along the MSR, so the geographical location had a greater impact on the evolution result; second, in addition to geographical location, the main reason for this phenomenon is the impact of sustainable development level. In the past few decades, China has had many resource and energy consuming industries that have resulted in higher CO2 emissions per unit of GDP, and the current measured level of sustainable development is very low. Compared with the ports in northern China, ports such as Dubai and Jeddah whose shipping distances to Southeast Asia are shorter, their position in the evolution network is much higher due to the advantages of sustainable development. Therefore, in order to improve the status of ports within the network, China must accelerate the transformation of the mode of its economic development and reduce the proportion of industries with high energy consumption and high pollution levels. Furthermore, it should strengthen the construction of port sustainable development capacity, and use the opportunity of global value chain adjustment to improve the quality of economic development.

Based on the evolution simulation of the port network along the MSR, total traffic volume, a widely used indicator, is proved to be inaccurate in reflecting the actual development of ports (Xu *et al*., 2015). Environmental pollution, infrastructure quality, customs clearance efficiency and other sustainable development factors play an important role in the development of a port (Bailey and Solomon, 2004; Li *et al*., 2004; Portugal-Perez and Wilson, 2009; Homsombat *et al*., 2013). The major ports under construction along the MSR are mostly located in Southeast Asia and South Asia, with superior geographical locations. Moreover, the infrastructure quality and customs clearance efficiency of these ports are relatively high, and affected by the economic structure of these ports’ hinterland, so the CO2 emissions per unit GDP in these areas are lower. Therefore, considering the influence of various factors on the evolution of port network, the ports under construction, such as Melaka Gateway, Kyaukpyu, Hambantota and Gwadar, are expected to become important nodes in the network and have an important impact on the overall network structure.

The difference in the position of ports in the network between the north and the south of China is mainly affected by three aspects: economic growth trend of the hinterland, geographical location, and the conditions for distribution and upgrading of the industrial chain. First, considering the rapid development of the Yangtze River Delta, Pearl River Delta and Guangdong-Hong Kong-Macao Bay area in recent years, compared with those ports in northern China, the hinterland economic growth trend of Haikou, Zhuhai, Shenzhen and other southern ports in China is stronger. This provides much better conditions for them to achieve an advantage in the future of network evolution. Second, compared with the ports in northern China, ports in southern China are closer to the two economic centers, ASEAN and EU, which means they will have better economic resources and shipping convenience. This report finding is aligned with Yap and Lam's (2006) analysis of the evolution of Hong Kong, Busan and Kaohsiung ports. Moreover, due to the geographical location, the evolution results of ports in southern China are more optimistic. Third, in the process of the fourth global industrial migration, China (particularly the southern region) attracted the transfer of labor-intensive industries from all over the world with low land cost and surplus labor force, which promoted the rapid development of the economy. With the technological catchup in some fields, China has begun to transform to capital-intensive industries and establish its entire industrial chain system and manufacturing system. Due to this new process, the southern region undoubtedly has better industrial foundations and upgrading conditions, which means that it will have more economic influence in the future port network.

1. **Conclusions**

Sustainable development has become a global governance issue. In response, this paper has explored the evolution of the port network along the MSR from the perspective of sustainable development. We have selected the corresponding indicators from three aspects of sustainable development, namely: environment, economy and social. Furthermore, we have introduced them into the calculation of attractiveness in order to optimize the AB model, which is based on our established MSR port network evolution model. The results of evolution simulation show that, under the influence of sustainable development and other factors, ports in Southeast Asia and South Asia are expected to become the core nodes in the network while the status of China's ports in the network will decline significantly. The results further show that the frequency of nodes close to the mid-value increases significantly and that the ports under construction, such as Melaka Gateway, Hambantota and Gwadar, will have an important impact on the network structure. This paper provides a useful reference to study the port network evolution in other regions. Additionally, this paper also provides an important reference for ports along the MSR to adjust their own development strategy from the perspective of sustainable development.

Due to the limitations of data availability, the details on the quality of port infrastructure, efficiency of customs clearance process and CO2 emissions are all based on the data of the country where the port is located, rather than the data of each specific port. However, this does not affect the outcome of our research motivation. This article is exploratory in that it only focusses on the impact of sustainable development on the evolution of the port network along the MSR. The major limitation of this paper is that our research on port evolution is geographically limited to the scope of the MSR, without considering the impact of other routes in the world, such as the Ice Silk Road (Chang, 2019; Wang *et al*., 2019). In addition, in terms of model construction, we have ignored the role of some influencing factors and the dynamic future changes of the factors, which may have a great impact on the attractiveness of the model, and may show certain interference with and influence on the prediction. Finally, in future research, a more comprehensive index framework could be established to reflect the impact of port evolution to improve the model’s prediction and interpretation ability.

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**Appendix A**. Throughput, annual GDP change rate, quality of port infrastructure, efficiency of customs clearance process, reciprocal of CO2 emissions of ports

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Port | Throughput (teu)\* | Economic growth trend of port hinterland\*\* | Quality of port infrastructure | Efficiency of customs clearance process\*\*\* | Reciprocal of CO2 emissions (kg per PPP $ of GDP)\*\*\*\* |
| Shanghai | 42010200 | 9.815 | 4.6 | 3.3743 | 2.1772 |
| Singapore | 36599300 | 4.74 | 6.7 | 4.2348 | 9.235 |
| Ningbo-Zhoushan | 26351000 | 9.815 | 4.6 | 3.3744 | 2.1772 |
| Shenzhen | 25740000 | 6.555 | 4.6 | 3.3744 | 2.1772 |
| Guangzhou | 21922100 | 6.555 | 4.6 | 3.3744 | 2.1772 |
| Hong Kong | 19596000 | 6.555 | 6.5 | 3.9797 | 9.7712 |
| Qingdao | 19315400 | 9.175 | 4.6 | 3.3744 | 2.1772 |
| Tianjin | 15972000 | 7.855 | 4.6 | 3.3744 | 2.1772 |
| Dubai | 14954000 | 4.49 | 6.2 | 3.9669 | 2.6562 |
| Hambantota | 14000000 | 6.17 | 4.5 | 4.4172 | 13.2107 |
| Port Klang | 12316003 | 5.335 | 5.4 | 3.1902 | 3.5632 |
| Xiamen | 10702300 | 10.6 | 4.6 | 3.3744 | 2.1772 |
| Kaohsiung | 10445726 | 4.69 | 5.2 | 3.3744 | 2.1772 |
| Dalian | 9770000 | 8.385 | 4.6 | 3.3744 | 2.1772 |
| Tanjung Pelepas | 8960900 | 5.335 | 5.4 | 3.1902 | 3.5632 |
| Laem Chabang | 8070000 | 4.82 | 4.3 | 3.1381 | 3.6027 |
| Tanjung Priok | 7800000 | 5.695 | 4 | 2.789 | 6.1742 |
| Colombo | 7000000 | 6.17 | 4.5 | 4.4172 | 13.2107 |
| Ho Chi Minh City | 6586190 | 10.805 | 3.7 | 2.7762 | 2.9553 |
| Yingkou | 648700 | 8.385 | 4.6 | 3.3744 | 2.1772 |
| Jawaharlal Nehru | 5133247 | 7.315 | 4.6 | 3.3597 | 3.6725 |
| Manila | 5085139 | 7.405 | 2.9 | 2.6048 | 7.5752 |
| Taicang | 507100 | 9.92 | 4.6 | 3.3744 | 2.1772 |
| Kyaukpyu | 4900000 | 9.98 | 2.6 | 2.6448 | 14.5598 |
| Lianyungang | 4710700 | 8.48 | 4.6 | 3.3744 | 2.1772 |
| Mundra | 4418700 | 7.315 | 4.6 | 3.3597 | 3.6725 |
| Jeddah | 4116935 | 4.36 | 4.7 | 2.6239 | 2.6737 |
| Rizhao | 4040000 | 9.175 | 4.6 | 3.3744 | 2.1772 |
| Tanjung Perak | 3865646 | 5.695 | 4 | 2.789 | 6.1742 |
| Cai Mep | 3566994 | 10.805 | 3.7 | 2.7762 | 2.9553 |
| Dongguan | 3500000 | 6.555 | 4.6 | 3.3744 | 2.1772 |
| Fuzhou | 3400000 | 10.6 | 4.6 | 3.3744 | 2.1772 |
| Salalah | 3385000 | 4.015 | 4.6 | 2.59551 | 2.4862 |
| Nanjing | 3230000 | 9.92 | 4.6 | 3.3744 | 2.1772 |
| Ambarli | 3194196 | 5.67 | 4.5 | 3.317 | 6.2372 |
| Port Said | 3050000 | 4.04 | 4.7 | 3.0184 | 5.1963 |
| Yantai | 3001600 | 9.175 | 4.6 | 3.3744 | 2.1772 |
| Tangshan | 2958332 | 7.855 | 4.6 | 3.3744 | 2.1772 |
| Chittagong | 2903996 | 8.73 | 3.6 | 2.672 | 7.1465 |
| Quanzhou | 2400000 | 10.6 | 4.6 | 3.3744 | 2.1772 |
| Zhuhai | 2310000 | 6.555 | 4.6 | 3.3744 | 2.1772 |
| King Abdullah | 2301595 | 4.36 | 4.7 | 2.6239 | 2.6737 |
| Karachi | 2198648 | 4.305 | 4 | 2.949 | 5.8776 |
| Bandar Abbas | 2021542 | 1.03 | 4 | 2.3729 | 2.1711 |
| Khorfakkan | 2000000 | 4.49 | 6.2 | 3.9669 | 2.6562 |
| Haikou | 1850000 | 7.42 | 4.6 | 3.3744 | 2.1772 |
| Taichung | 1744126 | 4.69 | 5.2 | 3.3744 | 2.1772 |
| Abu Dhabi | 1740000 | 4.49 | 6.2 | 3.9669 | 2.6562 |
| Jiaxing | 1722800 | 9.49 | 4.6 | 3.3744 | 2.1772 |
| Mersin | 1722000 | 5.67 | 4.5 | 3.317 | 6.2372 |
| Taipei | 1659999 | 4.69 | 5.2 | 3.3744 | 2.1772 |
| Haifa | 1470000 | 3.755 | 4.7 | 3.643 | 5.0031 |
| Melaka Gateway | 1000000 | 5.335 | 5.4 | 3.1902 | 3.5632 |
| Kuantan | 185000 | 5.335 | 5.4 | 3.1902 | 3.5632 |
| Gwadar | 100000 | 4.305 | 4 | 2.949 | 5.8776 |

 Note: \*The throughput of Hambantota, Kyaukpyu, Haifa, Melaka Gateway, Kuantan and Gwadar are officially published estimates. \*\*The economic growth trends of port hinterland are the average of 2010-2019. \*\*\*The efficiency of customs clearance process in 2018 is estimated by the value of 2007-2016. \*\*\*\*The CO2 emissions are estimated by the value of 1995-2014.

**Appendix B**. Matlab code of evolution program

function b = addedge(a,m,D)

b=a; n=length(a);

for i = 1:m

 deg = sum(b);

 pai = (deg + 1) / sum(deg + 1);

 for j = 1:n

 gama(j) = (((1/beta1 \* exp(beta1\*Q(j)) + 1/beta2 \* exp(beta2\*Z(j)) + 1/beta3 \* exp(beta3\*S(j)))) + 1/beta5 \* exp(beta5\*E(j)) - 1/beta4 \* exp(beta4\*O(j)));

 end

 LP1 = zeros(1,n);

 LP2 = zeros(n);

 for j =1:n

 LP1(j)=pai(j)\*gama(j);

 for k = 1:n

 LP2(j,k) = LP1(j)/(1/beta \* exp(beta\*D(j,k)));

 end

 end

 flag1 = randperm(n,1);

 while flag1 <= n && deg(flag1) == n-1

 flag1 = randperm(n,1);

 end

 count = LP2(flag1,1);

 ind = 1;

 for i = 2:n

 if flag1 ~= i && b(flag1,i) == 0 && LP2(flag1,i) > count

 count = LP2(flag1,i);

 ind = i;

 end

 end

 b(flag1,ind) = 1; b(ind,flag1) = 1;

end

function b = deleteadd(a,m,D)

b=a; n=length(a);

for i = 1:m

 deg = sum(b);

 pai = (deg + 1) / sum(deg + 1);

 for j = 1:n

 gama(j) = (((1/beta1 \* exp(beta1\*Q(j)) + 1/beta2 \* exp(beta2\*Z(j)) + 1/beta3 \* exp(beta3\*S(j)))) + 1/beta5 \* exp(beta5\*E(j))) - 1/beta4 \* exp(beta4\*O(j));

 end

 LP1 = zeros(1,n);

 LP2 = zeros(n);

 for j =1:n

 LP1(j)=pai(j)\*gama(j);

 for k = 1:n

 LP2(j,k) = LP1(j)/(1/beta \* exp(beta\*D(j,k)));

 end

 end

 flag2 = randperm(n,1);

 while deg(flag2) == 0

 flag2 = randperm(n,1);

 end

 ind1 = find(b(:,flag2));

 rnum2 = randperm(length(ind1));

 cnode = ind1(rnum2(1));

 count2 = LP2(flag2,1);

 ind2 = 1;

 for i = 2:n

 if flag2 ~= i && b(flag2,i) == 0 && LP2(flag2,i) > count2

 count2 = LP2(flag2,i);

 ind2 = i;

 end

 end

b(flag2,cnode) = 0; b(cnode,flag2) = 0;

b(flag2,ind2) = 1; b(ind2,flag2) = 1;

end

clear

clc

load('DISTANCE.mat');

D = DISTANCE;

p = 0.5;

q = 0.5;

pf = [p,q];

pp = cumsum(pf);

m0 = 55;

m = 1;

count = 1000;

ave = zeros(count,m0);

for z = 1:count

a = zeros(m0);

a = addedge(a,m,D);

 for i = 1:2000

 ind = find(pp>=rand);

 if ind(1)==1

 a = addedge(a,m,D);

 else

 a = deleteadd(a,m,D);

 end

 end

 degcount = sum(a);

 ave(z,:) = degcount;

end

gave = sum(ave);

deg = zeros(1,m0);

for i =1:m0

 deg(i) = gave(i)/count;

end