Article

Geo-Economic Analysis Based on an Improved Ant Colony Optimization

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Abstract: This paper addresses the optimal path selection problem for economic corridors, which is a significant issue in the field of geo-economics. The paper has utilized the spatiotemporal characteristics of geo-economics and identified the development needs in this field to propose an improved ant colony optimization (ACO) strategy. The proposed strategy focuses on enhancing the heuristic function, functional area setting, and pheromone updating strategy. The heuristic factors and transfer probabilities have been improved to couple the path nature, which were based on an analysis of the factors that influence geo-economics. This improvement enhances the applicability of the ACO to path selection problems in macrospace. Additionally, the paper has differentiated the priority of path nodes by setting functional areas, which adds directionality to path selection. The improved ACO has been applied to analyze the optimal path in macroscopic economic space. The experimental validation was conducted in the Indo-Pacific region and economic corridors in China within this region, and corresponding potential geo-economic hubs were analyzed. The experimental results were validated using the Mann–Whitney U test and an evaluation method based on path effectiveness. The feasibility and objectivity of the proposed method were verified. This research provides a valuable exploration of the problem of path selection in macrospace and time and provides decision aid for the construction and adjustment development of a country’s geo-economic relations in a given region. It is a technical reference for establishing sustainable development strategies and national and regional economic planning. Overall, this work contributes significantly to the field of geo-economics and demonstrates the effectiveness of the proposed method through experimental validation.

Keywords: geo-economics; geo-economic factor; improved ACO; economic corridors; economic hubs

1. Introduction

A geo-economy is the result of the effect of geographical conditions on the economy itself [1]. Geo-economic relations are the sum of economic relations between pairs of countries or organizations of countries influenced by geographical conditions. Geo-economic relations are formed when economically relevant flows of geo-economic factors move between economies. The interaction of geo-economic factors is constantly reshaping new geo-economies [2]. The process of geo-economic factor interaction is often influenced by the spatial location, resource endowment, economic strength, security and development needs of an economy. The flow paths of geo-economic factors can reflect the willingness and demand preferences of economies to establish economic interests in a given region. Economic corridors in the spatial sense are the core channels for the efficient clustering and diffusion of geo-economic factors in space. Selecting an appropriate economic corridor will not only promote the positive development of relations between economies but also have an important impact on the economic development of the economies and their influence in the region. Furthermore, economic corridors can strengthen economic linkages and...
spatial reorganization among the associated economies, thus promoting associations among these countries and generating economic regions with important value chains. Moreover, there are key nodes in economic corridors that play pivotal roles. For example, economic hubs serve as fulcrums for these economies and support the construction of networks of economic relations in the surrounding region. Economic hubs form around a particular region due to certain economic, technological, and social factors. Therefore, the selection of reasonable economic corridors and economic hubs is of great importance to the sustainable development of national and regional economies.

Existing studies on economic corridors have focused on spatial patterns [3–6], regional impacts [7–9], effectiveness assessment [10], and security and risk [11–13] analyses of economic corridors. The most commonly used research methods are empirical methods [14] and qualitative analysis methods [15]. These methods are characterized by strong subjective dependence, and the feasibility and correctness of their conclusions are largely influenced by the personal perceptions and judgments of the researchers involved. Moreover, these methods are often difficult to generalize. Other studies have introduced methods such as gravity models [16] and metacellular automata models [17], but they are used to analyze the impact or effectiveness of establishing economic corridors, and quantitative analysis methods or optimization algorithms have not been applied for the siting of economic corridors.

The process of path selection can be described as follows. Economic factors (e.g., traded goods) originate from the economy in which they are produced, are influenced by economic demands, and flow between economies as geo-economic factor flows (e.g., trade flows). During the flow process, various paths in a region can influence the effectiveness of flows. If there are multiple alternative paths, then a factor flow will gradually become concentrated along the fastest flow path, and the fastest path in the flow process will vary for different flows. The path with the largest flow-to-speed ratio is chosen as the optimal path. Key nodes in the optimal path can quickly promote the flow of factors; access important materials, information, and resources; and act as economic hubs. Path selection in the geo-economic factor flow process is very similar to the process of foraging by ants. When ants forage for food, they initially find their way at random, but later, many ants gradually become increasingly concentrated along the shortest path from the nest to food. Through this natural selection process, optimal path selection can be achieved.

Inspired by the foraging process of ant colonies, Dorigo M. proposed ant colony optimization (ACO) [18]. The ACO is a probabilistic algorithm used to find the optimal path by exchanging information among individuals who assist each other in finding the shortest path between the starting and ending points. As a heuristic algorithm [19,20], the ACO is an algorithmic framework. There are also other population intelligence optimization algorithms that simulate the behavior of groups of insects, herds of animals, flocks of birds, and other organisms. These groups of organisms search for food according to a cooperative approach. Members of a group change their search approach by learning from their own experience and that of other members to find the optimal solution. For example, particle swarm optimization (PSO) [21], which simulates the flight foraging behavior of a flock of birds, has the advantage of requiring few parameters that must be set and is mainly used to solve continuous optimization problems. In the artificial bee colony (ABC) algorithm [22], bees use information from other bees in the colony and neighboring bees to find the best food source. Moth-flame optimization (MFO) [23] is a novel SI algorithm that simulates the spiral movement of moths around light sources at night to perform optimization. Some scholars have proposed other intelligent optimization algorithms [24]. These algorithms are applied in problems to find optimal solutions. The movement process of geo-element flows involves finding paths in space, which is similar to the phenomenon of ant foraging, and the path planning problem is an NP-hard problem. Compared with other intelligent algorithms, the ACO has a faster convergence speed and solution accuracy and is widely used in various path decision problems. Therefore, the ACO is applied in this paper.

Of course, there are other algorithms in addition to the ACO, such as the A* algorithm [25] and Dijkstra’s algorithm [26], that can be applied to solve path selection problems.
The A* algorithm establishes heuristic search rules in the search process as a way to measure the distance between a real-time search position and a target position so that the search direction is preferentially directed toward the target point, and the search efficiency is improved. Dijkstra’s algorithm [26,27] mainly solves the optimal path planning problem by traversing nodes one by one based on a greedy principle and then using a relaxation method to optimize the path selection process, before finally storing the optimal paths in a readable list. All these algorithms involve static planning methods under the condition that global information is known, and the set of constraints is often complex. In contrast, path planning in the socioeconomic domain is constrained by diverse factors, and it is difficult to accurately and comprehensively determine the constraints; therefore, it is difficult to meet the requirements of solving the optimal path problem for geo-economic factor flows. The ACO uses a positive feedback mechanism; provides strong robustness, good global optimization capability, and easy implementation on computers; exhibits high improvement flexibility according to the application scenario; can be integrated with other methods; and has displayed excellent performance in solving many optimization problems. Since the method works efficiently in graph and network space, it has been widely used in the field of spatial path analysis [28].

Many studies are currently improving the ACO to increase the performance and applicability of the algorithm in various application scenarios. The main improved aspects can be divided into four classes: structural improvement of the ACO [29], parameter optimization of the ACO, improvement of the pheromone initialization method, and improvement of the pheromone update rule. The main classic improvement methods consist of the max-min ant system (MMAS) and the ant colony system (ACS) and rank-based ant system (RAS). The MMAS [30] was proposed in 2000. In this algorithm, after each iteration, only the optimal ant updates the pheromone along the optimal path through which it passes, and the other ants do not participate in the update process, thus giving each path a chance to be selected and reducing the possibility of algorithm stagnation. The main feature of the ACS approach [31] is reflected by the fact that in addition to the global updating of the pheromone after each iteration, the ants support the local updating of the pheromone along local links during the iterative selection of the next node. Bullnheimer [32] proposed the RAS to alleviate the potential drawbacks associated with elite strategies. In recent years, researchers have focused on enhancing ant colony algorithms for path planning problems. These improvements have been concentrated on three main areas: the pheromone update mechanism, parameter optimization of the ant colony algorithm, and the application of fused ant colony algorithms. In terms of the pheromone update mechanism, Gong [33] has proposed an adaptive adjustment of the pheromone intensity value, which helps to optimize the pheromone updating strategy. Sangeetha [34] has introduced a sigmoid gain function to enhance the ant colony system’s pheromone update mechanism during path planning, resulting in better exploitation. Concerning the parameter optimization of the ant colony algorithm, Zhang [35] developed a 3D-ACA algorithm and implemented it into an ice routing model to make decisions on a ship’s passing waypoints and sailing speeds along each waypoint. Zhu [36] introduced a hybrid ant colony optimization algorithm, which uses distance, demand, and time as heuristic factors to improve its applicability in various domains. Regarding the application of fused ant colony algorithms, Sui et al. [37] have proposed an ACO + PSO + A* algorithm model for multi-task path planning, which produces optimal collision-free path planning with shorter generation length and higher safety. Lyridis [38] has designed an improvement of ACO that incorporates fuzzy logic to address the multi-objective problem of USV path planning and obstacle avoidance. All of these improvements have made ACO more applicable and efficient in solving decision problems.

Additionally, some studies have improved the ACO for different application areas. For example, one study focused on relief channel selection and the improvement of the algorithm parameters [39]. Wei et al. [40] proposed an improved ACO for urban bus network optimization based on existing bus routes, and another group of researchers [41]
proposed a path planning algorithm for unmanned surface vehicles based on the ACO. These improved methods have solved the algorithm efficiency problem and expanded the algorithm application field. However, most of them are oriented to mesoscopic spatial scales, such as those of cities and neighborhoods. Few studies have been conducted at macroscopic scales, such as global or regional scales.

Based on the above factors, the importance of this study can be clarified as follows. On the one hand, in terms of practical needs, economic corridors have a positive effect on the economic security and development of economies in a region. Selecting a reasonable economic corridor is an important way for economies to build good geo-relations in the region, but the existing methods used to select sites for corridors lack the support of intelligent algorithms for data analysis. On the other hand, in the context of the current state of research on path selection methods, the ACO provides an algorithmic framework for optimal path selection, but the classic algorithm needs to be improved for application in the geo-economic domain. Thus, it is necessary to study the ACO, explore the applicability of intelligent algorithms in the macro-socioeconomic field and provide technical support for economic development strategies at the country scale.

The main purpose of this paper is to improve the ACO, considering geo-economic elements such as geospatial relations, national relations, and economic and social factors [42], as well as the characteristics and requirements of path selection in macrogeographic space. Using the methodology proposed in this paper, valuable economic corridors and hub economies in a region can be identified, thus providing a new approach to geo-economic research.

In summary, the main contributions of this paper are as follows:

1. The construction of path networks based on macroeconomic relationships and physical path networks based on transportation systems yields a two-layer path network that can abstract complex relationships in the geo-economy;
2. The priority of path nodes is differentiated by setting functional areas, which adds directionality to path selection;
3. Heuristic factors and transfer probabilities are calculated based on geo-economic characteristics, which improves the applicability of the ACO to path selection problems in macrospace;
4. Eight valuable economic corridors, three potential economic hub countries and four ports in the Indo-Pacific region were identified, providing a referenceable method for the location of economic corridors and the identification of hub economies. This approach provides a decision aid for the construction, adjustment, and sustainable development of a country’s geo-economic relations in a given region.

The structure of the paper is arranged as follows. In Section 1, the research background is introduced, and the relevant literature is reviewed. In Section 2, the research area and research data are introduced. In Section 3, the construction method of a base network of geo-economic factor paths is studied, focusing on improving the ACO, mainly including the improvement of the heuristic function, functional area setting and pheromone updating strategy. In Section 4, experiments are conducted using open-source data to verify the feasibility of the improved ACO proposed in this paper and to analyze China’s potential economic corridors and geo-hubs in the Indo-Pacific region. In the Section 5, the discussion is presented.

2. Materials

2.1. Study Area

As a geopolitical concept, the Indo-Pacific region has become a region of international interest in recent years, with a number of scholars arguing that “the 21st century’s central economic nexus will be centered on the Indo-Pacific region” [43,44]. The US Indo-Pacific Strategy [45] released in 2019 and the competitive and cooperative behavior of countries in the region, such as the US, China, Japan, Australia, India and New Zealand, fully reveal the importance of the region in regard to the balance of power at a worldwide scale. China, Japan, South Korea, Australia, New Zealand and the 10 Association of Southeast Asian
Nations (ASEAN) countries in the region account for approximately 30% of the global total population, economic volume and trade. Therefore, the establishment of a good geopolitical network in the Indo-Pacific region holds significant importance for China.

The scope of the Indo-Pacific region includes countries and political entities in the vicinity of the Indo-Pacific waters and is broader in scope than the Asia-Pacific region. That is, it incorporates the Indian Ocean littoral and Indian subcontinent countries in addition to those in the Asia-Pacific region [46]. It has been argued that the use of the term “Indo-Pacific” will change the traditional conception of the region [46]. Both geographic and geopolitical perspectives are combined, considering data availability, for 24 countries in the region, which comprise the study area of this paper and include the following: China, the United States, Japan, South Korea, Australia, the Philippines, Indonesia, Thailand, Singapore, New Zealand, India, Sri Lanka, the Maldives, Bangladesh, Nepal, Vietnam, Malaysia, Brunei, Laos, Cambodia, North Korea, Russia, Myanmar, and Mongolia (Figure 1). In addition, the Indian Ocean and Pacific Ocean sea lanes are important to both the geo-economy of the Indo-Pacific region and the world. According to China’s demand for maritime transportation discourse in the Indo-Pacific region and its strategic requirements for the layout of the “Maritime Silk Road” port network, two routes and the related ports in the South Pacific and the Indian Ocean, namely, the Indo-Pakistani route and the Southeast Asian route, are selected as the spatial scope of the economic hubs to be studied.

![Figure 1. Scope of the study area. Note: This map is based on the standard map of GS (2021)5450 from the standard map service website of the Ministry of Natural Resources of China, with no modification to the base map.](image-url)

China is selected as the main research subject, the geographic object flow path network in the Indo-Pacific region is constructed based on the method proposed above, an improved ACO is applied to find the optimal path, and the spatial distribution characteristics of the economic corridors and nodes are analyzed to discover potential geo-economic hubs.

2.2. Data Sources

3. Methods

The choice of paths for geographic object flows is a macroscopic problem at the national, regional and global scales, and the geo-economic system is complex and variable. Thus, various spatiotemporal objects and pathfinding conditions in geo-economics need to be abstracted and simplified.

3.1. Framework

Optimal path selection for geo-economic factor flows, oriented to the macroscopic intereconomy relationships in geographic space, interest demands, and characteristics of various types of physical transportation corridors, can improve the ACO and make it applicable to the problem of optimal path selection for economic corridors.

The method proposed in this paper includes three steps (Figure 2). First, based on the regional geographical conditions and spatial characteristics of economies, nodes of economies and various transportation routes are identified in the region, forming a collection of paths and establishing a regional path network with a hierarchical structure. The abstraction of the complex real world is achieved with a certain degree of innovation. Then, according to the characteristics of economic corridors and economic hubs, the starting and ending points oriented to the economic development needs of specific geopolitical bodies are set, the heuristic factors of the ACO are improved, and the elite ant strategy is introduced so that the algorithm can be applied to solve path selection problems in macroscopic socioeconomic fields. This approach is innovative in terms of the applicability of the algorithm in various domains. Finally, the filtered optimal paths and the nodes along the paths are statistically and analytically analyzed to support the identification of macroeconomic corridors and specific economic hubs. The method used to draw conclusions through mathematical and rational analyses is somewhat innovative.

![Figure 2. Framework of the study.](image)

3.2. Construction of the Path Network

The path network is constructed by forming a path set of all optional paths in the region to provide a basis for optimal path selection. The set of optional paths in the region consists of all existing and possible paths between economies in the region. One or more paths may exist between two economies, and there are multiple types of paths, such as land transportation routes and pipelines, sea routes, aircraft routes, and underground pipelines (cables). Different geo-economic factors vary for different types of paths (Table 1).

<table>
<thead>
<tr>
<th>Geospatial Class</th>
<th>Type of Path</th>
<th>Type of Geo-Economic Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onshore</td>
<td>Railways, roads, and pipelines</td>
<td>Commodities, oil, and gas</td>
</tr>
<tr>
<td>Sea</td>
<td>Vessel routes</td>
<td>Commodities</td>
</tr>
<tr>
<td>Aerial</td>
<td>Aircraft routes</td>
<td>Commodities</td>
</tr>
<tr>
<td>Underground</td>
<td>Pipelines; electrical and fiber optic cables</td>
<td>Oil, gas, and information</td>
</tr>
</tbody>
</table>
Various types of paths exist between economies, and the path network composition is highly complex; thus, to abstractly express information from the complex real world without losing key information, it is necessary to abstract and comprehensively evaluate various paths based on the spatial locations of economies, the nature of paths, and the types of nodes. Furthermore, it is necessary to define and constrain the elements in a path network to construct the path network foundation.

(1) A path network consists of nodes (economies) and the edges (paths) between nodes; the nodes in the path network are divided into two levels: parent nodes \( P \) and child nodes \( S \). The parent nodes are independent economies, which mainly include countries in the region. Child nodes are stations in the transportation system, including ports, airports, transportation stations, etc., within the spatial scope of parent nodes to which they belong.

(2) For parent nodes \( P_i, P_j \), the set of parent layer paths consisting of parent nodes \( P_{-d} \) can be expressed as:

\[
P_{-d} = \{(P_i, P_j), i = 1, 2 \ldots; j = 1, 2 \ldots; i \neq j\}
\]

(3) Each parent node is associated with several child nodes (denoted as \( S_{ij} \)), and there may be several different paths between two adjacent parent nodes. After traversing all the child nodes, the set of sublevel paths \( S_{-d} \) is obtained and can be expressed as:

\[
S_{-d} = \{(S_{ij}, S_{ij'}), i = 1, 2 \ldots; j = 1, 2 \ldots; i' = 1, 2 \ldots; j' = 1, 2 \ldots; i \neq j; i' \neq j'\}
\]

In Equation (2) \( S_{ij} \) is the \( i \) th child of parent node \( P_i \), and \( S_{ij'} \) is the \( j \) th child of parent node \( P_i \).

A schematic diagram of the hierarchically nested path network is shown in Figure 3. Figure 3 showcases the parent node \( P \) and child node \( S \), which are interconnected through a comprehensive relational path. Each child node corresponds to a different path type between the parent nodes, forming a hierarchical path network.

Figure 3. Schematic diagram of the nested paths of the geographic object flow hierarchy.

3.3. Algorithm Design
3.3.1. Algorithm Flow

The ACO simulates the foraging process of ants: ants leave a certain concentration of pheromone along their path when foraging, and because ants traverse the shortest path often, this path has a high concentration of pheromone, leading future ants to prefer it; this process is a positive feedback mechanism, so the shortest path, which has a high concentration of pheromone, will eventually become dominant [50]. The ACO is improved
in this paper based on the path network characteristics and path selection requirements of geo-element flows (Figure 4).

![Flowchart]

**Figure 4.** A schematic diagram of the improved ACO.

The solution procedure is as follows:

1. **Parameter initialization.** First, the relevant parameters are initialized. Then, it is necessary to read the data into the program, set the target point of the selected path, and determine $\varphi_{ij}(t)$ according to Equation (3). Moreover, $M$ is defined as the maximum iteration number.

2. **Establishment of the solution space.** Ants are placed at the start nodes. For Ant $k$ ($k = 1, 2, \ldots, m$), the next node to which it travels is calculated according to Equation (9) until ants have traveled to all nodes.

3. **Updating of pheromones.** After traversal of all nodes, the total length of the route is calculated, and the shortest path among those at the current iteration is recorded. The pheromone concentrations on the paths are updated according to Equations (10) and (11).

4. **Judgment of termination.** First, it is necessary to determine whether the maximum number of iterations is reached. If not, the procedure enters the second step with Ant K; otherwise, the values of K and M are compared. If K does not equal M, the procedure proceeds to the second step with the next ant, numbered K + 1; otherwise, the obtained optimal solution is evaluated according to Equations (12) and (13). Second, the current optimal solution needs to be assessed based on whether it meets the established preference conditions. If not, the parameters are reset, and the procedure enters the next round of iterations until the optimal solution is reached; otherwise, the current optimal solution is output as the final optimal solution.

3.3.2. Path Search Target Settings

The path search target is based on two mechanisms:
(1) The spatial location of the end node is well defined, i.e., from a specific economy to a target economy that is at a specified spatial location. If the optimal path from Vietnam to Sri Lanka is found, the spatial location of the destination “Sri Lanka” is clear, and then the path selection process is guided by the spatial location.

(2) The function of the destination is determined, i.e., the path ends at an economy with a specific function, e.g., from Vietnam to an economy that “provides crude oil”. Then, a functional judgment of the next node is required in the path selection process, and this process is guided by the above function. In reality, the selection and construction of macroeconomic corridors is a national strategic issue with a high cost and high impact and has considerable requirements for the universality and utilization of the selected paths; therefore, the node concentration areas that meet the functional requirements are designated as functional areas. Nodes in these functional areas have a high probability of being selected, which makes pathfinding somewhat tedious but purposeful. Depending on whether the path between nodes \( i \) and \( j \) falls within the search zone at moment \( t \), different values may be set, as follows:

\[
\varphi_{ij}(t) = \begin{cases} 
  m(m > 1) \land (i, j) \subset S \\
  n(n \leq 1) \land (i, j) \not\subset S
\end{cases}
\]  

3.3.3. Heuristic Function Improvement

Suppose that there is Ant \( k \) \((k = 1, 2, \ldots, m)\). During movement, the state transfer probability for the ant is calculated based on the concentration of pheromones on each path and the corresponding information. \((P_{ij}^k(t))\) denotes the transfer probability of Ant \( k \) moving from node \( i \) to node \( j \) at moment \( t \), that is,

\[
p_{ij}^k(t) = \begin{cases} 
  \frac{[\tau_{ij}(t)]^\alpha[\eta_{ij}(t)]^\beta}{\sum_{s \in \text{allowed}_k} [\tau_{is}(t)]^\alpha[\eta_{is}(t)]^\beta}, & j \in \text{allowed}_k, \\
  0, & j \not\in \text{allowed}_k
\end{cases}
\]  

In Equation (4), \( \text{allowed}_k \) is the set of the next nodes that Ant \( k \) is allowed to choose when located at node \( i \), which is a key factor in the ant’s path construction process. \( \tau_{ij}(t) \) is the pheromone concentration on path \((i,j)\) at moment \( t \). The starting pheromone concentration \( \tau_{ij}(0) = 0 \) in all sections. \( \eta_{ij}(t) \) is the heuristic function, also known as visibility, which indicates the expectation of ants moving from node \( i \) to \( j \). \( \alpha \) is the information heuristic factor, which indicates the relative importance of trajectories and reflects the role of the information accumulated by ants during their movements in the selection of paths. The larger the value of this variable is, the more likely the ant is to choose the paths used by other ants and the higher the tacit understanding among ants. \( \beta \) is the degree of importance of the heuristic factor, which indicates how much importance the heuristic information is given when an ant chooses a path during its movement process. The larger the value of this variable is, the closer the state transfer probability method is to a greedy method.

In the ACO, the heuristic function is \( \eta_{ij}(t) = \frac{1}{d_{ij}} \), and \( d_{ij} \) represents the spatial distance between two adjacent nodes, which is inversely proportional to the transfer probability and can be used to find the shortest path. A geo-economic factor flow in path selection is influenced by the attractiveness of the path and the length of the path, where the attractiveness of the path is mainly associated with the relationship between economies and the nature of the path. The length of the path is the spatial distance (center distance) between economies or the physical length of a certain type of path (such as the length of a route between two ports). Therefore, in this paper, the heuristic function is improved to couple the path nature, intereconomy distance and intereconomy relationship so that the path search process of ants is governed by directionality. The relevant heuristic factors and descriptions are as follows:
(1) \( \text{sur}_{ij} \): path nature heuristic factor. The nature of geographic object flow paths refers to the type of physical paths between two economies, such as land routes, sea routes, aircraft routes and underground pipelines. The different natures of paths influence the types of geo-economic goods that can be transported and the efficiency of their delivery. As there are various types of geographic objects, e.g., energy, information, and commodities, different types of geographic objects correspond to different path classes. For example, oil is usually transported by pipeline or sea, digital information is transported via fiber optic cables, and grain is shipped. There are differences in the flow rate or efficiency of different paths. Geo-economic factors tend to be transported along the most efficient routes, and \( \text{sur}_{ij} \) is calculated as follows:

\[
\text{sur}_{ij} = a \cdot \text{class}_{ij},
\]

In Equation (5), \( \text{class}_{ij} \) is the transport performance, and \( a \) is the match between the geo-economic factor type and the relevant subbase.

(2) \( \text{dis}_{ij} \): distance cost heuristic factor. The spatial distance between economies directly affects the cost and time of geographic object flows in the process of movement. As there are multiple path types, the distance is judged differently for different paths. For example, for sea routes, the distance between two ports is considered. In the case of land transport, the distance between the nearest stations of the two economies is considered. In the case of air routes, the closest route between the two economies is chosen, and for underground pipelines, the shortest distance between the borders of the economies is chosen. For similar geographic objects and path types, the greater the distance is, the higher the cost. Since low cost is sought in path selection, the inverse of the distance between two nodes is used here and calculated as follows:

\[
\text{dis}_{ij} = \frac{1}{d_{ij}},
\]

In Equation (6), \( d_{ij} \) is the spatial distance between two nodes.

(3) \( \text{rela}_{ij} \): relationship heuristic factor. This factor drives ants to prefer nodes with high relationship rating values for the originating economy and adjacent nodes. The relationship rating comes from two perspectives: the relationship between the originating economy and the \( j \)-th node and the relationship between the \( i \)-th and \( j \)-th nodes. The higher the combined relationship rating of these two factors is, the more attractive the nodes are for geographic objects. Thus, the relationship heuristic factor consists of three main parameters: one is the relationship rank value \( \text{rela}_{ij} \) between the originating economy and each nodal economy, which can be quantified as a rank based on the relationship status between the economies as friendly, cooperative, average or conflicting. The second is the number of pairs of adjacent nodal economies that are members of the same intergovernmental international organization \( \text{org}_{ij} \). The greater the number of international organizations of the same affiliation is, the greater the political and economic consensus between the two economies. The third is the maturity of the existing paths between two adjacent nodes \( \text{fac}_{ij} \). If paths exist between two economies, then the more mature they are, and the better the relationship between the two economies. Maturity can be measured by the normalized geographic object flow value, which is calculated as follows:

\[
\text{rela}_{ij} = a \cdot \text{rela}_{ij} + b \cdot \text{org}_{ij} + c \cdot \text{fac}_{ij},
\]

In Equation (7), \( a, b \) and \( c \) are the weights of each of the 3 parameters. Based on the above heuristic factors, it follows that:

\[
[\eta_{ij}(t)]^g = [\text{sur}_{ij}(t)]^\gamma \cdot [\text{dis}_{ij}(t)]^\omega \cdot [\text{rela}_{ij}(t)]^\delta,
\]

In Equation (8).
In summary, the improved transfer probabilities are as follows:

\[
p_{ij}^k(t) = \begin{cases} 
\sum_{s \in \text{allowed}_k} [\tau_{ij}(t)]^{\alpha} [\text{sur}_{is}(t)]^{\gamma} [\text{dis}_{is}(t)]^{\omega} [\text{rela}_{is}(t)]^{\delta} & , \ j \in \text{allowed}_k, \\
0, \ j \notin \text{allowed}_k
\end{cases}
\]

In Equation (9), \( \alpha, \gamma, \omega, \) and \( \delta \) are factor weights.

### 3.3.4. Pheromone Updating Strategy

To avoid scenarios with too much residual pheromone, causing the residual information to overwhelm the new information, the residual information is updated with pheromone after each ant has taken a step or completes the traversal of all nodes. Pheromone updating strategies often require a balance between group intelligence and individual strengths. Pheromone renewal involves two processes: pheromone release and volatilization. Release means that the colony will release pheromones along the path that it travels. Volatilization mimics the pheromone properties of nature, and over time, the pheromone intensity of each route will decrease due to volatilization. To accelerate the convergence of the algorithm, the pheromone is updated using an elite ant strategy to increase the probability of the optimal route being discovered. The elite ant strategy is an improvement of the original ACO approach and is designed to provide an additional pheromone increment to the optimal path after each completed iteration [51]. The pheromone updating strategy is given in the following equation:

\[
\tau_{ij}(t+n) = (1 - \rho) \tau_{ij}(t) + \sum_{k=1}^{m} \Delta \tau_{ij}^k + e \rho \in (0, 1),
\]

In Equation (10), \( \tau_{ij}(t+n) \) is the original pheromone residue on road segment \((i, j)\), \( \rho \) is the pheromone volatilization factor, and \((1 - \rho)\) is the information residue factor. \( \Delta \tau_{ij}^k \) denotes the pheromone increment for the \( k \)-th ant on road section \((i, j)\). Thus, \( \sum_{k=1}^{m} \Delta \tau_{ij}^k \) is the sum of the pheromones released by all ants, \( \Delta \tau_{ij}^k \) is the additional pheromone added along the optimal path, and \( e \) is the incremental weight.

The ant pheromone updating method is based on the ant quantity system local updating strategy that was proposed by Dorigo M.; in this approach, the pheromone level is updated along a path after each step the ant takes, which can effectively prevent ants from converging on the same path [25]. This method is expressed in the following equation:

\[
\Delta \tau_{ij}^k = \begin{cases} 
Q / I_{\text{best}} & , \ (i, j) \in T^\text{best} \\
0 & , \ (i, j) \notin T^\text{best}
\end{cases}
\]

In Equation (11), \( Q \) is the pheromone intensity, \( I_{\text{best}} \) is the optimal route, and \( T^\text{best} \) is the set of nodes associated with the optimal route.

Since the path constructed by each ant is not necessarily a feasible solution but rather a “component” of a feasible solution, the phenomenon of no feasible solution can be avoided by increasing the number of ants (large ant population), which is also one of the strategies used in the application of ACOs.

### 3.4. Testing and Evaluation

#### 3.4.1. Testing Method

The Mann–Whitney U test, sometimes called the Mann–Whitney–Wilcoxon test or the Wilcoxon rank sum test, is used to test whether two samples are from the same population. The Mann–Whitney U test is used to determine whether the path samples obtained from the algorithm in this paper are significantly different from randomly selected samples. The multiple preferred paths derived using the method introduced in this paper
are used as the experimental group (sample), and the randomly generated paths in the region are used as the control group (sample), with the length of paths and corresponding trade flows as the quantitative statistical attributes of a sample. If the variability in the two groups of samples is significant, the method proposed in this paper is considered credible.

The test steps are as follows:

1. The preferred and random paths are grouped, the length of and trade flow along each path are calculated, and the data are assessed to see if they are normally distributed.
2. The two sets of sample data are mixed, and the ranks are arranged in ascending order based on dataset size.
3. The rank sum of the two samples $R_1$ and $R_2$ is calculated.
4. The Mann–Whitney U test statistics $U_1$ and $U_2$ are obtained.

\[
U_1 = R_1 - \frac{n_1(n_1+1)}{2} \\
U_2 = R_2 - \frac{n_2(n_2+1)}{2}
\]  

(12)

In Equation (12), $n_1$ and $n_2$ are the sizes of the samples.

5. A judgment is made. The minimum value between $U_1$ and $U_2$ is compared with the significant value $U_\alpha$. If $U_{\text{min}} < U_\alpha$, there is a difference between the two samples, i.e., the optimal path derived with the method proposed in this paper is advantageous.

3.4.2. Evaluation Method

This paper focuses on the effectiveness of the algorithm based on the role and impact of the optimal path in the geo-economy. It is evaluated from two perspectives: the amount of trade flows along the optimal path and the coverage of the nodes on the optimal path.

1. The economic utility of the optimal path in this paper is evaluated based on the difference in factor flows on the optimal path derived in this paper and the preferred path derived with other methods.

\[
FlowP_{d} = \sum_{i=1}^{n} Flow(i,j) \\
R = \frac{FlowP_{d_{\text{best}}}}{FlowP_{d_{\text{other}}}}
\]  

(13) (14)

In Equations (13) and (14), $FlowP_{d}$ is the total element flow on any one path, $i, j$ are the two nodes at the ends of the path, and $n$ describes the total number of nodes on a path. In Equation (12), $FlowP_{d_{\text{best}}}$ is the total element flow on the preferred path derived with the method proposed in this paper, $FlowP_{d_{\text{other}}}$ is the total element flow on any one path determined with other methods, and $R$ is the ratio of the element flows on two paths. If $R > 1$, the preferred path derived with the proposed method is advantageous; otherwise, another path is best.

2. The coverage of a path node reflects the extent of the path’s influence in the region.

\[
\text{cov} = \frac{\sum n}{N_{\text{all}}} \\
r = \frac{\text{cov}_{\text{best}}}{\text{cov}_{\text{other}}}
\]  

(15) (16)

In Equations (15) and (16), $n$ is the total number of nodes along a preferred path, $N_{\text{all}}$ is the number of all nodes in the region, and cov is the node coverage. $\text{cov}_{\text{best}}$ is the node coverage along the preferred path with the method proposed in this paper, $\text{cov}_{\text{other}}$ is the node coverage along any one path derived with other methods, and $r$ is the ratio of the node coverage obtained with the proposed method to that obtained with another method.
If \( r > 1 \), the preferred path derived by the proposed method is advantageous; otherwise, it has no advantage.

4. Results and Analysis

In the experiments, China is selected as the research subject, the path network of China’s geo-economic factor flows in the Indo-Pacific region is constructed, the improved ACO is applied to find the optimal paths of geo-economic factor flows, the optimal paths are analyzed, and the characteristics of key nodes in the path are assessed to identify potential economic corridors and economic hubs in the Indo-Pacific region.

The data used in this study cover 24 countries within the focus study area and 332 ports, and they are comprised of 3 main parts. The spatial data include the geographic coordinates of the center point of the spatial range of the economies, and the distance between two ports is calculated as the distance of the route between the two points. The relationship data assess the basic relationship value between two economies comprehensively by considering the number of international organizations that the two economies belong to and the official classification of the definition of the relationship between the economies (such as strategic partnerships). Additionally, the import and export trade volume is used as an assessment value for the economic relationship exchange. The path characteristics data provide a quantitative assessment based on the type and number of channels between two economies.

In terms of algorithm parameters, we have set \( \alpha = 1 \) and \( \beta = 2 \), with a population of 150 ants and a maximum of 150 iterations.

4.1. Path Network Construction and Experimental Results

4.1.1. Path Network Construction

A path network is constructed from two levels, as follows:

1) At the macroeconomic level, the macro-, abstract and integrated regional economic relations and comprehensive transportation system are used as the background; the main economies in the region, in this case, countries, are selected as the parent nodes \( P \); and the center points of the national spatial scope are used as the node positioning points to build an abstract path network based on intercountry economic and trade relations (Figure 5). Figure 5 represents the path network consisting of 24 nodes constructed based on the spatial location of 24 national center points in the study area.

2) At the level of physical facilities such as transportation routes and transportation stations, a physical path network based on transportation systems is constructed using facilities such as ocean routes, pipelines, railroads and ports in the region. Since China’s economic and trade interactions in the Indo-Pacific region depend mainly on maritime transport [52], the ports are used as subnodes, and maritime routes are used as optional paths to build a maritime route-based, specific path network (Figure 6). It illustrates the path network built on 332 ports by considering the existing routes in the key areas of the study region. We have chosen schematic diagrams to depict the path network for the sake of a better display scale.
4.1.2. Experimental Results

Before using the ACO for optimal path selection, the starting and ending nodes of each path are set according to the two methods of start- and end-point setting in the approach described above. The first method is spatial location guidance. The starting point is China, and the path termination nodes are the other 23 countries in the study area, which can correspond to 23 generated geo-economic flow paths. In the second approach, functional guidance, two important Chinese ports, Guangzhou Port and Shanghai Port, are selected as the starting points, and the nodes at the western edge of the Indian Ocean that are choke points for ocean routes, namely, the Cape of Good Hope and the west coast region of the Gulf of Aden, are selected as end points.

The first approach yields an integrated, macroeconomic corridor in the context of economic relations, effectively representing China’s economic relations in the region. The second approach yields an economic corridor in the context of maritime transportation interests, effectively representing China’s specific economic and trade corridors in the Indo-Pacific region.

The starting point of a geo-economic factor flow is often set according to the subject of the study; for example, since the subject in this study is China, the starting point is set to China, and the starting point of a route path is determined from among China’s important ports that service India-Pakistan routes and Southeast Asia routes.

The experimentally derived preferred paths are further processed to remove directly connected paths and merge duplicate paths to identify China’s macroeconomic corridors in the Indo-Pacific region (Table 2) and the preferred paths based on ports in the Indo-Pacific region. (Table 3).

Table 2. Economic corridors in the Indo-Pacific region.

<table>
<thead>
<tr>
<th>S/N</th>
<th>Economic Corridors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>China-Vietnam-Brunei Darussalam-Indonesia-Australia-New Zealand</td>
</tr>
<tr>
<td>2</td>
<td>China-Vietnam-Cambodia-Malaysia-Singapore</td>
</tr>
<tr>
<td>3</td>
<td>China-Vietnam-Philippines</td>
</tr>
<tr>
<td>4</td>
<td>China-Myanmar-Bangladesh</td>
</tr>
<tr>
<td>5</td>
<td>China-Myanmar-Lao, People’s Dem. Rep.-Thailand</td>
</tr>
<tr>
<td>6</td>
<td>China-Myanmar-Sri Lanka-Maldives</td>
</tr>
<tr>
<td>7</td>
<td>China-Rep. of Korea-Japan</td>
</tr>
<tr>
<td>8</td>
<td>China-Rep. of Korea-United States of America</td>
</tr>
</tbody>
</table>
Table 3. Preferred paths based on ports in the Indo-Pacific region.

<table>
<thead>
<tr>
<th>S/N</th>
<th>Preferred Paths</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>China-Bont LNG Terminal-Cochin-Destination</td>
</tr>
<tr>
<td>2</td>
<td>China-Kota Kinablu-Destination</td>
</tr>
<tr>
<td>3</td>
<td>China-Bont LNG Terminal-Lankaw-Destination</td>
</tr>
<tr>
<td>4</td>
<td>China-Cochin-Galle-Destination</td>
</tr>
</tbody>
</table>

4.2. Tests and Evaluations of the Experimental Results

4.2.1. Test

The results of the Mann–Whitney U test described above are shown in Table 4.

Table 4. Mann–Whitney U test results.

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Variable Value</th>
<th>Sample Size</th>
<th>Median</th>
<th>Standard Deviation</th>
<th>Statistic</th>
<th>p</th>
<th>Cohen’s d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>Economic corridors</td>
<td>8</td>
<td>4,068,738.932</td>
<td>4,167,259.539</td>
<td>10</td>
<td>0.012</td>
<td>1.495</td>
</tr>
<tr>
<td></td>
<td>Random corridors</td>
<td>9</td>
<td>11,068,921.917</td>
<td>4,052,252.494</td>
<td>61</td>
<td>0.016</td>
<td>1.143</td>
</tr>
<tr>
<td>Trade flow</td>
<td>Economic corridors</td>
<td>8</td>
<td>758.416</td>
<td>702.663</td>
<td>0.016</td>
<td>1.143</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Random corridors</td>
<td>9</td>
<td>237.626</td>
<td>201.488</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In Table 4, the p values of 0.012 and 0.016 for the length and trade flow sample groups, respectively, indicate statistically significant results. The Cohen’s d values that characterize the magnitude of the differences are 1.495 and 1.3, respectively, indicating that the magnitude of the differences is large.

4.2.2. Evaluations

Based on the approach proposed in Section 3, the trade flow characteristics on the economic corridor can be used as an indicator to evaluate the performance of the economic corridor. Additionally, the coverage of the nodes derived from the two methods is compared from the perspective of the corridor’s influence range.

All eight corridor trade flows derived from the method proposed in this paper display an increasing trend (Figure 7). The Figure 7 presents the trade flow trends of the eight Eco-corridors (Eco-corridor 1 to Eco-corridor 8), which correspond to the eight corridors listed in Table 2. The curves display the total trade flow trends of each corridor in the last five years. The upward trend of all eight curves suggests that corridors have had a positive impact on trade flows.

Figure 7. Annual growth rate of corridor trade flows derived from the improved ACO introduced in this paper (based on 2017 trade flows).
Several ACO variants have been proposed in the literature. Owing to their superior performance over other alternatives, the most popular ACO algorithms are Rank-based Ant System (AS-Rank), Max-Min Ant System (MMAS) and Ant System with elitist strategy (EAS) which used in this paper. We compare the algorithm in this paper with AS-Rank and MMAS.

We used the AS-Rank and MMAS in the same study area and select parameters that have not been improved as heuristic factors. Then preferred paths are identified (Table 5), and the trend of trade flow changes on the paths can be represented accordingly (Figure 8). The Figure 8 illustrates the trends of the total trade flows of the Eco-corridors derived from two algorithms, AS-Rank and MMAS. The Eco-corridor 1’ to Eco-corridor 8’ and Eco-corridor I to Eco-corridor VIII refer to the corridors listed in Table 3. The increases in the relevant trade flows on the preferred paths identified with the AS-Rank and MMAS over the past 5 years are not obvious. The \( R \) which is the ratio of the flows on the preferred paths derived from different algorithms, can be calculated. Values of the \( R_{AS-Rank} \) and \( R_{MMAS} \) are 2.6 and 1.6, respectively, which preferred path derived with the proposed method is advantageous; it can be verified that the economic corridors identified in this paper provide obvious economic utility. By comparing the economic trade performance of the optimal paths derived from different variants, we find that what really affects the application of the algorithm in the geo-economic domain is the ability to choose the appropriate heuristic factors and to determine the appropriate transfer probabilities.

Table 5. Preferred paths derived from the AS-Rank and MMAS of ACO.

<table>
<thead>
<tr>
<th>S/N</th>
<th>Preferred Paths</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>1'</td>
<td>China-Lao, People's Dem. Rep.-Thailand-Cambodia-Malaysia</td>
</tr>
<tr>
<td>2'</td>
<td>China-Lao, People's Dem. Rep.-Cambodia-Brunei Darussalam-Indonesia</td>
</tr>
<tr>
<td>3'</td>
<td>China-Lao, People's Dem. Rep.-Viet Nam-Brunei Darussalam</td>
</tr>
<tr>
<td>4'</td>
<td>China-Myanmar-Sri Lanka-Maldives</td>
</tr>
<tr>
<td>5'</td>
<td>China-Lao, People's Dem. Rep.-Thailand-Malaysia-Singapore</td>
</tr>
<tr>
<td>6'</td>
<td>China-Lao, People's Dem. Rep.-Thailand</td>
</tr>
<tr>
<td>7'</td>
<td>‘China-Lao, People’s Dem. Rep.-Cambodia-Viet Nam</td>
</tr>
<tr>
<td>8'</td>
<td>China-Nepal-India</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Preferred Paths</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>China-Lao, People’s Dem. Rep.-Vietnam-Brunei Darussalam-Indonesia</td>
</tr>
<tr>
<td>II</td>
<td>China-Lao, People’s Dem. Rep.-Vietnam-Brunei Darussalam-Australia</td>
</tr>
<tr>
<td>III</td>
<td>China-Lao, People’s Dem. Rep.-Thailand-Cambodia-Brunei Darussalam</td>
</tr>
<tr>
<td>IV</td>
<td>China-Lao, People’s Dem. Rep.-Thailand-Cambodia-Malaysia-Singapore</td>
</tr>
<tr>
<td>V</td>
<td>China-Lao, People’s Dem. Rep.-Thailand-Cambodia-Vietnam</td>
</tr>
<tr>
<td>VI</td>
<td>China-Myanmar-Sri Lanka-Maldives</td>
</tr>
<tr>
<td>VII</td>
<td>China-Rep. of Korea-Japan</td>
</tr>
<tr>
<td>VIII</td>
<td>China-Vietnam-Indonesia-Australia-New Zealand</td>
</tr>
</tbody>
</table>

Figure 8. Annual growth rate of corridor trade flows derived with another ACO variant (based on 2017 trade flows).
The resulting number of path nodes identified using the proposed method in this paper is 74%, while those of the two ACO variants are 57% and 60%. This result suggests that the economic corridors derived with the method proposed in this paper have a wide range of influence.

4.3. Economic Corridor Analysis

China’s economic corridors in the Indo-Pacific region exhibit two characteristics. First, the spatial distribution pattern of the corridors is consistent with the direction of spatial trade extension. For example, the China-Vietnam-Cambodia-Malaysia-Singapore corridor is arranged according to spatial distance, from near to far. Second, the number of nodes varies from path to path. Paths with a large number of nodes, such as China-Vietnam-Brunei-Indonesia-Australia-New Zealand, pass through four nodes between the start and end points; paths with a comparatively smaller number of nodes, such as China-Korea-Japan, have only one node in between the start and end points. The number of nodes is somewhat related to the economic volume of the economy.

Next, the screened economic corridors are analyzed from three aspects in conjunction with the actual situation.

In terms of relationship connectivity patterns, a number of countries have direct links with China, including Vietnam, Myanmar and the Republic of Korea; Sri Lanka, the Maldives, the Philippines, and Malaysia have indirect associations. Directly connected and interconnected countries play different roles in the corridors. Directly connected countries generally have relatively sensitive geopolitical relations with China, and they have stronger economic influences or economic contact with China and the potential to become economic hubs. Interconnected countries, on the other hand, have a greater potential role in the extension of China’s economic development space, as directly connected countries can be used as corresponding points of contact. These interconnected economies should be taken seriously in future trade, investment and other economic transactions.

In terms of spatial distribution characteristics, the countries in the corridor that are directly connected to China are relatively close to China in terms of spatial distance, and they all border China by land or sea, indicating that China will be most influenced and constrained by neighboring countries when developing its geo-economic network in the Indo-Pacific region. Other countries are mostly noncontiguous and relatively distant in space, and they often need to pass through other nodal countries when establishing a relationship channel with China. Thus, it appears that geographic location still plays an important role in geo-economics and is an influential factor in China’s expansion in the Indo-Pacific region.

In terms of economic and trade exchanges, countries in the economic corridor are more important in China’s foreign trade. The importance of these corridors in China’s foreign economy can be assessed based on the trade volume share of countries in the abovementioned eight economic corridors with China from 2017 to 2021. Four economic corridors accounted for approximately 20% of China’s trade in the Indo-Pacific region from 2017 to 2021, and one corridor was close to 50% (Figure 9). Moreover, the goods traded between China and the countries in the Indo-Pacific region mainly fall within the following sectors: agricultural products, mechanical and electronic equipment industries, and mineral resources. Notably, Vietnam and Myanmar, which are in the economic corridor, are ranked 6th and 10th, respectively, in terms of agricultural trade value as China’s agricultural trade partners.
The main partners for E&E import trade with China are concentrated in the “peninsular countries” of Southeast Asia, with dense economic corridors, such as Vietnam-Cambodia-Malaysia, Myanmar-Bangladesh, Myanmar-Lao, and People’s Dem. Rep.-Thailand. This concentrated pattern is due to the abundant labor population and relatively low labor costs in peninsular Southeast Asian countries, which have led to the transfer of manufacturing industries to Southeast Asian countries [53], with an important contribution to China’s construction of the “21st Century Maritime Silk Road” [7].

Through the economic corridor analysis, we can explore the economies in the region that can be linked, and form development axes from these economies, which is conducive to the formation of a large-scale economic development space with strong linkages in the region.

4.4. Economic Hub Analysis

An economic hub is an economy that plays a communicative role in an economic corridor or region. When an economy is linked to other economies in a specific spatial and temporal context, it often requires the participation or support of specific economies, and if certain economies are always “needed”, then they are considered to play the role of a geohub. These geohubs can be countries, political centers, seaports, land border crossings, etc., and they are usually key nodes (nodal) in the paths of geo-economic relations. In contrast to the definition of nodal in Cohen’s Geopolitics [54], the key node here is primarily oriented toward a specific economy, usually a country or region where that economy plays an important linking role in the development of regional economic relations. These nodes have certain advantages relative to other economies in terms of geographical location, socioeconomics, infrastructure, closeness of relationships and cultural perceptions. Additionally, they could become a geo-economic concern for China. Based on the hierarchical nature of China’s pathway network in the Indo-Pacific region, the following analysis is conducted from the perspectives of both hub countries and hub ports.

4.4.1. Hub Countries

The nodes in each of China’s preferred paths in the Indo-Pacific region are counted. Nodes with higher occurrence rates generally play a more pivotal role in the region and are often of greater positive significance to China’s economic development in the Indo-Pacific region.

The statistical analysis shows that the rate of being an intermediate node along a path varies considerably from country to country (Figure 10); the probabilities are as follows: Vietnam at 32%, Myanmar at 16%, South Korea at 12%, and Cambodia and Indonesia at 8%. These results indicate that the nodal roles of Vietnam, Myanmar and South Korea are relatively obvious and that these countries have value as economic hubs as China develops its geo-economy in the Indo-Pacific region.
which is the fourth-largest energy import corridor, are the main geopolitical corridors with corresponding different modes of transport. Among them, Vietnam and Myanmar are the specific region.

The closest route between South Korea and China is only 102 nautical miles and includes approximately 12 ports and 15 shipping routes, making communication among countries convenient in all areas.

The geo-economic relational network of the Indo-Pacific region relies heavily on the sea as a link. Ninety percent of China’s international trade is conducted by sea, with most of the navigable routes passing through the Indian Ocean and the South China Sea. China is a global manufacturing center, dependent on the import of materials and minerals via maritime transport. The countries in Southeast Asia can exert control over the connecting routes between the Indian and Pacific Oceans, and port construction in these countries is vital for maritime geostrategic security. Therefore, the economic corridors of China in the Indo-Pacific region are geared toward the need for security and stable development, and the characteristics of China’s trade in the Indo-Pacific region are integrated to identify port hubs with certain potential.

In the port path analysis using the ACO, the range of relevant countries along the Southeast Asian route and the Indo-Pak route within the Indo-Pacific region is used to constrain a functional zone; the delivery performance parameters are mainly selected based
on the evaluation of parameters such as the tonnage and berth of a port; the spatial distance is the length of the sea route between two ports; and the association relationships are based on the relationship data from the country where a port is located.

From the experiment, the ports with hub potential along the two routes are the Bontang LNG Terminal in Indonesia, Kota Kinabalu in Malaysia, Galle Harbor in Sri Lanka and Cochin in India.

In terms of spatial distribution, most of the ports are on China’s corridor linking the Indian Ocean and the South Pacific, located at the entrance and exit of the Kra Isthmus, with good spatial connectivity to other countries and a certain radiation effect on surrounding areas. The port of Bontang LNG Terminal, also known as Makassar, is located at the southern entrance to the eastern side of the Makassar Strait in eastern Indonesia, which is a major transportation route between Asia and Australia. This port is a distribution center for internal and external trade in northeastern Indonesia. The port of Kota Kinabalu is located on the west coast of Gaya Bay, on the northwest coast of Saba, in the northern part of the island of Kalimantan, Malaysia, and on the southern side of the South China Sea. Galle is located on the southwest coast of Sri Lanka, bordering the northern side of the Indian Ocean, and it is the main port in southern Sri Lanka. The port of Cochin is located on the southwestern coast of India, facing the Arabian Sea, and it has an excellent harbor with well-developed water transport. It is one of the main ports on the Indo-Pak route.

In terms of existing port conditions, of the five ports mentioned above, Kota Kinabalu and Cochin are currently medium-sized ports, and Port Galle and Bontang LNG Terminal are both smaller ports. However, most ports have the capacity for large ships. Among them, Cochin Port has nearly 20 berths throughout the territory, with an annual throughput of approximately 5 million tons, and its international container depot is the largest container trans-shipment center in India. Kota Kinabalu is the main port in Sabah, Malaysia. There are nine berths in the port area, and they can accommodate 30,000-ton tankers. Additionally, the port’s warehouses and other supporting facilities are relatively complete. Galle is the main port in southern Sri Lanka, with three berths at the main quay and two ten-thousand-ton vessels. Galle and Bontang LNG Terminal are currently not directly available as ports for cargo ships, and they need to be further upgraded and developed based on the local natural conditions.

Tapping into the port hubs could aid in the creation of an economic corridor linking China to the Indian Ocean and promote China’s economic and trade development. The Chinese government’s “One Belt, One Road” project, the Maritime Silk Road, focuses on building a network of ports through the construction and expansion of ports and the development of industrial zones in port cities, from the eastern coastal cities of China through the South China Sea, the Indian Ocean and the Mediterranean Sea, connecting with the Atlantic Ocean to European ports and forming a major artery through Eurasia. By investing in the construction of ports in the countries bordering the Indian Ocean, China is strengthening its cooperation with the countries in the region and building a network of geo-economic relations that will contribute to sustainable development.

5. Discussion

The main results of this research are oriented to the real problem of economic corridor selection. From the perspective of optimal path selection for economic factor flows, the optimal path, as an economic corridor in the region, can be identified by improving the ACO-based path network for the macro-region. Economic corridors include macroscopic economic corridors in the context of intercountry relations and physical economic corridors in the context of transportation corridor facilities. Countries and ports in the corridors with economic hub values are identified. In the geo-economic analysis of China in the Indo-Pacific region, the methodology developed in this paper is used to identify eight valuable economic corridors, three potential economic hub countries and four ports.
The relevance of this paper is to provide methodological and analytical concepts for the siting of cross-border economic corridors at the macroscopic scale and to provide a decision aid for the sustainable development of the national geo-economy.

The main innovations of this paper are as follows:

(1) An improved ACO suitable for solving path selection problems in macroscopic socio-economic spaces is proposed. The ACO is improved in terms of constructing hierarchical path networks and heuristic functions. The hierarchical network takes into account the needs of both the economic relationship paths and the specific physical paths of a country. The improvement of the heuristic function fully considers the realistic characteristics of geo-economics and various factors, such as the distance, relationship, and efficiency of multiple possible routes between two nodes. By setting functional areas, path selection is characterized by a certain direction and priority, which is in line with realistic requirements. The improved ACO improves the applicability of the algorithm in geo-economic application scenarios, and its feasibility is verified through experiments.

(2) A method for mining geographic hubs is explored. The frequency of node occurrences along the preferred path is used to mine geographic hubs. That is, if a node appears several times along the preferred path of a particular economy, then to some extent, the node plays a pivotal role in trade, transport or national relations and has the potential to become an economic hub for the sustainable development of the region.

(3) The experimental results are evaluated from two perspectives: the flow of corridor economic factors and the coverage of corridor nodes. Thus, the feasibility of the method can be assessed, and the utility of economic corridors in the geo-economy can be verified.

Compared with previous methods, the proposed method provides the following advantages, but it also has some limitations.

(1) The ACO finds the shortest path among a large number of feasible paths via the movement pattern of the whole colony, i.e., the goal is to find the shortest path, but the path strategy for geo-economic factor flows is not the “shortest is the best” strategy. Therefore, it is necessary to define the optimal path according to the requirements of the macro-socioeconomic field. The improved ACO and similar optimization algorithms have improved evaluations of optimal paths and involve provincial (continental) relief corridors [46], public economic environment monitoring and management [56], and heavy-haul railway networks [57], but they are still not applicable for solving the intercountry economic corridor selection problem. In this paper, the heuristic factors are determined by coupling the path nature, the relationship between economies, and the trade distance to determine the priority in path selection according to the realistic needs of economic corridors.

(2) The nodes in the classic ACO and ACO variants are all at the same level, and there is a lack of constraints on nodes and paths at different levels. Although some studies have considered the problem of the nesting of levels [41,58], the constraints between different levels are not clearly defined. In this paper, the method of geo-element flow path selection considers the attribution relationship between parent—child nodes, and a network with two levels is developed from the macro-abstract relationship perspective and the concrete physical path perspective.

(3) The classic ACO and ACO variants do not consider the priority differentiation of some specific nodes after setting the transfer probability. Although some studies have defined “hot zones” [59] and “reasonable areas” [60], the setting of hot zones is fixed and cannot be flexibly set according to different “ant” preferences, which is not in line with the general logic of path selection in the geo-economic field. In this paper, the functional zones are set according to the development needs of the economy, and there are different functional zones for different needs.

There are also some limitations to the research in this paper:
In conducting the experimental analysis, the physical paths were verified and analyzed mainly using the marine transportation system as an example, without considering other types of paths, such as railroads, oil and gas pipelines, and fiber optic channels. This paper also does not address mixed paths, such as the case in which an economy is used as a traffic switching node from land-based to maritime transport. Therefore, in future research, it is necessary to expand the existing analysis to improve the diversity and comprehensiveness of node types and channel types.

In the port-based geo-economic relation analysis, there may be some countries with missing ports due to problems such as lack of data completeness or lagging updates for individual countries. However, this issue does not exclude the existence of hub potential at these ports. Therefore, further refinement of the data is required to identify other possible key nodes and geographic hubs.

The importance of this study can be summarized as follows:

1. By constructing the path network, setting functional areas, and optimizing the heuristic factors, the applicability of the ACO is improved for solving path selection problems in macro-space.

2. The method for selecting reasonable economic corridors and economic hubs is of great importance to the sustainable development of national and regional economies. The paper provides a referenceable method for the location of economic corridors and the identification of hub economies and can assist as a decision aid in the construction, adjustment and sustainable development of geo-economic relations among countries in a region.

The findings of this paper are as follows. Path networks based on macroeconomic relationships and physical path networks based on transportation systems can be used to abstract complex paths in geo-economics and provide a path network basis for path selection at different levels. Functional areas in the ACO can be set to determine the priorities of path nodes and add directionality to optimal path selection. The optimization of parameters in the ACO allows the algorithm to be applied to path selection problems in macroscopic space. The improved ACO is used to derive eight valuable economic corridors, three potential economic hub countries and four ports for China in the Indo-Pacific region. The comparison with the ACO variants and the analysis of realistic economic characteristics verify the effectiveness of the method proposed in this paper. It can be argued that the research presented in this paper provides a referenceable method for the location of economic corridors and the identification of hub economies, which can provide decision aid for the construction, adjustment and sustainable development of geo-economic relations among countries in the studied region.

It is crucial to explore more advanced optimization algorithms for decision-making in economic and social fields. While this paper focuses on the ant colony algorithm, there exist other advanced optimization algorithms that can solve complex decision problems, such as custom heuristics and metaheuristics, hybrid algorithms, and adaptive algorithms. In future research, it is important not only to explore the applications of these algorithms in the socioeconomic field but also to combine them to take advantage of their different strengths in solving decision problems. There are many domains where advanced optimization algorithms have been used as solution approaches, including online learning [61], scheduling [62–64], multi-objective optimization [65], transportation [66] and so on. From the application of these algorithms in various fields, it is clear that they have the potential to effectively solve complex decision problems. In the socioeconomic field, applying advanced optimization algorithms could help reduce the uncertainty brought by social factors in decision-making and improve decision accuracy. Looking ahead, there is a need to investigate how these algorithms can be used in the socioeconomic field to address complex decision-making problems. This could involve adapting existing algorithms or developing new ones specifically designed for this purpose. Overall, the application of advanced optimization algorithms could pave the way for more accurate and effective decision-making in the socioeconomic field.
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