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# Generational evolution and spatial distribution characteristics of ports along the belt and road initiative☆

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A R T I C L E I N F O

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A B S T R A C T

Ports serve as essential nodes in global trade and economic development, offering valuable insights into both historical transformations and contemporary advancements. This study develops a port generational model using the latitude average clustering algorithm to systematically examine the evolution of investment ports along the Belt and Road Initiative (BRI) from 2013 to 2022. Key findings include: (1) A general improvement in the generational levels of ports along the BRI, with rapid development expanding from East Asia and Southeast Asia in 2013 to encompass regions such as the Persian Gulf, Eastern Europe, and West Africa by 2022. (2) The generational distribution of ports along the BRI shows a random spatial pattern rather than significant geographical clustering. BRI investments strategically manage regional risks by acquiring resources, technology, and market opportunities across different areas, aligning with China's domestic industrial and market needs, and supporting global trade objectives. (3) Ports with robust development are primarily located in East Asia, Southeast Asia, and parts of Europe, while those in decline are mainly spread across Africa, South Asia, and Eastern Europe. (4) In terms of investment approaches, contracted ports demonstrate stronger generational advancement in the first and second generations, whereas operated ports excel in the third generation and above. (5) A comparative analysis of BRI ports and surrounding ports shows that BRI investments not only elevate the development levels of the ports themselves but also positively influence the progress of nearby ports, without fostering competitive tensions.

## 1. Introduction

With the increasing interconnectedness of the global economy, international trade and cooperation have become prominent trends in globalization (Liu et al., 2024; Xu et al., 2024). Maritime transportation plays a crucial role in sustaining national economic development (Zhang et al., 2024). In this framework, ports serve as crucial nodes linking international trade and logistics, highlighting their strategic role in the global economic system. The Belt and Road Initiative (BRI), initiated by the Chinese government, is a significant driver in the expansion of the global port network. The BRI is not only a response to the current development of global port networks but also an innovative exploration into global economic integration, resource distribution, and regional economic collaboration. By investing in and developing ports along its routes, the BRI provides new opportunities for enhancing and streamlining the global supply chain, as well as offering expansive development prospects and cooperative platforms for governments and business leaders (Zhang and Wu, 2023). Currently, China emphasizes commercial port construction, particularly along the “21st Century Maritime Silk Road”, which extends from the Indian Ocean and the Red Sea to the Mediterranean, involving several key port projects (Zou, 2022).

In this context, examining the generational development of ports under the BRI is particularly important. Generational research on ports, which analyzes the development features and functional evolution of different port generations, sheds light on changes in their roles and economic impacts within the global supply chain. Despite the extensive

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attention on port development along the BRI, there is a research gap concerning the generational evolution of these ports. Thus, it is essential to establish a port generational model and study the generational progression of ports along the BRI. This research aims to gather data from investment ports along the BRI, evaluate the impact of BRI investments on their generational evolution, and provide factual evidence regarding BRI port investments. The objective is to offer scientifically grounded references for governments and business decision-makers, promote the sustainable development of BRI ports, and enhance their competitiveness and status within the global supply chain.

## 2. Literature review

### 2.1. Research on port generational development

The progressive development of ports represents a significant historical phenomenon. The transformation and upgrading of original port functions illustrate the fundamental economic trends of various time periods, showing unique historical and regional attributes (Wang et al., 2010). In this study, the classification of port generations is grounded in the foundational research reports by United Nations Conference on Trade and Development (UNCTAD), namely "*Development and Improvement of Ports: The Principles of Modern Port Management and Organization*" (UNCTAD Secretariat, 1992a) and "*Technical Note: Fourth-Generation Port*" (UNCTAD Secretariat, 1999). These seminal works, along with additional literature on port generations, inform the categorization based on key dimensions such as port service functions, scope of activities, organizational structure, and production characteristics. The concept of "generations" is employed to delineate the evolution of port functions, effectively distinguishing between various levels of port development. According to UNCTAD's framework, temporal progression is identified as a pivotal driving force in the advancement of successive port generations.

In 1992, UNCTAD introduced the concept of port generations in a research report aimed at classifying ports' developmental levels based on their timeframes and functions (Secretariat, 1992a). Prior to 1960, ports worldwide were classified as first-generation ports, primarily fulfilling basic transportation and transshipment roles. Their core services were limited to cargo handling and storage, without the integration of modern logistics, information services, or industrial processing facilities. For instance, the Port of Liverpool in the early 20th century depended significantly on traditional mechanical handling equipment. Its operations were relatively straightforward, tailored to address fundamental transportation requirements. These ports were adequately equipped to handle regional and small-scale logistics demands during a period characterized by limited globalization. However, as international trade grew, the functionality of these ports faced increasing limitations.

Between 1960 and 1980, ports evolved to include industrial processing and commercial services in addition to their traditional transportation functions, thereby diversifying and expanding their service offerings. This evolution signified the advent of second-generation ports, which were distinguished by the establishment of industrial zones adjacent to ports to accommodate light industrial processing and warehousing needs. For instance, by 1963, the Port of New York had developed facilities such as steel processing plants, ship repair yards, food processing factories, and textile and garment industries. This enabled the import of raw materials through the port, which were then processed locally and subsequently exported or distributed to other regions, establishing the port as the world's largest by cargo throughput. During this era, containerized maritime shipping began to gain prominence in the United States, with the Port of New York emerging as a significant beneficiary of this technological advancement. This development not only facilitated international trade but also considerably stimulated industrial growth in the surrounding areas. From 1980 to 1990, third generation ports developed as trade and logistics centers, incorporating advanced shipping capabilities, commercial services, information consulting, port parks, and logistics distribution (Secretariat, 1992b). By the late 20th century, the Port of Singapore had firmly established itself as a global supply chain hub and a pivotal trade center for Southeast Asia. This achievement was facilitated by the development of modernized port zones, such as the Jurong Industrial Estate, along with the implementation of advanced information and consulting systems. These enhancements enabled the port to efficiently manage complex logistics operations and support a wide range of industrial activities, thereby reinforcing its strategic importance in global trade networks.

In 1999, UNCTAD further refined the classification by introducing fourth generation ports, which are characterized as "organizations that are physically separated but interconnected through public operators or management departments". These ports provide high-end hub services and offer flexible, information-based services through port and shipping alliances. Fourth generation ports integrate the functions of the previous three generations, accommodating large-scale, highly information-driven, and networked cargo while adapting to flexible market demands and exhibiting refined production characteristics (Secretariat, 1999; Zhao and Wang, 2010). Inaugurated in 2006, Busan Port exemplifies the characteristics of fourth-generation ports by significantly enhancing operational efficiency through the integration of automated cargo handling equipment, intelligent logistics systems, and data-sharing platforms. These advancements not only streamline port operations but also enable the port to swiftly adapt to evolving market demands, demonstrating a high degree of flexibility and responsiveness in its operations.

Currently, fourth generation ports continue to evolve, with discussions in scholarly research also addressing fifth generation and sixth generation ports. Fifth generation ports are distinguished by a collaborative network model that connects hub ports with feeder ports, emphasizing symbiosis and cooperation within the port system (Xi, 2012). Furthermore, the development of green ports and low-carbon initiatives has become a significant objective for fifth generation ports. These ports increasingly incorporate Internet of Things (IoT) technologies to facilitate smart development (Chen, 2009; Li, 2013). Sixth generation ports face complex challenges, including large-scale public health crises, digital transformation, and decarbonization requirements. Researchers have proposed innovative models to enhance the adaptability and resilience of these ports (Song et al., 2024; Fahim et al., 2022).

In the context of regional port generational classification, researchers have explored the interactive relationship between the evolution of port functions and regional economic and urban development. Changes in port generations not only reflect the influences of technological advancements and globalization but are also closely tied to the development levels and planning of the cities in which they are situated. Recent studies indicate that the process of port generational evolution is gradual and characterized by ambiguous transitional phases, suggesting that upgrades in port functions are not linear but influenced by multiple factors. For instance, as urban economies grow and port functions evolve, the interdependence between ports and cities becomes increasingly complex, driving the development of port generations and imposing new management requirements (Yang, 2022). The

**Table 1**
Generational functions and evolution patterns of ports.

| Generations | Functions |
|---|---|
| First generation port | Basic transportation and transshipment |
| Second generation port | Transportation, port-based industries, and commercial services |
| Third generation port | Advanced shipping capabilities, commercial services, information consulting, port parks, and logistics distribution |
| Fourth generation port and above | Container ports, port alliances, flexibility, privatization, greening, smart ports |

generational functions and evolution patterns of ports are summarized in Table 1.

Under the BRI, the generational evolution of ports has also revealed new characteristics, such as trends in regional cooperation and functional integration (Hu and Li, 2016). Research indicates that the evolution of port functions is non-linear, exhibiting gradual and ambiguous transitional features, which reflect the stepwise transitions and states between port generations (Jiang et al., 2015). Moreover, port generational classification methods are continuously evolving. Techniques such as fuzzy recognition and cluster analysis have been employed to uncover subtle differences and generational variations in port function evolution. These methodologies assist in identifying the actual developmental stages of ports within specific regional and economic contexts. To further improve classification accuracy, various evaluation models, such as uncertainty measurement models and the analytic hierarchy process (AHP), have been introduced, offering precise and systematic tools to support port management and policy-making (Wu et al., 2014; Zhou et al., 2014).

### 2.2. Research on port development under the belt and road initiative

Since its launch, the BRI has been widely discussed and debated. Some researchers assert that the BRI has substantially boosted gross domestic product growth in participating countries through infrastructure development and economic cooperation. For instance, China's significant investments and infrastructure projects enhance its connectivity with global markets while offering numerous countries opportunities for rapid economic growth (Lu and Liang, 2020). The Port of Piraeus in Greece, managed by China COSCO Shipping Corporation, has transformed into a major logistics hub in the Mediterranean, significantly enhancing local economic activity and employment rates (Zhou, 2020). However, the initiative has also faced criticisms. Some argue that China's large investments in the BRI could be economically disadvantageous (i.e., a "bad deal"), suggesting that these funds might yield more direct benefits if invested domestically (Lai et al., 2020). Additionally, there are international concerns that the BRI might be a form of "economic imperialism", with China allegedly using a "debt trap" strategy to control strategic resources in other countries (Himmer and Rod, 2023; Carmody et al., 2021; Taylor and Zajontz, 2020; Brautigam, 2019). The Hambantota Port project in Sri Lanka exemplifies this controversy, as Sri Lanka had to lease the port to Chinese enterprises for 99 years due to debt issues, raising international concerns about China's investment strategies and intentions (Wibisono, 2019; Gangte, 2020).

In recent years, the BRI has garnered significant attention in academic research concerning port development. This body of work primarily focuses on several key areas. A considerable number of researchers have investigated the economic impacts of the BRI on ports situated along its routes. Research indicates that these ports function as essential multimodal transport nodes, effectively linking maritime and terrestrial routes. Projects initiated under the BRI are designed to enhance both inter-regional and intra-regional connectivity (Liu et al., 2020). Notably, investments in these ports have facilitated trade and infrastructure development, with data showing that port city clusters along the BRI experienced an average annual growth rate of 5.2 % from 2000 to 2020 (Li et al., 2024b).

Furthermore, studies have highlighted the BRI's significant influence on the relocation of manufacturing industries and the reconfiguration of port systems. The development of optimization models for port clusters aids in identifying the most effective networks, capacities, and regional manufacturing scales (Chen and Yang, 2018). Some researchers have employed the Condition, Capacity, Potential, and Efficiency (CCPE) model to assess ports along the BRI, utilizing extensive data related to geographic environments, shipping trajectories, port infrastructure, and regional socio-economic factors to evaluate port competitiveness based on various criteria (Peng et al., 2018).

Additionally, there has been considerable interest in enhancing port logistics capabilities and developing comprehensive port networks. Research indicates that the demand for sustainable development has prompted the port network along the BRI to reveal trends and challenges through connectivity model optimization and evolutionary simulations, informed by data from major ports along the Maritime Silk Road (Zhao et al., 2021). Scholars have also analyzed the motivations behind BRI projects in the post-COVID-19 context from the perspective of China's economy. They propose diverse research agendas that encompass global supply chains, shipping and rail transport, humanitarian logistics, regional economic development, port digitalization, and green shipping (Chan et al., 2019; Qian, 2023; Chen et al., 2022; Lee and Song, 2023). The port system is a crucial component of the efficient global supply chain, and cooperation among ports along the BRI is vital for ensuring the effective flow of goods and services (Feng et al., 2023).

Moreover, the construction of maritime shipping corridors and international shipping networks has been emphasized, along with the assessment of port resilience and supply capacities (Wan et al., 2021; Jiang et al., 2023). Research analyzing China's container shipping data over various time frames has explored the spatial patterns of the shipping network connecting China with countries along the Maritime Silk Road, identifying key hub ports and providing theoretical support for developing shipping networks and enhanced cooperation (Wang and Zhu, 2017). Other studies have evaluated the trade resilience of ports along the BRI, focusing on their capacity for resistance and recovery, and investigating their spatiotemporal evolution patterns. These studies underscore the importance of port resilience in maintaining supply chain stability (Jiang et al., 2024). Additionally, a comprehensive evaluation system that integrates multi-source port and shipping data, along with remote sensing data, has provided robust support for assessing the supply levels of ports along the BRI (Su and Wang, 2024).

Despite the extensive exploration of port development under the BRI from various angles—such as economic benefits, logistics enhancements, and network development—there remains a lack of systematic analysis concerning the generational development of these ports. This perspective is crucial for understanding the evolution of port functions and statuses at different investment stages, thereby offering new empirical insights for port development. Future research should concentrate on the dynamic changes in port generational development and examine its role and impact within the framework of the BRI.

Based on existing research, studies on port generational development primarily emphasize the formulation of generational theories and the classification of current port generations. The port function classification developed by UNCTAD has been widely acknowledged for its effectiveness in categorizing ports based on key factors, including port services, operational scope, organizational structure, and production characteristics. This classification employs generational concepts to illustrate the evolution of port functions, enabling a clear distinction between various levels of port development. Existing methods for port generational classification often utilize techniques including cluster analysis, fuzzy recognition, and AHP. Nevertheless, cluster analysis frequently encounters challenges related to high variability in experimental results and differing outcomes based on various parameters. Similarly, fuzzy recognition and AHP models may suffer from subjectivity and may not yield highly precise quantitative results, often leaning more towards qualitative analysis.

To tackle these challenges, this research adopts the dimension average value clustering algorithm to construct a port generational classification model. By analyzing multidimensional data from ports along the BRI routes and matching this data with the functional characteristics of various port generations, the model provides an objective framework for generational classification. Considering the lack of a unified theory for fifth-generation and higher ports, the study treats fourth-generation and above ports as the highest generational level for substitute modeling. This approach not only reduces the influence of subjective judgments but also enhances the predictive accuracy and practical applicability of the model. Additionally, by emphasizing data-driven quantification, the model achieves significant reductions in subjective bias, enabling automated classification and offering higher practicality and broader adaptability compared to traditional methods.

## 3. Research framework and related technologies

This study utilizes the dimension average value clustering algorithm to construct a port generational model aimed at investigating the generational changes of investment ports along the BRI routes from 2013 to 2022. This study leverages the generational theory as defined by UNCTAD, alongside related literature on port generations, to develop the essential dimensional data required for classifying port generations. In alignment with the principles of comprehensiveness, comparability, independence, and data availability, the dimensions encompass factors such as the number of port berths, port area, number of vessels, port tonnage, and port infrastructure, among others. Variables such as port area and logistics capacity are identified as key indicators due to their critical roles in supporting both container and bulk cargo operations. Specifically, port area determines the operational space and infrastructure capacity of a port, playing a crucial role in activities such as container stacking and bulk cargo handling. Furthermore, logistics capacity—comprising elements such as logistics service facilities and transportation efficiency—serves as a core dimension for evaluating a port's overall service level. For container ports, logistics capacity directly influences loading and unloading efficiency as well as cargo turnover rates. In contrast, for bulk cargo ports, logistics capacity determines the efficiency of bulk cargo handling and its pivotal role within the supply chain.

These dimensions are systematically aligned with the functional characteristics of ports, facilitating a robust classification framework. Subsequently, a correlation analysis is performed to identify the top 19 features most closely associated with port generational changes. These

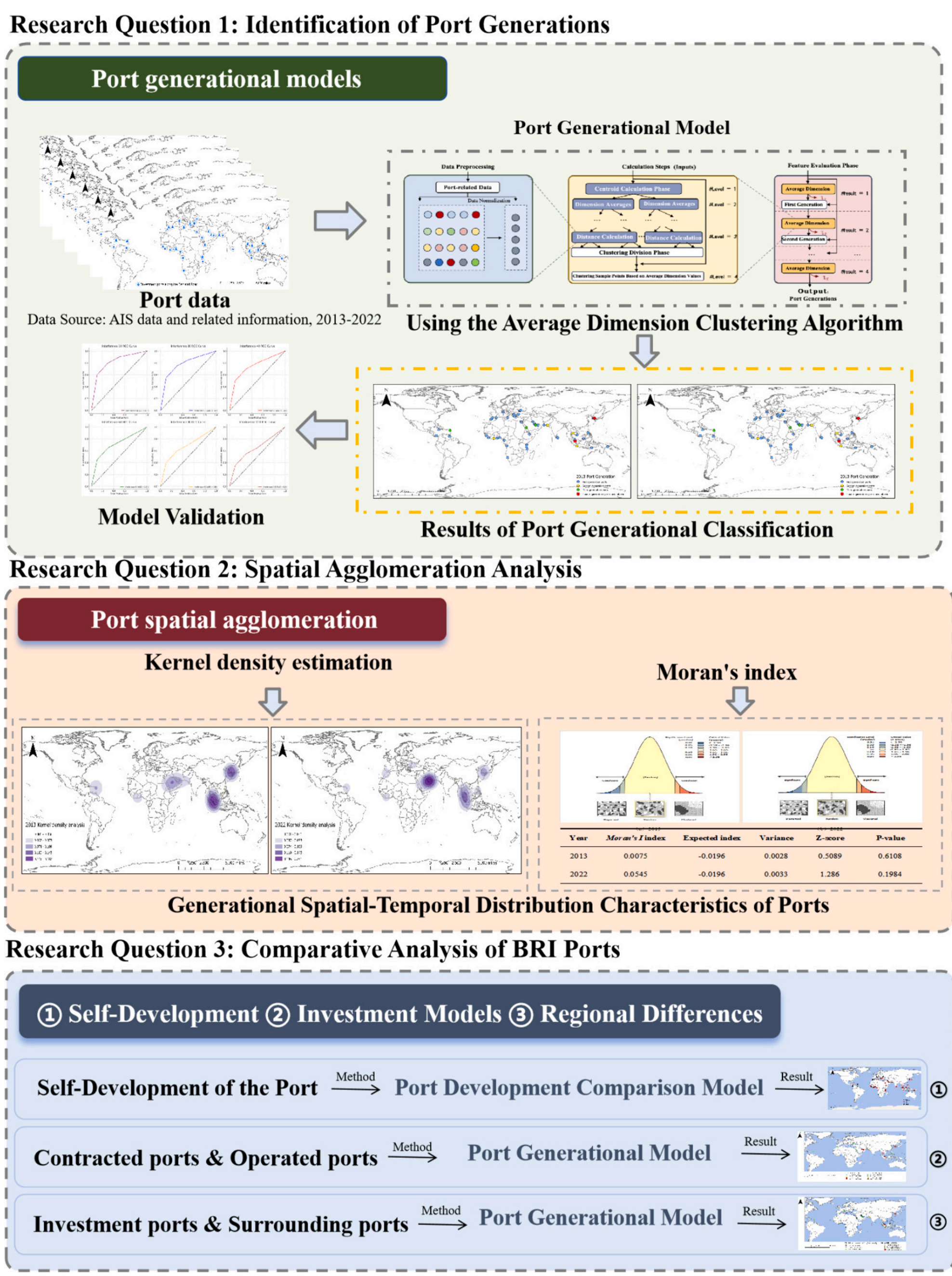


**Fig. 1.** Research framework diagram.

features serve as input values for the port generational model, facilitating the acquisition of port generational distribution results and an assessment of the model's robustness. Following this, a temporal and spatial analysis of the port generational results from 2013 to 2022 is conducted to uncover their distribution patterns. Finally, a comparative analysis is undertaken to evaluate the self-development of ports along the Belt and Road Initiative, examining various investment models and the generational characteristics of adjacent ports. This analysis provides a comprehensive assessment of the generational evolution of investment ports along the route, highlighting their regional synergies and developmental disparities. The research framework is shown in Fig. 1.

### *3.1. Research subjects and data sources*

The research subjects for this study include 61 ports along the BRI in which China has invested. Due to data unavailability for a few ports, the final analysis focuses on 52 ports, as depicted in Fig. 2. In Fig. 2, the numbers 1 to 52 correspond to the index numbers assigned to the ports under study, serving to identify the specific locations of BRI investment ports on the map. These numbers are generated sequentially, following the alphabetical order of the ports' English names, ranging from A to Z. These ports are distributed across various regions, including Asia, Europe, and Africa, with a comparatively lower number of ports in North and South America.

The relevant data for the analyzed ports is primarily sourced from the United States National Geospatial-Intelligence Agency, the International Maritime Organization, the Lloyd's Register of Shipping, AIS data, the World Bank, and the UNCTAD, as detailed in Table 2. To assess the overall trends and characteristics of port development, this study analyzes data from 52 ports along the Belt and Road Initiative (BRI) routes, focusing on the years 2013 and 2022. The research sample includes key indicators such as the number of berths, port area, number of vessels, and cargo throughput. Table 3 presents detailed descriptive statistical results, including sample size, mean, minimum, and maximum values, to illustrate the data distribution characteristics and their evolving trends over the specified period.

Table 3 illustrates a notable expansion in port infrastructure and functional areas over the study period. The average number of berths increased from 17.48 in 2013 to 24.88 in 2022, indicating significant growth in port infrastructure. Similarly, the average port area expanded from 3.22 $km^2$ to 4.29 $km^2$, with the maximum area increasing from 34.81 $km^2$ to 49.60 $km^2$. This reflects a continuous enlargement of port functional areas. Furthermore, cargo throughput reached a peak of 2916.82 million tons in 2022, highlighting a substantial enhancement in cargo handling capacity.

**Table 2**
Data and sources.

| Data Name | Descriptions | Source | Year |
|---|---|---|---|
| Port production data | Port infrastructure, number of berths, handling capacity, etc. | Port Entry Guide | 2013–2022 |
| Port transportation data | Number of connections, number of ship arrivals, deadweight tonnage, etc. | AIS Data | 2013–2022 |
| Port service data | Data on maintenance supplies, fuel supply, medical facilities, etc. | Port Entry Guide | 2013–2022 |
| Port environmental data | Natural constraints such as tides and surges | United States National Geospatial-Intelligence Agency | 2019 |
| Port safety data | Number of ship accidents and incidents hindering safe navigation | International Maritime Organization | 2010–2020 |
| Port storage data | Port storage area for different types of goods | Sea web Ports module by IHS Markit | 2021 |
| Shipping service companies | Data on 12 types of shipping service companies | Lloyd's Register of Shipping | 2019 |
| Port remote sensing image data | Wharf area, berth area, coastline length, etc. | Google Earth | 2021 |
| Port natural condition data | Channel depth, port size, cargo wharf depth, etc. | United States National Geospatial-Intelligence Agency | 2019 |

The decade from the launch of the BRI in 2013 to 2022 marks a critical phase, encompassing the initiative's inception through to its mid-term implementation. Throughout this period, China's investments in and collaborative projects with ports along the BRI routes progressively materialized. Consequently, the infrastructure and operational models of these ports began to demonstrate trends indicative of generational evolution.

The selection of this 10-year time span is justified by several reasons. Firstly, it effectively captures the outcomes of policy implementation from the early to mid-stages of the BRI, particularly highlighting the initial impacts of investments and cooperative efforts on the

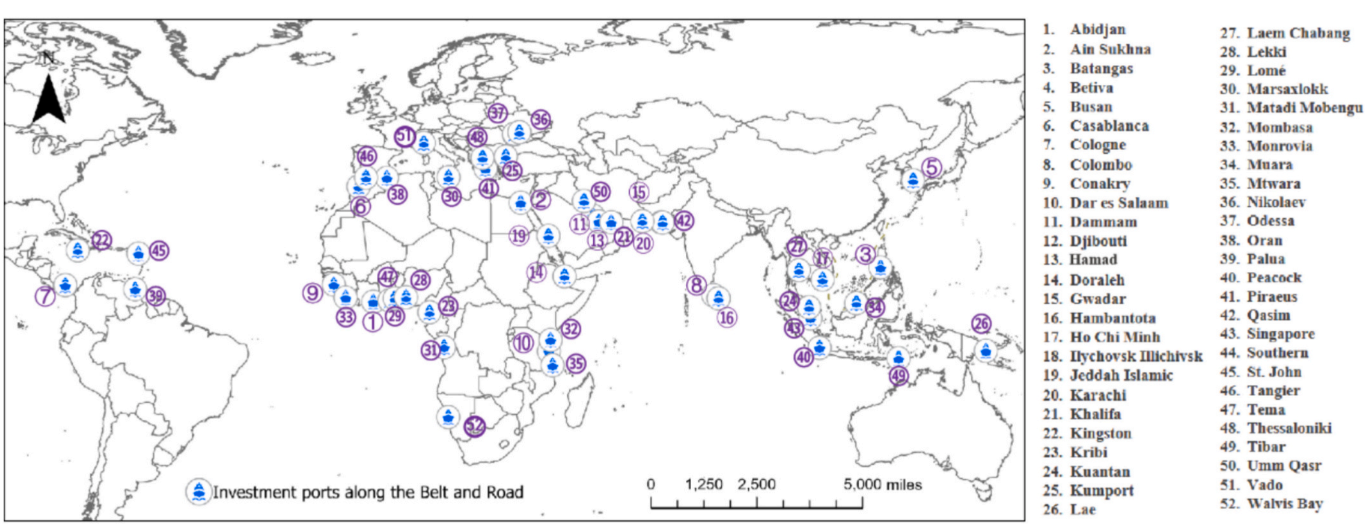


**Fig. 2.** The 21st century maritime silk road along the port spatial distribution.

**Table 3**
Descriptive statistics for port indicators in 2013 and 2022.

| Year | Statistic | Count | Mean | Min | Max |
|---|---|---|---|---|---|
| 2013 | Number of port berths | 52 | 17.48076923 | 1 | 126 |
| 2013 | Port area (km2) | 52 | 3.220129586 | 0.175 | 34.80652377 |
| 2013 | Annual number of ship calls | 52 | 6.142865385 | 0.15 | 107.072 |
| 2013 | Port deadweight tonnage | 52 | 14.85914726 | 0.12 | 292.2276648 |
| 2022 | Number of port berths | 52 | 24.88461538 | 2 | 126 |
| 2022 | Port area (km2) | 52 | 4.295242864 | 0.186 | 49.60170283 |
| 2022 | Annual number of ship calls | 52 | 6.903519231 | 0.18 | 104.599 |
| 2022 | Port deadweight tonnage | 52 | 170.4225074 | 0.77 | 2916.824108 |

generational development of ports along the routes. Secondly, while the generational evolution of ports is inherently a medium- to long-term process, significant trends such as equipment upgrades and enhancements in operational models have already emerged within this timeframe. For example, during this period, some ports progressed from first-generation to second-generation status, while others advanced from second-generation to third-generation ports. This demonstrates that a 10-year span is adequate to capture the key characteristics and changes occurring during the early stages of policy implementation.

In this study, the concept of "port generations" is defined through a comprehensive evaluation of the overall functions and operational characteristics of ports. This classification primarily relies on multidimensional data, including port area, number of berths, and logistics capacity, to characterize the overarching attributes of port systems. While ports typically comprise multiple terminals with varying levels of equipment and distinct functional roles, the focus of this study is on the generational analysis of a port's integrated operational functions. This analysis considers the overall scale, infrastructure development, and functional positioning of the port, rather than the specific attributes of individual terminals. As illustrated in Fig. 3, a systematic examination of the business activities of 52 ports indicates that the majority are engaged in multiple business types. These ports handle a diverse range of cargo, including containerized cargo, bulk cargo, liquid cargo, and roll-on/roll-off cargo. Conversely, only a limited number of ports specialize in a single business type. For instance, Khalifa Port and Ho Chi Minh Port primarily focus on container transport, Palua Port specializes in liquid transport, and Monrovia Port is dedicated to iron ore transport.

This phenomenon highlights the growing diversification of functional characteristics among ports within the global supply chain. Notably, the business type classification presented in the chart effectively illustrates the primary business combinations of each port. This classification serves as a critical foundation for further investigation into the relationship between port types and their generational evolution characteristics.

### 3.2. *Construction of port generational models based on the average dimension clustering algorithm*

Identifying port generations is essential for assessing the development levels of ports and the disparities in their developmental degrees. Traditional generational models typically rely on hierarchical or fuzzy analysis, which often involves subjective scoring. This subjectivity can limit their effectiveness compared to quantitative analysis. Therefore, establishing data-driven port generational models is particularly important. The core principle of the average dimension clustering algorithm is to process multi-dimensional data by calculating the average value of each dimension across various generations and using these averages as centroids for the current dimension combinations. This method effectively delineates distinct port generations.

Initially, the average value for each dimension is calculated for various dimension combinations (i.e., different generations), which are then employed as the centroids for the current generation. Next, the average dimensional distance from all points in the current sample to the centroid is calculated and recorded, using data from the current dimension combination. When considered globally, this average dimensional distance serves as an indicator to differentiate between various port generations.

Given that the next generation of ports is developed based on the previous generation, an inclusion relationship exists in generational attributes. This implies that the attributes of the next generation must encompass those of the preceding generation. Consequently, when determining the classification results for the next generation, it is crucial to reference the final results of the previous generation's classification rather than the initial sample set.

In the new sample set, the new centroid and the average dimensional distance from all points in this set to the centroid are calculated based on the current generation's dimension combination. These distances are then compared with those from the previous generation, and points with smaller distances are recorded. These recorded points form the sample set for calculating the classification of the next generation, and this iterative process continues.

Furthermore, the inclusion relationship among generational attributes leads to strong data coupling. Traditional clustering algorithms such as K-means and K-means++ struggle to mitigate this coupling and are easily affected by noise points, resulting in suboptimal clustering

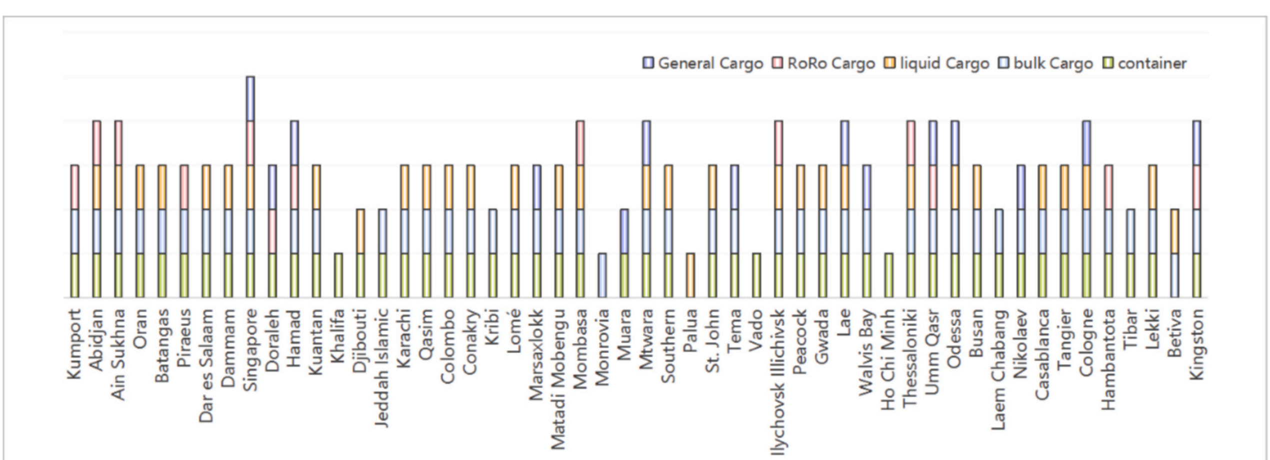


**Fig. 3.** Distribution of business types across ports in the belt and road initiative.

performance. Although the density-based spatial clustering of applications with noise (DBSCAN) clustering algorithm can somewhat reduce data coupling, it remains susceptible to noise, which can lead to clustering inaccuracies. To address these challenges, the average dimension clustering algorithm has been proposed for constructing port generational models.

*3.2.1. Theoretical algorithm*

The subsequent sections will delve into the algorithmic principles and implementation process of the port generational model from a theoretical standpoint. This includes a thorough introduction to the model's design framework, core steps, and computational methods. By integrating the model framework (Fig. 4) with the computational schematic (Fig. 5), the explanation elucidates how the Dimension Average Clustering Algorithm executes port generational classification and validation. This process involves key steps such as data preprocessing, centroid calculation, distance analysis, and classification output.

*3.2.1.1. Model framework.* The port generational model, based on the average dimension clustering algorithm, begins by normalizing the multi-dimensional data to ensure comparability across dimensions. For the current sample set and the dimension combination defining the current generation, the average values for each dimension are calculated, and these averages serve as the centroid for that generation. Subsequently, the average dimensional distance from all points in the current sample set to the centroid is computed. From a global perspective, these average dimensional values are regarded as key indicators for distinguishing between different port generations.

Fig. 4 illustrates the logical framework of the port generational classification model, which automates the classification process through a series of steps: data preprocessing, centroid calculation, distance analysis, and classification output. The framework utilizes 19 key dimensions, including port area, number of berths, and logistics capacity, as input variables. Distances between generational centroids and sample points are computed using Eqs. (1) and (2). The model's performance is assessed using metrics such as precision and recall, with the corresponding results presented in Table 6 and Fig. 9. The framework diagram effectively simplifies the complex computational steps, while the specific calculation methods are thoroughly explained in the methodology section.

To develop the port generational model, a structured process is followed, involving several critical steps. Initially, the Sklearn library is utilized to normalize the dataset, effectively reducing the impact of varying data ranges on the final results. The procedure starts with all ports in the original dataset being categorized as first generation ports (Set*1*).

For these first generation ports, the centroid $d_1$ is computed based on their attribute dimensions, and the average dimensional distance from the sample points to the centroid is calculated and recorded as Distance*1*. Following this, a new centroid $d_2$ is determined for the second generation ports using the Set*1* data, with the average dimensional distance of the Set*1* ports to this new centroid being calculated and recorded as Distance*2*.

By comparing the distances (Distance*1* and Distance*2*), ports with smaller distance values are identified and classified as second generation ports (Set*2*), ensuring that this set more accurately represents its centroid $d_2$, reflecting a more uniform feature set. This process is repeated iteratively to calculate centroids $d_3$ and $d_4$ and classify ports into third generation (Set*3*) and fourth generation (Set*4*) categories.

Through these successive iterations, which involve recalculating average dimensional distances between centroids and sample points, the port generational model is constructed. This model effectively categorizes ports into their respective generations. Fig. 5 provides a visual representation of the centroid calculation process for $d_1$ and $d_2$.

*3.2.1.2. Principles of the algorithm.* The algorithm uses the average dimensional distance as a key metric to differentiate between various port generations on a global scale. The process begins by identifying the centroid of the current port generation, which is calculated based on a combination of dimensions that define the generation. The formula for this calculation is as follows:

$$coord_j = \frac{\sum_{j=1}^{m} \sum_{i=1}^{n} x_{ij}}{n} \tag{1}$$

In this context, $m$ represents the total number of samples in the current set, while $n$ denotes the total number of ports within the current generation. The variable $x_{ij}$ signifies the attribute values for the $j^{th}$ dimension of the $i^{th}$ port in the current generation. The term $coord_j$ indicates the centroid coordinate of the $j^{th}$ dimension for the current port generation. This centroid, $coord_j$, reflects the average attribute values of all ports in the current generation across multiple dimensions. It serves as a reference point for calculating the distance between individual ports and the generational centroid in subsequent steps.

Subsequently, the average dimensional distance from all sample points in the current set to the centroid is computed using the following formula:

$$dist_i = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} \left(x_{ij} - coord_j\right)^2}{m} \tag{2}$$

In the equation, $dist_i$ represents the average dimensional distance of the $i^{th}$ port from the generational centroid. This metric, $dist_i$, quantifies

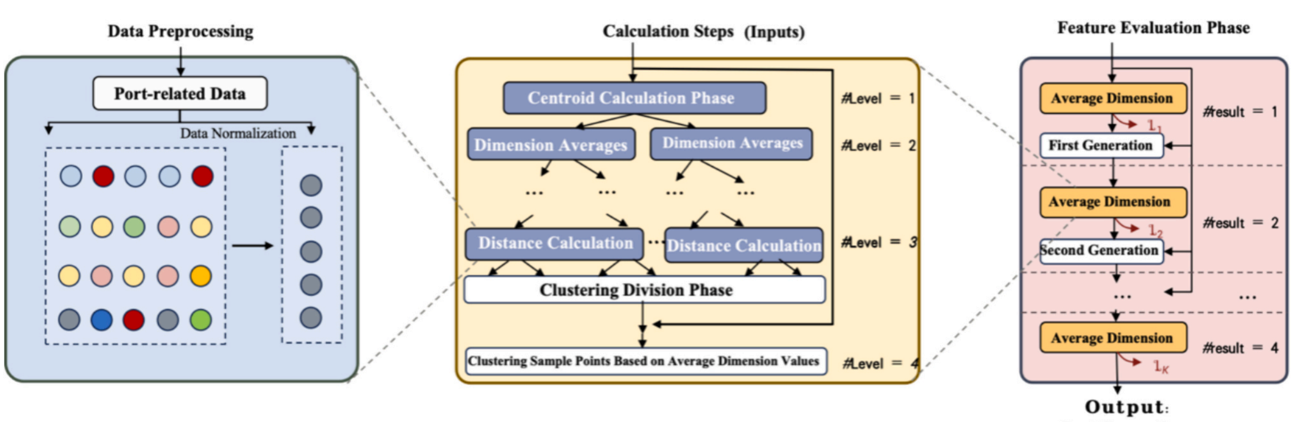


**Fig. 4.** Structure of the Port Generational Model.

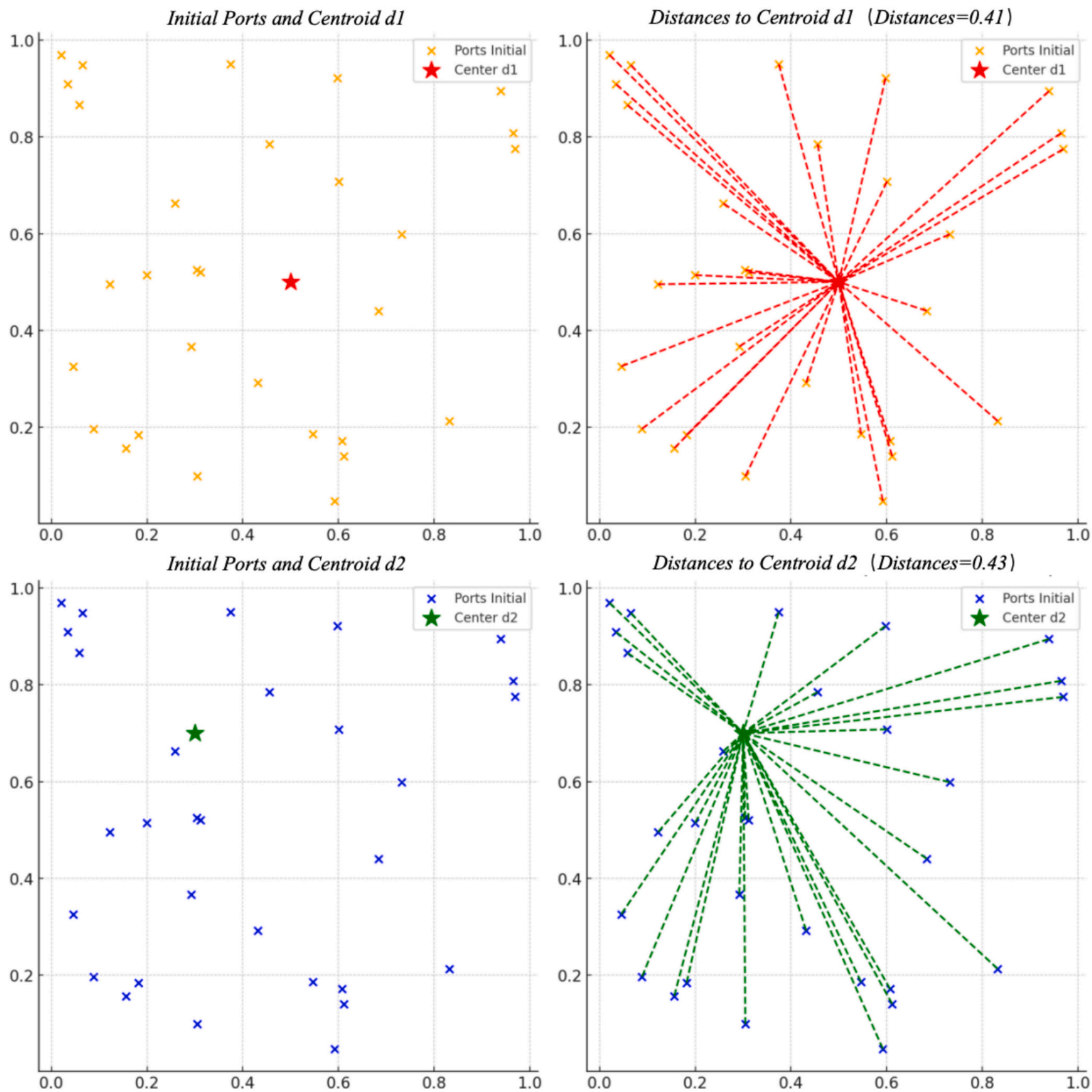


**Fig. 5.** Illustration of the calculation process for the port generational model.

the degree of deviation for each port across multiple dimensions within the current generation, indicating the average distance between the port's attributes and the generational centroid. A smaller $dist_i$ value suggests that the port closely aligns with the typical characteristics of the generation. Conversely, a larger $dist_i$ value may indicate that the port exhibits significant deviations or is situated in the boundary region of the generation.

### 3.2.2. Correlation analysis between port generations and characteristics

The relationship between port generations and their defining characteristics is deeply interconnected. This study employs principal component analysis (PCA) to statistically identify the characteristics most strongly associated with different port generations, with Pearson correlation analysis used for validation.

PCA is a widely adopted technique for reducing data dimensionality and analyzing feature correlations (El-Rawy et al., 2024). It reprojects the original data onto a new coordinate system, maximizing the variance and thus preserving essential information while simplifying the data structure and improving computational efficiency. The calculation formula is as follows (SPSSPRO, 2021):

$$X^T = \begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{1m} & \cdots & x_{nm} \end{pmatrix} \tag{3}$$

In the formula, $X$ denotes the dataset of port generational sample data. This dataset comprises $n$ samples, each consisting of $m$ attributes, forming an $m \times n$ matrix. The transposition of this data, represented as $X^T$, is performed to facilitate subsequent calculations, including the computation of covariance matrices or data projections.

The formula for calculating the average value of each dimension in the sample is as follows:

$$\mu_j = \frac{1}{n}\sum_{j=1}^{m}\sum_{i=1}^{n} x_{ij} \tag{4}$$

Variance calculation formula:

$$\sigma_j^2 = \frac{1}{n-1}\sum_{j=1}^{m}\sum_{i=1}^{n}\left(x_{ij}-\mu_j\right)^2 \tag{5}$$

Standard normalization calculation formula:

$$Z_{ij} = \frac{\sum_{j=1}^{m}\sum_{i=1}^{n}\left(x_{ij}-\mu_j\right)}{\sigma_j} \tag{6}$$

Obtain the matrix $Z$:

$$Z^T = \begin{pmatrix} z_{11} & \cdots & z_{n1} \\ \vdots & \ddots & \vdots \\ z_{1m} & \cdots & z_{nm} \end{pmatrix} \tag{7}$$

Correlation coefficient formula:

$$r_{ij} = \frac{\sum_{k=1}^{m} z_{ik} {}^{*} z_{jk}}{n-1}, (1 \le i \le j \le n) \tag{8}$$

where $r_{ij}$ represents the correlation between the data in the $i^{\text{th}}$ column and the $j^{\text{th}}$ column of the sample, with its value ranging from −1 to 1. After normalization, $z_{ik}$ and $z_{ik}$ represent the data values in the $i^{\text{th}}$ row and the $j^{\text{th}}$ column of the $k^{\text{th}}$ sample, respectively. The resulting correlation coefficient matrix is $R$:

$$R = \begin{pmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nn} \end{pmatrix} \tag{9}$$

where the resulting matrix $R$ is a symmetric matrix, i.e., $r_{ij} = r_{ji}$. Here, $r_{ij} = 1$ indicates a perfect positive correlation between the two corresponding columns, $r_{ij} = 0$ indicates no correlation, and $r_{ij} = -1$ indicates a perfect negative correlation. The greater the absolute value of $r_{ij}$, the stronger the correlation between the two columns.

Calculate the eigenvalues and eigenvectors: The eigenvalues and the corresponding eigenvectors of the correlation coefficient matrix $R$ are computed. Assuming the eigenvalues are $\lambda_1 \ge \lambda_2 \ge \lambda_3 \ge \cdots \ge \lambda_p \ge 0$, the orthonormalized unit eigenvectors obtained are as follows:

$$a_1 = \begin{bmatrix} a_{11} \\ a_{21} \\ \vdots \\ a_{p1} \end{bmatrix}; a_2 = \begin{bmatrix} a_{12} \\ a_{22} \\ \vdots \\ a_{p2} \end{bmatrix}; \ldots; a_p = \begin{bmatrix} a_{1p} \\ a_{2p} \\ \vdots \\ a_{pp} \end{bmatrix} \tag{10}$$

Calculate the contribution rate and cumulative contribution rate for each member based on the eigenvalues. The calculation formulas are as follows:

$$a_k = \frac{\lambda_k}{\sum_{k=1}^{m}\lambda_k}, (1 \le m \le p) \tag{11}$$

$$b_k = \frac{\sum_{p=1}^{k}\lambda_p}{\sum_{k=1}^{m}\lambda_k} \tag{12}$$

where $a_k$ represents the contribution rate of each member, and $b_k$ represents the cumulative contribution rate. The contribution rate and cumulative contribution rate of the members are utilized to determine the criteria for selecting the number of principal components and to assess how well these principal components retain the original information (Powers, 2001).

In this study, to verify the scientific validity and rationality of the features selected for port generational classification, a correlation analysis was conducted on the key functional dimensions of ports across different generations. The specific results of this analysis are presented in Table 4. This analysis quantifies the relationship between port generations and their functional characteristics, providing both theoretical foundations and data support for constructing the generational model. The selection of functional characteristics for port generations is based on the generational theory outlined by UNCTAD and related literature, adhering to the principles of comprehensiveness, comparability, independence, and data availability. First-generation ports primarily emphasize the scale and capacity of basic infrastructure, with features such as the number of berths, port area, and the number of vessel calls. Second-generation ports evolve from the first generation into integrated ports, incorporating production services, trade, and transportation functions. Third-generation ports focus on high-end logistics services and port management efficiency, characterized by logistics service capacity and the number of shipping service enterprises. Fourth-generation and higher ports prioritize regional coordination and socio-economic connectivity, with indicators highlighting regional economic activity and social linkages.

Table 4 assesses the relationship between the functional characteristics of ports and their generational classifications using correlation coefficients and significance levels ($P$-values). To conduct this analysis, principal component analysis was employed as the testing method. In this framework, higher correlation coefficients represent stronger relationships between variables, while smaller $P$-values (typically less than 0.1) indicate statistically significant correlations under the assumption that the null hypothesis is true. The results reveal that certain key features exhibit high correlations with generational classification. For instance, in first-generation ports, the correlation coefficient for port area is 0.679, with a significant P-value (<0.05), indicating that this feature has strong explanatory power for first-generation port classification. In second-generation ports, the production service capacity and the quality of trade and transportation facilities show correlation coefficients of 0.218 and 0.366, respectively, reflecting the

**Table 4**
Correlation analysis between port generations and port features.

| Generational Classification | Port Characteristics | Correlation Coefficient | P-value |
|---|---|---|---|
| First generation port | Number of port berths | **0.375** | **0.0002** |
| | Port area (km$^2$) | **0.679** | **0.006** |
| | Annual number of ship calls | **0.477** | 1.268 |
| | Port deadweight tonnage | **0.496** | **0.002** |
| Second generation port | Type of port infrastructure | 0.176 | 0.089 |
| | Port handling capacity | 0.218 | 0.035 |
| | Port production services | 0.145 | 0.163 |
| | Quality of trade/ transportation infrastructure | **0.366** | **0.0003** |
| | Port price competitiveness | 0.276 | 0.007 |
| Third generation port | Number of shipping service companies | 0.276 | 0.073 |
| | Customs/border clearance efficiency | **0.339** | **0.00086** |
| | Port logistics service capacity | **0.300** | **0.0034** |
| | Port cargo tracking ability | **0.293** | **0.0043** |
| | Port on-time arrival rate | 0.267 | 0.0096 |
| Fourth generation port and above | Port location | 0.284 | 0.005 |
| | Number of inter-port connections | 0.283 | 0.005 |
| | Changes in social facilities in port area | 0.070 | 0.504 |
| | Population activity in port area | 0.025 | 0.805 |
| | Social activity in port area | 0.195 | 0.061 |

development trend towards integrated services. For third-generation ports, logistics service capacity (0.3) and customs supervision efficiency (0.339) underscore the importance of logistics and management capabilities in higher-generation ports.

These results affirm the rationality of the selected functional characteristics as a foundation for classification. The findings provide robust data support for the generational classification model, enhancing both the credibility and scientific rigor of the model's results. These functional characteristics are integrated into the model's calculations through the Dimension Average Clustering Algorithm, forming the basis for constructing the port generational classification model. Furthermore, the analysis reinforces the theoretical foundations and practical value of port generational division, offering strong support for applied research on port generation classification along the BRI routes.

#### 3.2.3. Evaluation metrics

To evaluate the accuracy, generalization ability, and stability of the port generational model, this study employs several evaluation metrics, including the receiver operating characteristic (ROC) curve, accuracy, recall, and precision (Powers, 2001).

The ROC is a widely utilized graphical tool for measuring classification accuracy. A ROC value closer to 1 indicates better model performance. The ROC curve represents the performance of a classification model by plotting the true positive rate (TPR) against the false positive rate (FPR) on the horizontal and vertical axes, respectively.

Accuracy is defined as the proportion of correctly identified samples within the overall dataset. A high accuracy indicates that the model has performed well in the classification task. However, in scenarios involving imbalanced samples or significant differences between categories, accuracy alone may not suffice as an evaluation metric. Therefore, it is essential to consider additional metrics, such as precision and recall, for a comprehensive assessment of model performance. The formula for calculating accuracy is as follows (Sokolova and Lapalme, 2009; Görüş et al., 2024; Viola et al., 2022; Silverman, 1986):

$$Acc = \frac{TP + TN}{TP + TN + FN + FP} \tag{13}$$

where $TP$ represents true positives, $TN$ denotes true negatives, $FP$ indicates false positives, and $FN$ signifies false negatives.

Recall measures the model's capability to correctly identify positive samples, reflecting the proportion of actual positive cases that are accurately identified by the model. The calculation formula is:

$$R = \frac{TP}{TP + FN} \tag{14}$$

Precision measures the accuracy of the model's positive predictions by determining the ratio of true positive samples to the total number of samples that the model classified as positive. The formula for calculating precision is:

$$P = \frac{TP}{TP + FP} \tag{15}$$

In summary, the meanings and definitions for TP, FP, TN, and FN are outlined in Table 5.

**Table 5**
Meaning of indicators in the confusion matrix.

| Name | Meaning | Definition |
|---|---|---|
| True positive (TP) | Correct positive | Number of positive samples correctly identified as positive. |
| False positive (FP) | Incorrect positive | Number of negative samples incorrectly identified as positive (false alarm). |
| True negative (TN) | Correct negative | Number of negative samples correctly identified as negative. |
| False negative (FN) | Incorrect negative | Number of positive samples incorrectly identified as negative (missed detection). |

## 4. Experimental results

### 4.1. Port generational distribution and model validation

In this analysis, data from ports along the BRI in 2013 were utilized as input for the port generational model, resulting in the calculation of four centroids and the generational distribution of ports for that year. Subsequently, the 2022 port data were fed into the same model, using the 2013 centroid values as benchmarks to classify the ports by generation for 2022. The results revealed the generational distribution for that year.

As illustrated in Fig. 6, the majority of ports in both 2013 and 2022 were categorized as first generation ports, followed by second generation ports, with fourth generation ports and above being the least prevalent. Since 2013, there has been a significant shift in port generations. The number of first generation ports decreased from 43 to 38, while the number of second generation ports remained unchanged. Third generation ports increased from 3 to 5, and fourth generation ports and above rose from 2 to 5. Although first generation ports still dominate, there has been a noticeable advancement in the generational distribution of BRI ports over time.

Figs. 7 and 8 offer a spatial representation of the generational distribution of investment ports along the BRI for the years 2013 and 2022. In 2013, the ports classified as fourth generation ports and above included Busan Port and Singapore Port; third generation ports included Jeddah Port, Port of Hamad, and Port of St. John's; and second generation ports included Laem Chabang Port, Port of Peacocks, Port Qasim, and Port of Abidjan. By 2022, the generational expansion included additional fourth generation ports and above such as Laem Chabang Port, Hamad Port, and Khalifa Port. New third generation ports included Batangas Port, Odessa Port, and Casablanca Port, while Monrovia Port was added to the second generation category. The geographic range of port generational evolution expanded from East and Southeast Asia in 2013 to include the Persian Gulf, Eastern Europe, and West Africa by 2022.

The introduction and execution of the BRI have significantly influenced the strategic layout of China's overseas infrastructure investments, particularly in hub and mainline ports along the BRI. Ports that are naturally endowed with deeper waters and advantageous geographic positions may attract larger vessels and long-haul routes, whereas others may be constrained by limitations in water depth or lower accessibility to routes, thus serving specific vessel types or routes (He et al., 2024).Taking fourth generation ports and above as examples, Singapore Port and Busan Port, which served as key transshipment hubs in Southeast and Northeast Asia, respectively, were among the top-performing ports in both 2013 and 2022. These ports excel in terms of

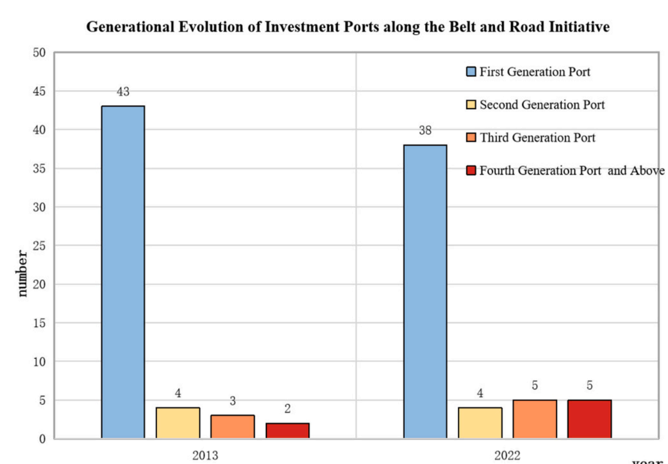


**Fig. 6.** Year distribution of port generations.

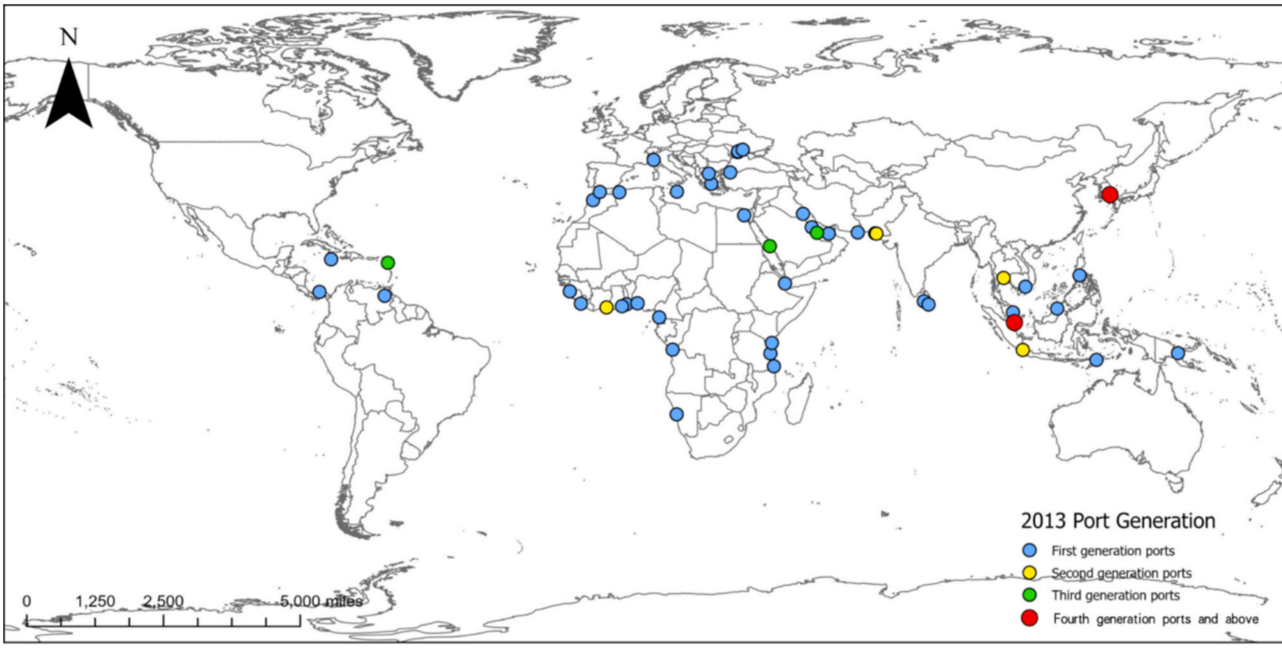


**Fig. 7.** Port generation distribution of coastal investment ports along the belt and road initiative in 2013.

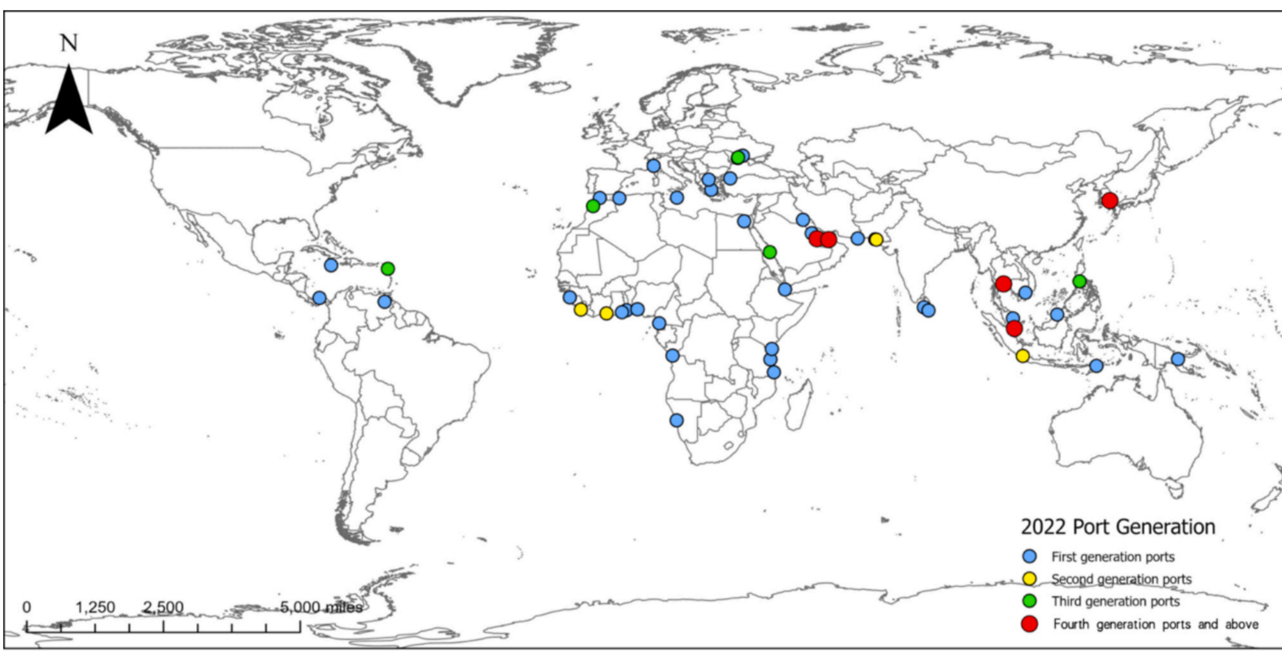


**Fig. 8.** Port generation distribution of coastal investment ports along the belt and road initiative in 2022.

the number of berths, port area, number of ship arrivals, and deadweight tonnage. Additionally, Laem Chabang Port, as Thailand's largest container port, has significantly enhanced its capacity, making it a critical gateway to Southeast Asia and elevating it to the fourth generation port and above by 2022.

In the Middle East, Hamad Port has thrived alongside the region's oil industry, benefiting from continuous expansion and modernization efforts, such as the New Hamad Port project—regarded as the largest dredged port project in history, led by China Harbor Engineering Company. Similarly, Khalifa Port in the Persian Gulf, primarily backed by China COSCO Shipping Corporation, is the first semi-automated terminal in the Middle East. It features an extensive port area, surpassing that of Singapore and Busan, with strong infrastructure and competitiveness.

Ports in Eastern Europe, such as Odessa Port in Ukraine on the Black Sea coast, play a vital role as key nodes linking the EU and Eurasian economies, facilitating regional trade and investment. Lastly, China's early investments in West Africa, particularly in the Gulf of Guinea, have concentrated on densely distributed ports, often supported by national aid under the BRI. The integration fostered by the BRI across diverse regions has been a key driver in the spatial evolution of port generations.

To assess the classification performance and robustness of the port generational model, this study introduced varying levels of interference items (10, 20, 40, 60, 80, and 100) and utilized precision, recall, accuracy, and the AUC value under the ROC curve as evaluation metrics. Additionally, the mean and standard deviation of these metrics were calculated, as detailed in Table 6 and illustrated in Fig. 9. The results indicate that the model exhibited optimal performance under low interference conditions (10 interference items), achieving an average performance metric of 97.06 % with a standard deviation of only 3.21. This reflects extremely high classification accuracy and stability in low-noise environments.

As the number of interference items increased, the average performance metrics gradually declined, accompanied by an increase in the standard deviation. For example, with 100 interference items, the average performance metric decreased to 71.14 %, and the standard deviation rose to 10.20. This suggests that high-noise environments present certain challenges to the model's performance. Nonetheless, even under maximum interference (100 items), the model's recall rate remained above 88.33 %, and the AUC values under the ROC curve exceeded 0.80. These results demonstrate the model's strong classification capability and robustness in complex environments.

Fig. 9 provides an evaluation of the model's overall performance using ROC curves. It illustrates that as the number of interference items increased from 10 to 100, the AUC value declined from 0.90 to 0.80, indicating some impact on performance. Despite this, the overall performance remained within an acceptable range. In summary, the port generational model proposed in this study demonstrated strong adaptability and reliability when processing datasets of varying complexity. This provides robust data support and theoretical foundations for the classification of port generations along the BRI.

### *4.2. Spatial distribution patterns of port generations*

Kernel density estimation (KDE) is a non-parametric technique used to estimate the probability density function of a random variable (Silverman, 1986). As a widely recognized method for analyzing geospatial correlations, KDE produces a smoothed estimate of the probability density, either univariate or multivariate, based on observed data. This technique involves calculating the density of various port generations within their surrounding areas, identifying how each generation of ports is concentrated in relation to its neighbors, and revealing the spatial distribution characteristics of different port generations within the region.

Figs. 10 and 11 depict the kernel density analysis of the generational distribution of investment ports along the BRI for the years 2013 and 2022. In 2013, the spatial distribution of port generations displayed varying levels of clustering, with distinct concentration centers emerging. The primary hubs included Busan Port in East Asia and the Strait of Malacca region in Southeast Asia, where Singapore Port served as the focal point. Additionally, secondary hubs were identified in the Red Sea and Persian Gulf regions, centered around Jeddah Port and Hamad Port. Other areas were represented by lighter colors, indicating a more dispersed distribution of port generations.

By 2022, some shifts in the primary clustering centers were observed. The Strait of Malacca region remained a significant hub, but another major center had emerged in the Red Sea and Persian Gulf regions. Secondary clustering centers were identified in the Busan area in East Asia, the Moroccan region on the eastern Atlantic coast, and the Ukrainian region in Eastern Europe. In contrast, the clustering intensity along the northern coast of Antigua in the Caribbean islands had diminished compared to 2013.

**Table 6**
Evaluation indicators for generational port models.

| Number | Precision | Accuracy | Recall | AUC value | Mean | Standard |
|---|---|---|---|---|---|---|
| 10 | 97.62 | 92.90 | 99.73 | 0.90 | 96.75 | 3.21 |
| 20 | 91.85 | 88.50 | 97.67 | 0.89 | 92.67 | 3.50 |
| 40 | 75.93 | 76.67 | 94.16 | 0.88 | 82.25 | 7.61 |
| 60 | 69.10 | 71.86 | 91.70 | 0.87 | 77.55 | 9.01 |
| 80 | 61.54 | 63.89 | 88.33 | 0.83 | 71.92 | 10.20 |
| 100 | 61.54 | 63.89 | 88.33 | 0.80 | 71.92 | 10.20 |

Through a comparative analysis of data from 2013 and 2022, it becomes clear that the kernel density clustering center has shifted from East Asia to the Middle East. Several factors contribute to this shift. Firstly, the BRI has spurred substantial investment in port infrastructure, leading to significant changes in key port characteristics. The Middle East, in particular, has seen considerable growth in port infrastructure, with notable increases in the number of berths, port area, and deadweight tonnage. Moreover, improvements in operational efficiency, handling capacity, production services, and logistics service quality have been significant. Secondly, Middle Eastern governments have actively engaged with the BRI by signing cooperation agreements with China, offering policy support and investment incentives. These actions have accelerated port development and attracted substantial trade flows to the region. Lastly, the Middle East's strategic geographical position, acting as a vital maritime corridor linking Asia, Africa, and Europe, has further enhanced the clustering of ports by facilitating intercontinental trade.

In contrast, the clustering intensity along the northern coast of Antigua in the Caribbean has diminished due to a lack of infrastructure investment. There has been no notable increase in port berths, port area, or significant improvements in handling capacity, logistics service quality, or operational efficiency.

Spatial autocorrelation analysis is a statistical approach used to assess the distribution patterns and relationships within spatial data (Tao et al., 2023). The core concept is that data values at nearby or adjacent locations may exhibit a degree of dependency or similarity, which typically diminishes or fades as the distance between these locations increases. This analysis technique helps in uncovering the regional structural patterns of spatial variables. In this study, Moran's I is applied as a global metric to evaluate the overall spatial clustering patterns of port generations associated with the BRI. The findings and visual representations of the Moran's I analysis are provided in Table 7 and Fig. 12, highlighting the spatial clustering dynamics of investment ports along the BRI. The significance thresholds for interpreting the results are summarized in Table 8.

Table 7 and Fig. 12 reveal that the distribution of port generations along the BRI does not show prominent geographic clustering, but rather a random spatial pattern. This random distribution highlights several strategic intentions:

First, the strategy of diversified investment is designed to spread investments across multiple regions, minimizing dependence on the economic, political, or market risks associated with any single area. Secondly, by targeting various regions, ports are positioned to effectively acquire resources, technology, and market opportunities that align closely with China's industrial supply chains and market needs. Lastly, this dispersed distribution supports global trade and strategic positioning, reflecting the importance and foresight of establishing a strategic presence on a global scale.

### *4.3. Comparison of development among ports along the belt and road initiative*

The generational classification results show a clear predominance of first generation ports compared to second, third, and higher generation ports. Despite some first generation ports experiencing improvements in infrastructure and cargo throughput, these enhancements have not been significant enough to elevate them to a higher generational classification. This suggests that while progress has been made, it has not been sufficient to shift these ports into the next generational tier. It is important to recognize that generational classification reflects a port's developmental stage, but the absence of generational advancement does not necessarily imply decline. A more nuanced analysis considering multiple factors is required to accurately assess a port's development status.

In this section, a longitudinal comparison model is developed to

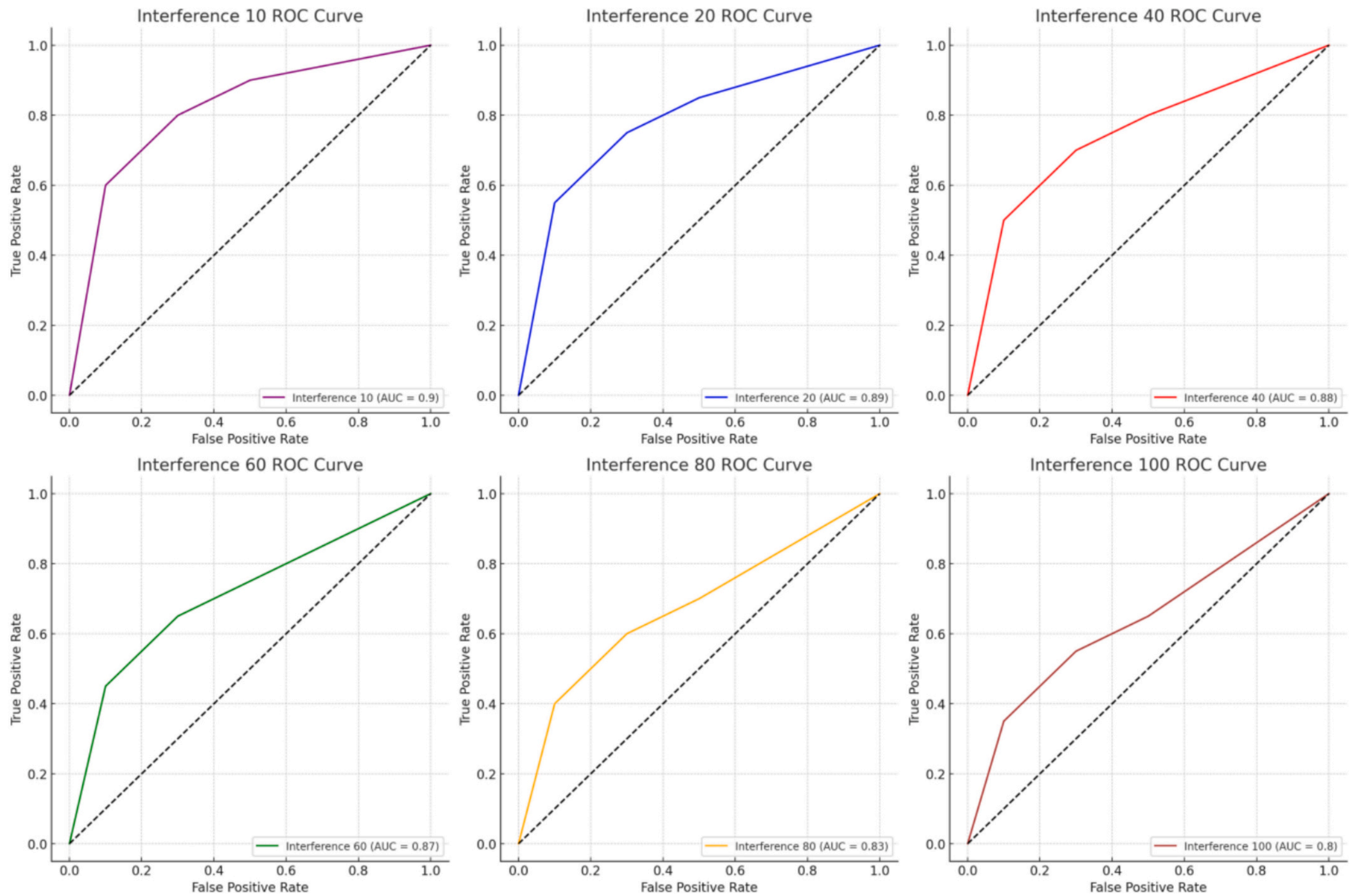


**Fig. 9.** Receiver operating characteristic curves for port generational models.

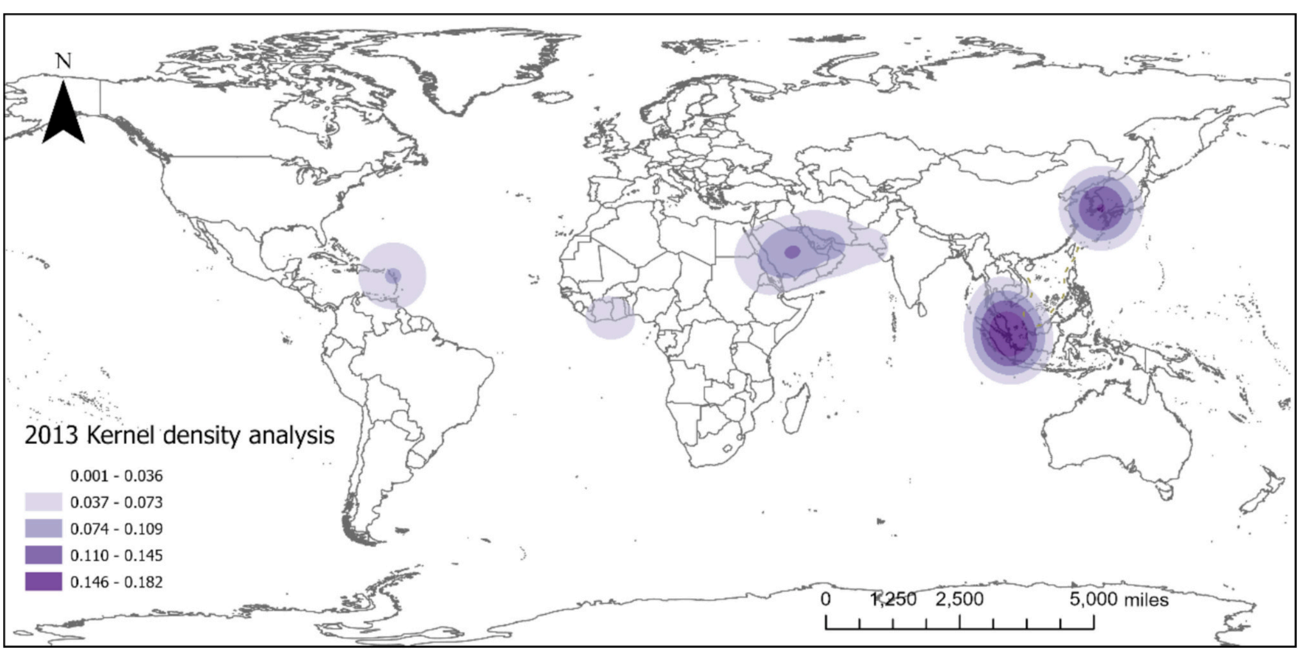


**Fig. 10.** Analysis of generational Kernel density of coastal investment ports along the belt and road initiative in 2013.

evaluate port development over time. This model integrates generational attributes and classification criteria to create a new dataset, which undergoes dimensionality reduction using PCA. The analysis yields correlation coefficients between each attribute and the generational classification, with the top ten features displaying the highest correlation selected for further analysis. If these features vary between 2013 and 2022, their combined set is used. Subsequently, the selected attributes from the 2013 and 2022 datasets are compiled into a new dataset,

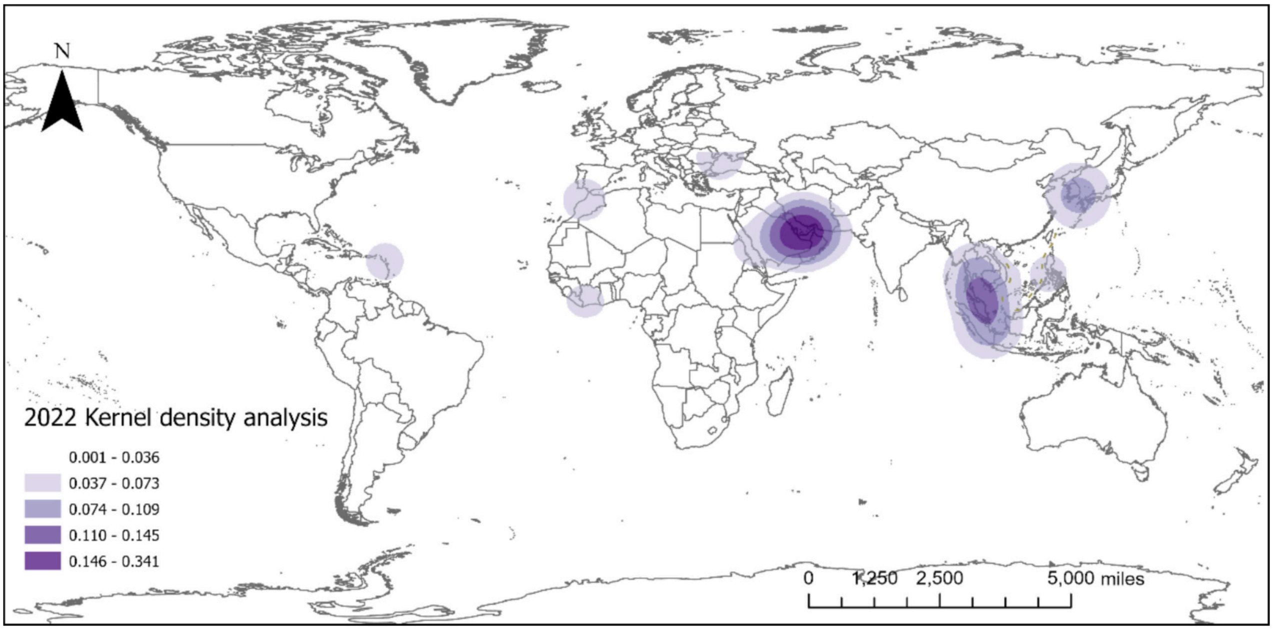


**Fig. 11.** Analysis of generational Kernel density of coastal investment ports along the belt and road initiative in 2022.

**Table 7**
Report on generational spatial autocorrelation in ports.

| Year | *Moran's I* index | Expected index | Variance | *Z*-score | P-value |
|---|---|---|---|---|---|
| 2013 | 0.0075 | −0.0196 | 0.0028 | 0.5089 | 0.6108 |
| 2022 | 0.0545 | −0.0196 | 0.0033 | 1.286 | 0.1984 |

which serves as input for the longitudinal comparison model. The model generates final development scores for each port. By comparing the scores from 2013 to those in 2022, the difference (2022 score minus 2013 score) indicates the port's developmental trajectory: a positive difference signifies progress, while a negative difference suggests decline.

As illustrated in Fig. 12, the chart compares the development scores of various ports between 2013 and 2022, highlighting their development status. When analyzing Figs. 13 and 14 together, it is evident that port development patterns under the BRI display distinct regional characteristics and trends.

Fig. 14 displays the global distribution of ports, with color coding representing their development status. Ports showing stronger development are concentrated in regions such as East Asia, Southeast Asia, and parts of Europe. Conversely, ports experiencing decline are scattered across Africa, South Asia, and Eastern Europe. In Asia, particularly in Southeast and East Asia, these regions have attracted significant infrastructure investments under the BRI. Notable examples include projects like the China-Myanmar Kyaukpyu Deep-Water Port, the China-Thailand Laem Chabang Phase III-1 Marine Project, and the China-Malaysia Port Klang Third Terminal Expansion. These investments

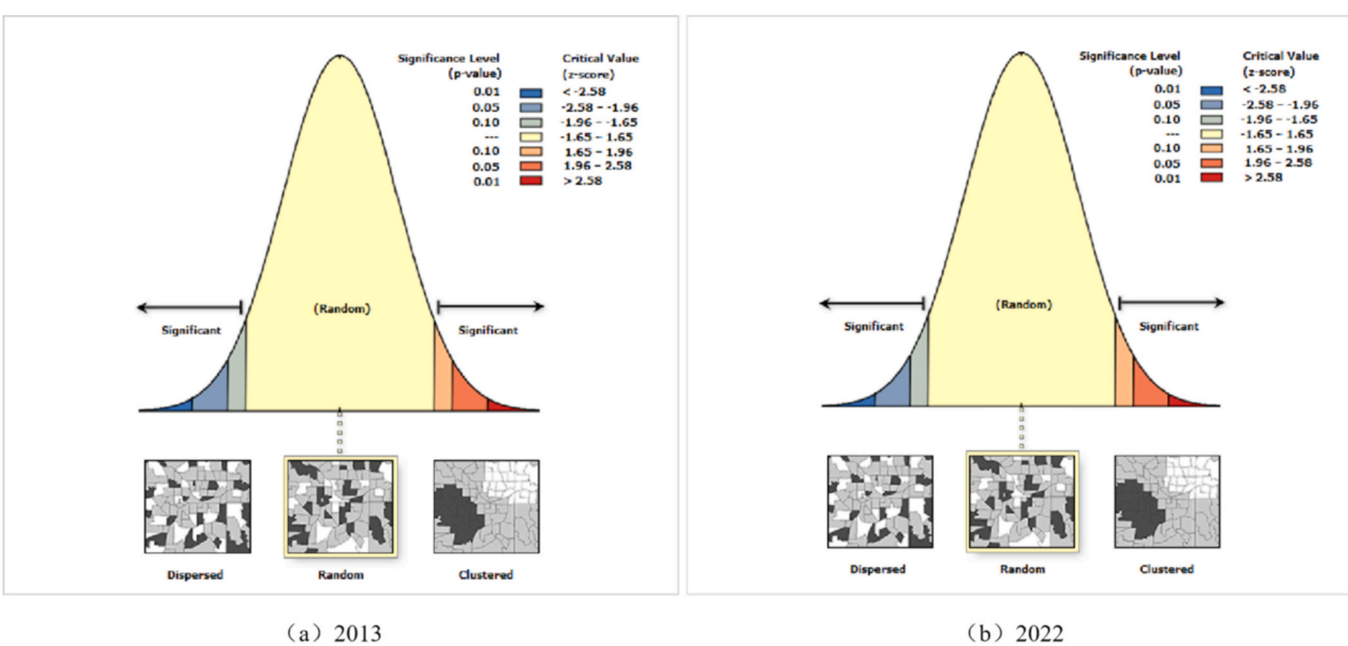


**Fig. 12.** Generational Moran's I analysis of investment ports along the belt and road initiative in 2013 and 2022.

**Table 8**
Z-score, P-value, and confidence level.

| Z-score (Standard Deviation) | P-value | Confidence Level |
|---|---|---|
| <−1.65 or >+1.65 | <0.10 | 90 % |
| <−1.95 or >+1.95 | <0.05 | 95 % |
| <−2.58 or >+2.58 | <0.01 | 99 % |

have substantially increased the number of berths, boosted handling capacity, and enhanced the quality of logistics services.

Meanwhile, although ports in the Red Sea and Persian Gulf regions are also developing, they are slightly less advanced compared to their counterparts in East and Southeast Asia. Although there has been some progress in increasing the number of port berths and enhancing handling capacity, the growth has been relatively modest. Similarly, while there have been advancements in the capacity and quality of logistics services, they still fall slightly short compared to the levels achieved in East and Southeast Asia. On the other hand, ports along the west coast of Africa, in Morocco, Algeria, Eastern Europe, and parts of North and South America are experiencing decline. These regions have seen minimal increases in berths and handling capacity, coupled with insufficient infrastructure investment. The logistics service capacity and quality in these areas have only marginally improved, resulting in lower operational efficiency.

Significantly, by 2022, all BRI ports in Ukraine were in a state of decline, with Odessa Port suffering the most severe downturn. While Odessa Port had progressed from a first generation port in 2013 to a third generation port by 2022, making it the top-performing port in Ukraine by generational classification, its development status has drastically deteriorated. Odessa Port, located on Ukraine's southwestern coast, is a vital grain export hub, supported by extensive agricultural lands. As the largest port in Ukraine, it handles an annual throughput of 21 million tons of dry cargo, 25 million tons of liquid cargo, and over 900,000 TEUs at its container terminal. However, the situation drastically changed when Russia launched a military operation against Ukraine in February 2022, leading to the closure of most Ukrainian ports, including the near-complete shutdown of Odessa Port. On February 24, 2022, Ukrainian authorities officially announced the closure of Odessa Port.

### 4.4. *Comparative analysis of contracted ports and operated ports along the belt and road initiative*

Under the BRI, China's port investments can generally be categorized into two types: those concentrated on infrastructure construction and those involving integrated investment in both construction and operations (Su and Wang, 2024). This classification is supported by multiple studies. For example, Wang et al. (2023) emphasized that the involvement of Chinese enterprises in ports has evolved from a focus solely on infrastructure construction to the adoption of diversified management models. This evolution reflects an adaptation to the varying investment demands of different regions (Chen et al., 2019; Su and Wang, 2024).

Additionally, the terms “construction ports” and “operational ports” employed in this study have been widely referenced in numerous works to describe various port investment models and their developmental characteristics (Wang et al., 2023; Su and Wang, 2024; Jia, 2021). By categorizing BRI ports into construction ports and operational ports, this study seeks to evaluate the impact of these distinct investment approaches on the generational evolution of ports within the BRI framework.

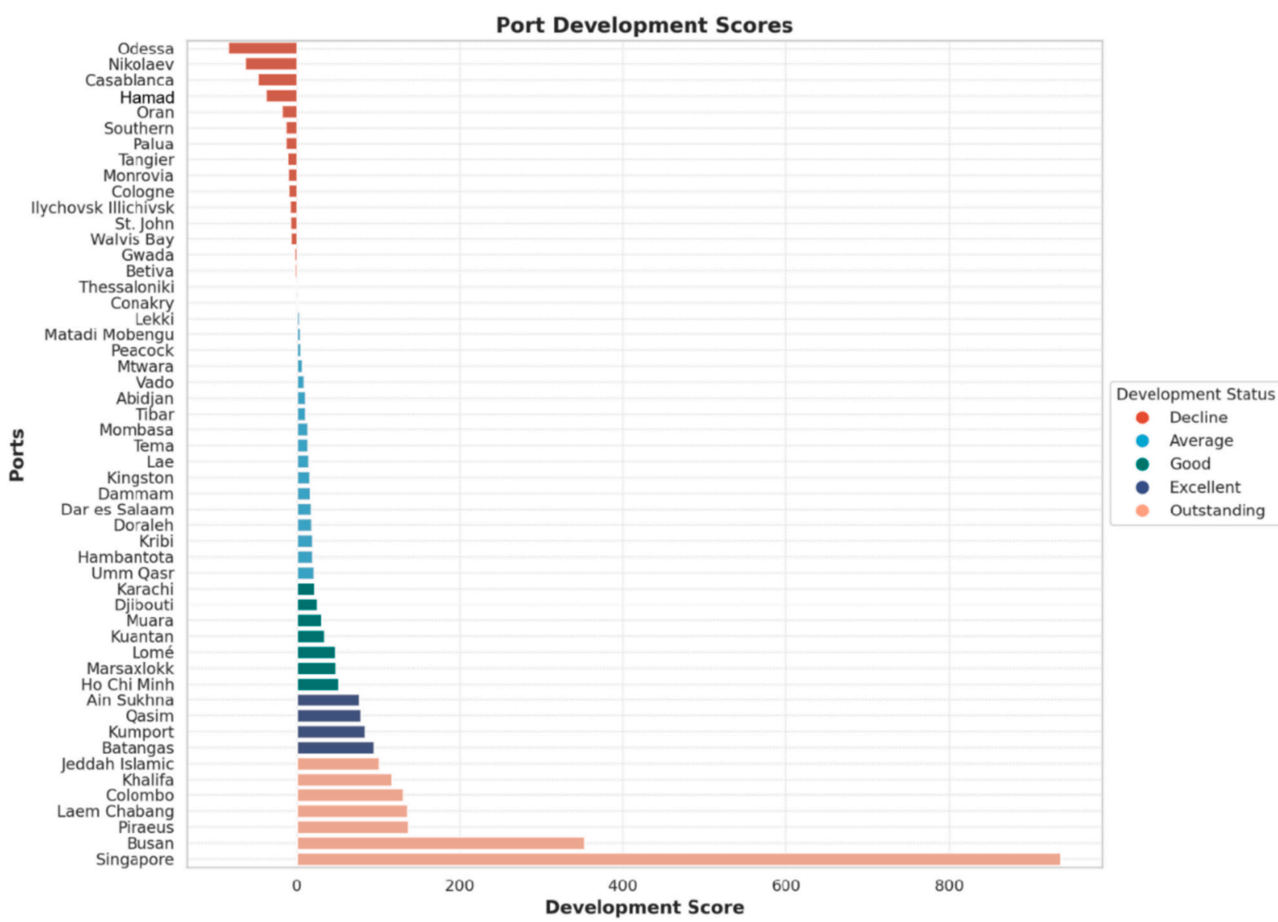


**Fig. 13.** Score comparison of coastal investment ports along the belt and road initiative in 2013 and 2022.

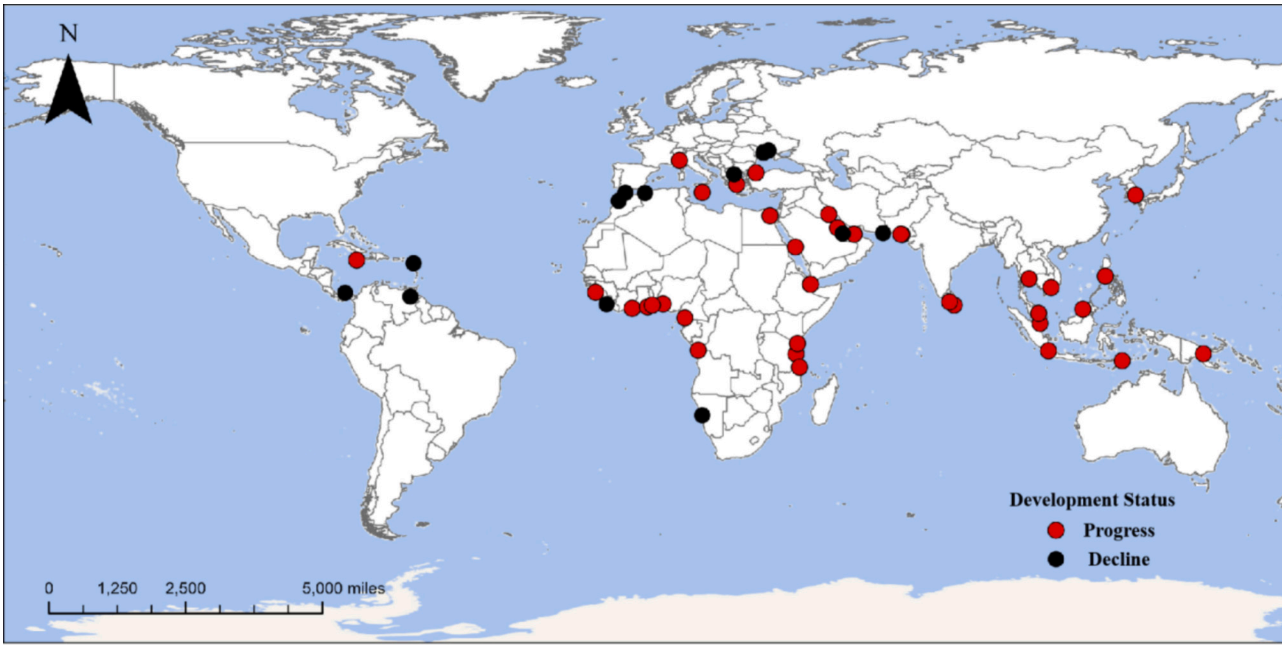


**Fig. 14.** Comparison of the development status of coastal investment ports along the belt and road initiative in 2013 and 2022.

Fig. 15 illustrates the generational progression of both contracted and operated ports along the BRI between 2013 and 2022. Both categories have shown positive development. However, the impact of these investment strategies on generational evolution varies. For first and second generation ports, contracted ports have exhibited more significant generational advancement compared to operated ports. Conversely, for third generation ports and those in the fourth generation and above, operated ports have demonstrated superior generational development.

Figs. 16 and 17 present the spatial distribution of generational changes for contracted and operated ports along the BRI in 2013 and 2022. In 2013, contracted ports were predominantly located in the Americas, Africa, the Red Sea, and the Persian Gulf, with most of them classified as first generation ports. Third generation ports were found in the Americas and the Persian Gulf, while second generation ports were more common in West Africa and Southeast Asia. On the other hand, operated ports were largely concentrated in East Asia, Southeast Asia, and Europe, with fourth generation ports and above primarily in East and Southeast Asia, third generation ports mostly in the Red Sea region, and second generation ports concentrated in Southeast and South Asia.

By 2022, notable generational advancements were observed in several contracted and operated ports. Contracted ports belonging to fourth generation ports and above emerged in the Persian Gulf. East Asia and Southeast Asia, benefiting from rapid economic growth and extensive infrastructure investment, saw the development of numerous high-generation ports, indicating a robust upward trend. The Red Sea and Persian Gulf regions also attracted significant investments due to their strategic importance, though their growth rates were slightly slower. In Africa and the Americas, investments were primarily directed towards improving infrastructure and enhancing operational efficiency, but the overall pace of development remained gradual.

These findings suggest that the generational progression of ports, whether contracted or operated, is closely tied to the broader regional development context. Strategic investment decisions tailored to the specific generational stages of ports can effectively support their evolution under the BRI.

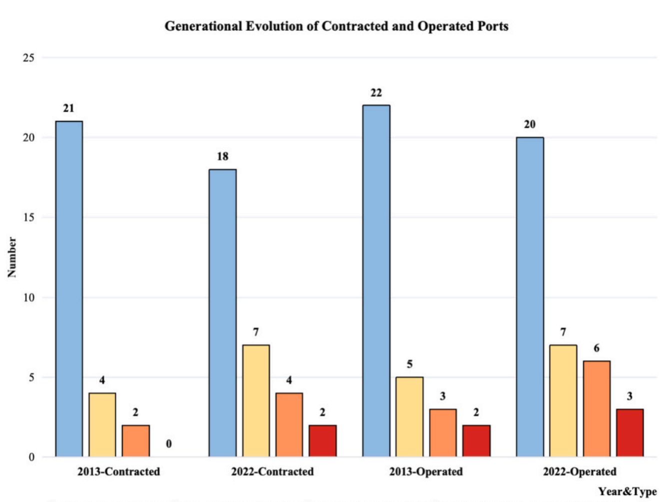


**Fig. 15.** Generational evolution of contracted and operated ports along the belt and road initiative in 2013 and 2022.

### *4.5. Generational comparison of ports along the belt and road initiative and surrounding ports*

In the era of globalization and the BRI, the development of ports has become a critical element in fostering international economic cooperation and trade. However, merely analyzing the generational progression and development of BRI ports does not provide a complete or objective picture of the actual impact of these investments, especially when considering the broader regional context that includes surrounding ports. Therefore, a thorough examination of the generational shifts in surrounding ports is vital for comprehensively understanding the port strategies and their effects on regional economies under the BRI framework.

This study focuses on 41 surrounding ports along the BRI for comparison purposes. Fig. 18 shows the generational advancement of both BRI investment ports and surrounding ports from 2013 to 2022. While both groups have shown positive development, surrounding ports have not yet achieved fourth generation status and above, a key area where they lag behind BRI investment ports.

Figs. 19 and 20 provide spatial visualizations of the generational evolution patterns for both investment ports and surrounding ports in 2013 and 2022. Over the past decade, fourth generation ports and above

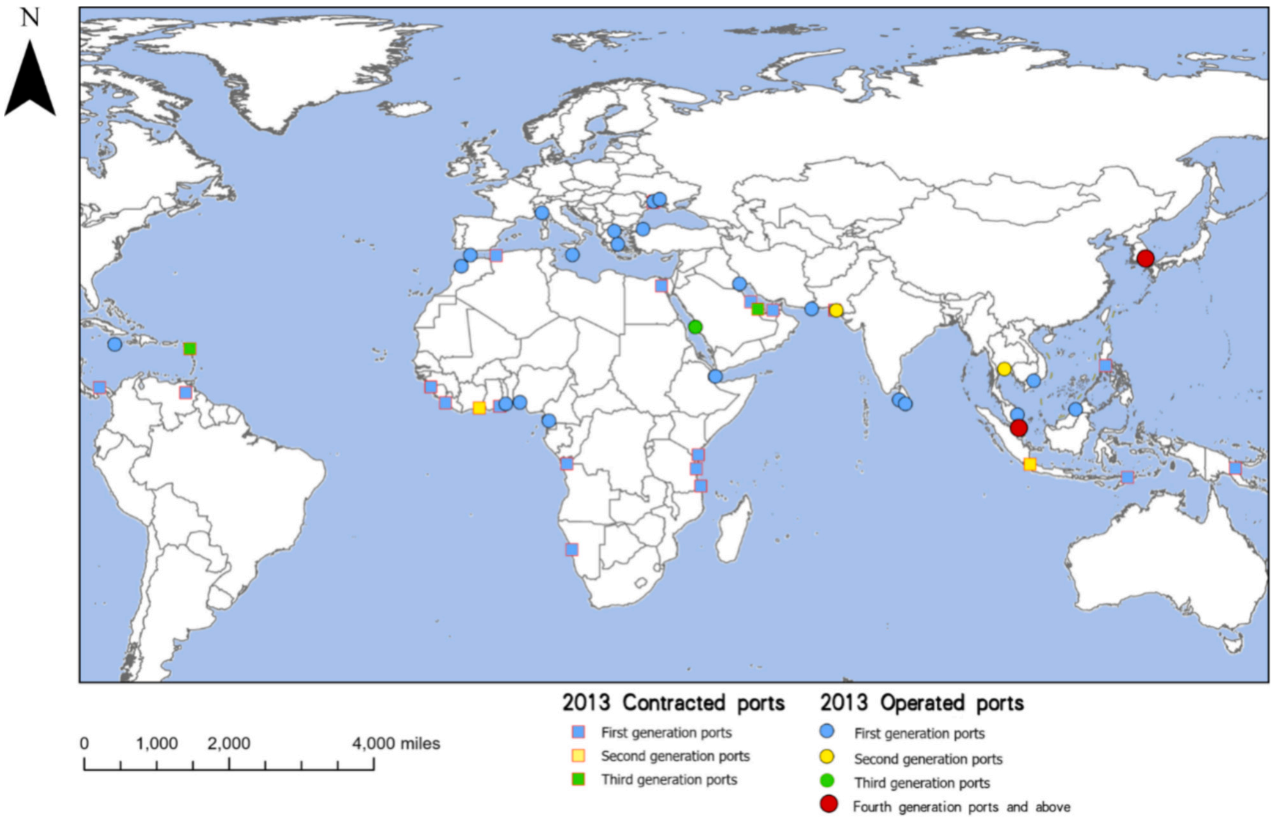


**Fig. 16.** Spatial distribution maps of contracted and operated ports along the belt and road initiative in 2013.

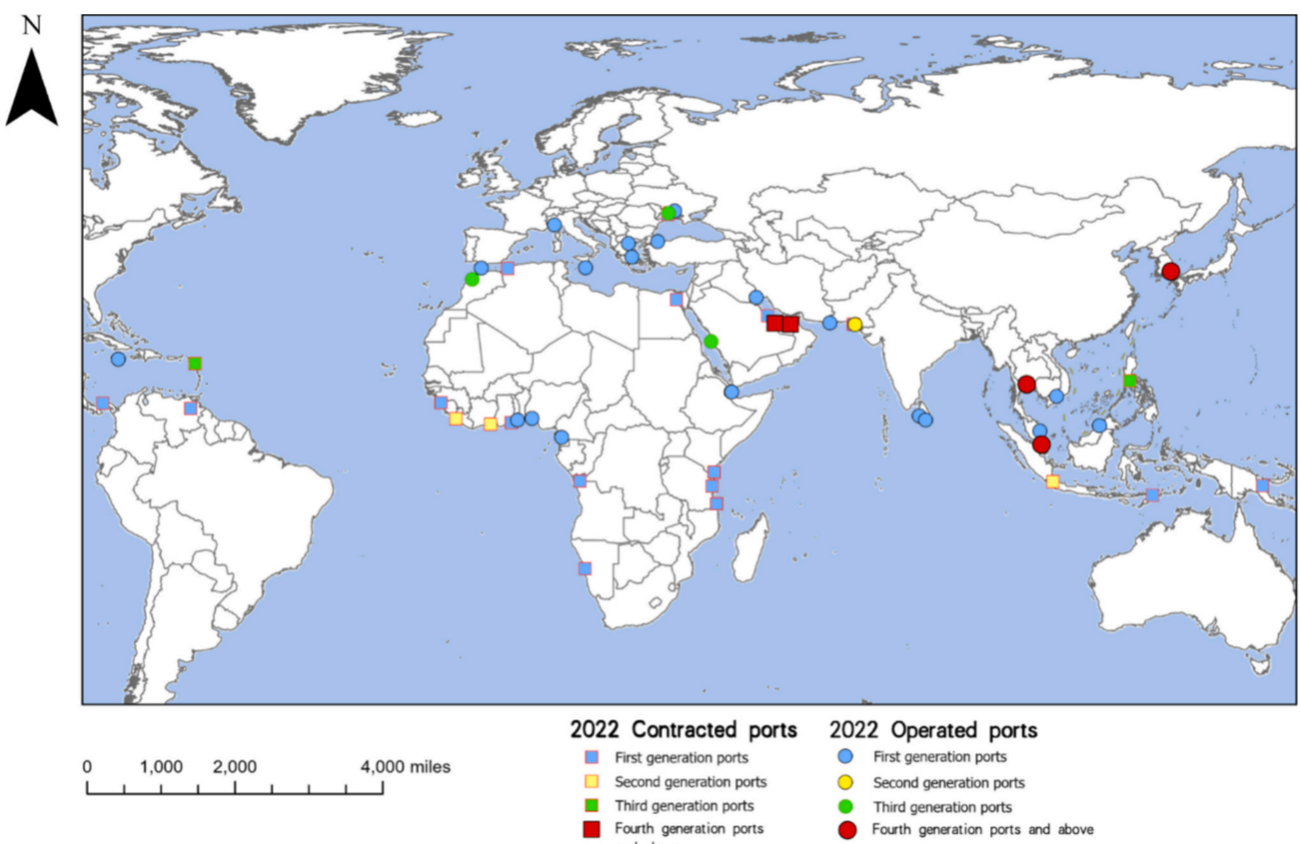


**Fig. 17.** Spatial distribution maps of contracted and operated ports along the belt and road initiative in 2022.

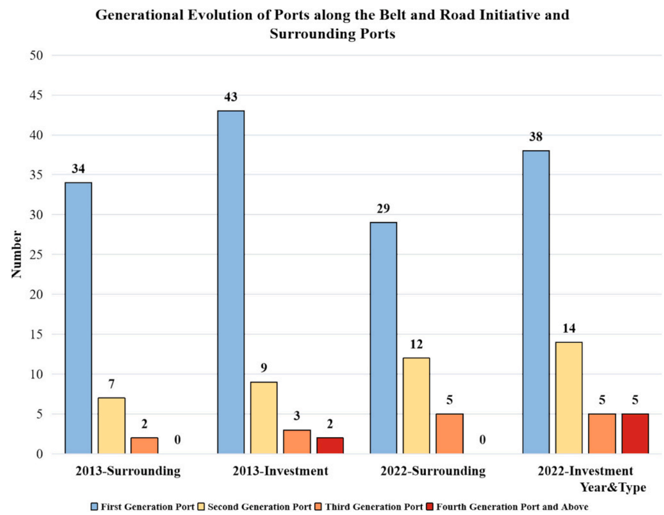


**Fig. 18.** Generational evolution of ports along the belt and road initiative and surrounding ports in 2013 and 2022.

like Busan Port and Singapore Port in Asia have maintained their leading positions, while ports such as Laem Chabang in Southeast Asia, Khalifa Port, and Hamad Port in the Persian Gulf have made significant strides in catching up. For third generation ports, those in the Red Sea, Persian Gulf, and the Americas held a slight edge in 2013. However, the generational development of BRI ports in Southern Europe was somewhat less advanced compared to surrounding ports. By 2022, investment ports in Southeast Asia, the Persian Gulf-Red Sea region, Eastern Europe, and the Americas had surpassed their neighboring ports.

Regarding second generation ports, in 2013, surrounding ports in Southeast Asia had a marginal advantage, while those in West Africa and the Americas lagged behind. By 2022, surrounding ports in South Asia showed a slight lead, and the development trends of surrounding ports and investment ports in West Africa were relatively similar. For first generation ports, most surrounding and investment ports fell into this category, but the number of first generation ports decreased in 2022 compared to 2013.

Overall, BRI investments have facilitated the development of surrounding ports and have not fostered a competitive dynamic with neighboring ports in terms of generational progression. For instance, Singapore Port, a key hub in the BRI, has stimulated economic activities in nearby Malaysian ports. The high volume of port operations in Singapore has boosted cargo transshipment and trade in Malaysian ports, enhancing the economic vibrancy of the entire Strait of Malacca region. Similarly, Laem Chabang Port in Thailand, along with Hamad and Khalifa Ports in the Middle East, has significantly contributed to the growth of nearby ports. For example, the expansion and modernization of Laem Chabang Port have spurred economic growth at Thailand's Si Racha Port, as well as Vietnam's Hai Phong and Nghe An Ports, improving regional logistics infrastructure. Likewise, ports in the Middle East have supported the development of ports in Kuwait and Iran.

## 5. Conclusion and limitations

### 5.1. Conclusion

The analysis of port generational shifts provides critical insights into the structure and operational dynamics of contemporary ports, offering historical context and valuable lessons for future development. This study holds significant academic value and provides practical recommendations for policymakers, port managers, and stakeholders, supporting the sustainable and healthy growth of ports.

This research broadens the theoretical framework of port studies. Unlike existing research, which typically focuses on port resilience, supply chains, efficiency, networks, and investments along the BRI, this study introduces a novel perspective by examining generational evolution. This approach offers a comprehensive understanding of the dynamics and mechanisms driving port development. Utilizing a port

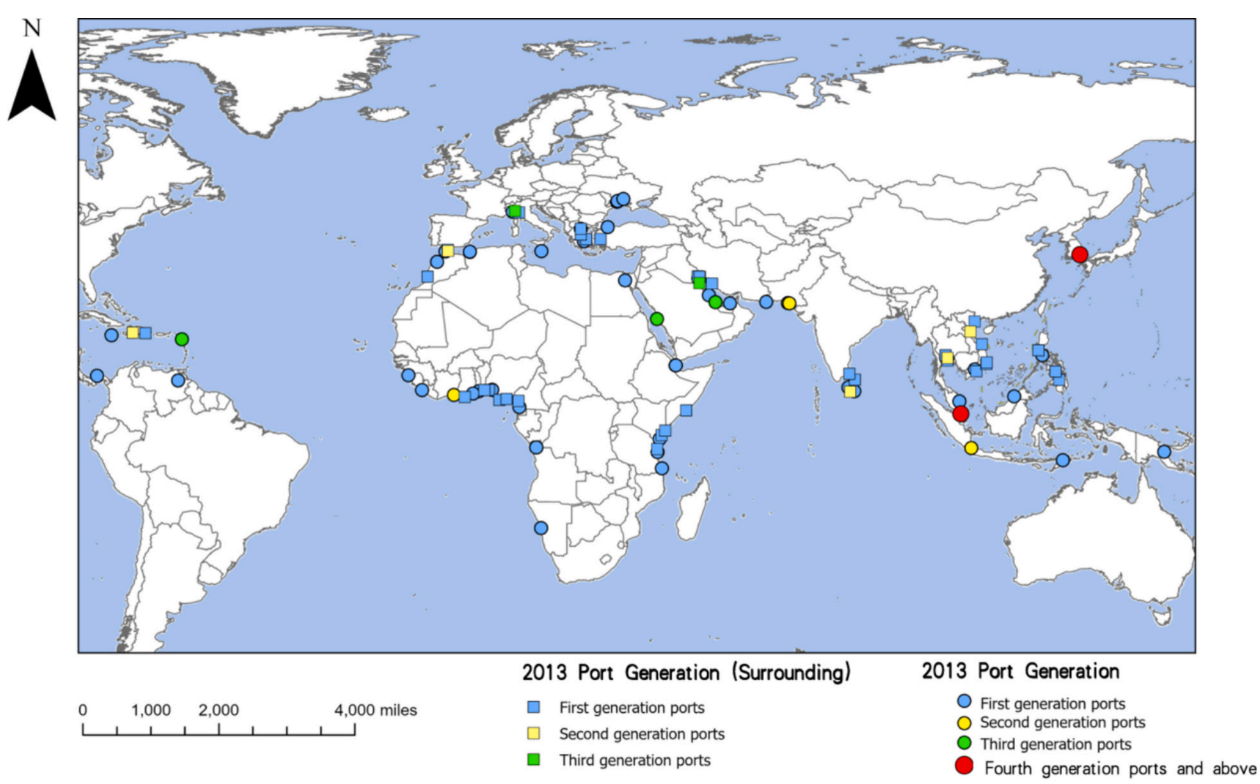


**Fig. 19.** Spatial distribution maps of ports along the belt and road initiative and surrounding Ports in 2013.

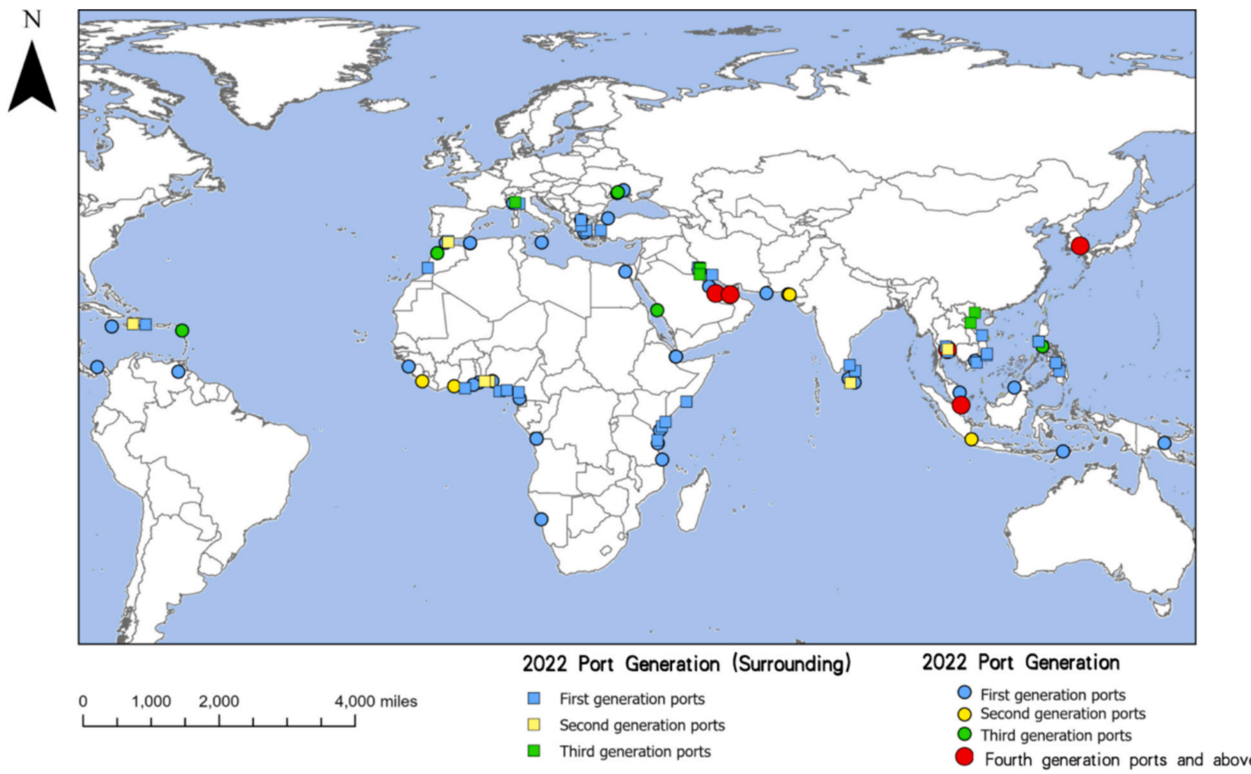


**Fig. 20.** Spatial distribution maps of ports along the belt and road initiative and surrounding ports in 2022.

generational model based on the average dimension clustering algorithm, the study systematically analyzes the trends in generational evolution and spatial characteristics of BRI ports from 2013 to 2022. The key conclusions are as follows:

- The generational levels of BRI ports have generally advanced, with significant progress in generational evolution. The spatial range of generational development has expanded from East Asia and Southeast Asia in 2013 to include the Persian Gulf, Eastern Europe, and West Africa by 2022. However, this improvement is moderate overall, with most ports still classified within the first generational level.
- Regions such as Southeast Asia, South Asia, the Persian Gulf, and the Red Sea have experienced faster generational development. The kernel density clustering of port generations has shifted from East and Southeast Asia in 2013 to the Persian Gulf and Red Sea regions in 2022. BRI port generational distribution exhibits a random spatial pattern rather than clear geographical clustering. BRI investments strategically diversify risks by securing resources, technology, and market opportunities across different regions, aligning with China's domestic industrial and market needs and supporting global trade strategies.
- Ports with stronger development are primarily located in East Asia, Southeast Asia, and parts of Europe, while those facing decline are more widespread across Africa, South Asia, and Eastern Europe. The rapid economic growth and substantial infrastructure investments in Southeast and East Asia have driven positive development trends. Ports in the Red Sea and Persian Gulf regions also show robust development but remain slightly behind those in East and Southeast Asia. In contrast, ports on Africa's west coast, in Morocco, Algeria, Eastern Europe, and parts of North and South America, are experiencing decline. These regional disparities underscore the importance of tailored port development strategies that consider local investment, policy support, and geographic advantages. The situation of Ukrainian ports, particularly amid geopolitical conflicts, illustrates the challenges and impacts of the BRI in unpredictable circumstances.
- The generational progression of contracted and operated ports exhibits distinct patterns. Contracted ports outperform operated ports at the first and second generational levels, while operated ports show superior performance at the third generation and above. This suggests that different investment approaches offer advantages at various stages of port development, highlighting the need to select appropriate investment strategies tailored to the specific conditions of each port to maximize development potential.
- BRI investments have facilitated the development of surrounding ports without creating competitive tensions in terms of generational advancement. Both BRI ports and their neighboring ports have shown positive evolutionary trends. The generational progress of BRI ports has not only enhanced their competitiveness but also positively influenced the development of surrounding ports, fostering coordinated regional development.

The conclusions drawn from this study highlight significant disparities in the development of ports along the BRI. These differences are primarily influenced by factors such as geographic location, policy support, existing infrastructure conditions, and investment models. These factors have profoundly impacted the generational evolution of ports within the BRI framework.

Firstly, in terms of geographic location, ports situated along major global trade routes enjoy significant locational advantages. For instance, ports such as Singapore and Busan have consistently maintained their leadership as fourth-generation ports, benefiting from high cargo volumes and dense logistics networks. In contrast, ports in more remote regions, such as those on the western coast of Africa, face higher logistics costs, lower market connectivity, and inadequate infrastructure, resulting in slower generational development.

Secondly, policy support has been a crucial driver of port development. For example, Thailand's Eastern Economic Corridor (EEC) strategy aims to transform Laem Chabang Port into a key logistics hub in

Southeast Asia through infrastructure development and regional coordination. Similarly, the UAE's Abu Dhabi Vision 2030 has positioned Khalifa Port as a regional logistics and trade center. Through partnerships, such as with COSCO Shipping, the port has further strengthened its hub role under the BRI. Conversely, Ukraine's Odessa Port has been hindered by geopolitical conflicts, leading to developmental stagnation and even risks of functional regression.

Additionally, infrastructure conditions play a significant role in influencing port development. Ports with superior initial infrastructure have advanced rapidly, while others have had to begin development from the ground up. Finally, investment models exhibit clear distinctions. Construction-focused ports excel during the initial stages of development. For example, Laem Chabang Port benefited from substantial infrastructure investments during its first- and second-generation phases. In contrast, operational-focused ports perform better at higher generational stages. Ports like Singapore and Hamad have leveraged their long-term operational experience and technological expertise to continuously optimize port functions and enhance market competitiveness.

It is important to emphasize that port development is a gradual process, not an overnight transformation. In the foundational stages, port growth relies heavily on large-scale infrastructure construction. Conversely, at higher generational stages, sustained development requires long-term capital investment, operational management expertise, and regional economic synergies. Only through sufficient developmental cycles and continuous optimization of functions and strategic positioning can a port secure a prominent place in the global port system.

### 5.2. Limitations and future directions

Section 5.1 of this study summarizes the generational changes and spatial distribution of ports along the BRI, emphasizing significant differences in geographical location, policy support, and investment models. Despite these variations, port development invariably requires the collaborative efforts of port managers, investors, and policymakers. In the foundational stages, development depends on infrastructure construction and initial investments. In contrast, higher generational stages necessitate operational optimization and regional economic synergy for sustained growth. Consequently, this section proposes three policy recommendations to promote balanced and high-quality development of regional ports along the BRI, considering the perspectives of port managers, investors, and policymakers.

First, port managers play a pivotal role in optimizing port functions and facilitating generational upgrades. Their management priorities should focus on enhancing high-end logistics services, transitioning to digitalized operations, and optimizing multimodal transport networks. By developing high-value-added functions such as cold chain logistics, bonded logistics, and logistics parks, ports can transform from simple cargo transfer hubs into regional economic agglomeration centers. For instance, Busan Port has significantly boosted its global competitiveness by offering integrated logistics services that range from warehousing to supply chain optimization. Furthermore, the widespread application of informatization and automation technologies can enhance port operational efficiency and reduce transport delays. Singapore Port, for example, has achieved improvements in both operational efficiency and hub status through its “Smart Port” initiative. In terms of multimodal transport, port managers must ensure efficient connectivity with railways, highways, and inland waterways to comprehensively optimize cargo distribution networks. Laem Chabang Port, drawing on the successful practices of Thailand's EEC initiative, offers valuable insights for BRI ports in this regard.

Second, investors' strategies have a direct impact on the speed and depth of port development. They should prioritize investments in geographically advantageous hub ports and ensure sustainable returns through long-term cooperation. Hub ports, strategically located at the core of international trade routes, boast high cargo throughput and extensive market reach. For instance, Singapore Port and Busan Port have capitalized on their hub status to secure long-term economic gains through transshipment businesses. While short-term infrastructure investments can rapidly enhance port conditions, long-term operational involvement provides better returns by optimizing investment structures. A notable example is COSCO's partnership with the UAE to develop a terminal at Khalifa Port, where sustained operational engagement has improved port facilities, management efficiency, and regional trade connections. For BRI investors, formulating diversified investment portfolios to balance regional economic and geopolitical risks is also a critical strategy.

Lastly, policymakers play a crucial role in optimizing the environment and fostering collaboration for port development. By streamlining administrative procedures and offering tax incentives, they can significantly enhance the regional investment climate. For instance, Malaysia's tax reduction policies have supported the development of Kuantan Port, attracting substantial international capital. In terms of port-regional economic synergy, the construction of port-industrial zones can amplify the industrial agglomeration effects of ports. Laem Chabang Port's integration with Thailand's EEC serves as an example, fostering deep linkages with regional manufacturing and providing sustained momentum for port growth. Policymakers should also promote coordination among ports to enhance overall network efficiency by optimizing resource allocation and reducing unhealthy competition. Such policy support not only strengthens regional competitiveness but also provides robust institutional guarantees for port development on a global scale.

While this study underscores the positive impacts of the BRI on the generational development of ports, several limitations remain that warrant further investigation. Firstly, due to data constraints, the study employs a generalized port generational model that encompasses various terminal types within the same port, including container terminals, bulk cargo terminals, and liquid cargo terminals. Although this approach provides a broad perspective, it inherently falls short in capturing the nuanced differences among specific port types. To address this, future research should delve deeper into these distinctions, particularly by comparing the generational evolution of container ports and bulk cargo ports. Such comparative analyses could focus on factors like port development models, technological advancements, and market competitiveness, offering a more detailed understanding of their unique characteristics. Secondly, the selection of a 10-year timespan for analyzing ports along the BRI may be inadequate to fully capture the long-term trends of generational evolution. Future studies could benefit from employing field research and utilizing more extensive data sources to comprehensively capture these long-term trends, thereby enhancing the reliability and scientific rigor of the findings. Moreover, modern port development must consider environmental impacts and sustainability alongside economic and operational efficiency. This study does not extensively explore the environmental impact and sustainability of ports. Future research should incorporate specific environmental assessments and sustainability indicators, such as port carbon emissions, shore power installations, energy efficiency, and smart technologies, to advance green and smart port development. This approach will provide a more comprehensive understanding of the complexity and diversity in port generational evolution (Li et al., 2024a).

In conclusion, this study offers significant theoretical and empirical insights into port generational evolution, along with actionable management recommendations. However, future research should further expand on aspects such as port types, data timespan, scope, and methodological integration to comprehensively uncover the dynamic mechanisms of port generational evolution. These efforts will provide stronger theoretical foundations and practical guidance for optimizing global port networks and fostering international economic cooperation.

## CRediT authorship contribution statement

**Liehui Wang:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Yang Yang:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology. **Qiang Mei:** Writing – review & editing, Project administration, Methodology, Conceptualization. **Rongxin Song:** Writing – review & editing, Validation.

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## Data availability

The authors do not have permission to share data.

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