Development of a decision-making system for transportation in remote inter-island area

Dang Quoc Hai, Pham Thai Hoang[*], Doan Thi Hoang Thao, Dinh Gia Huy, Le Thanh Tien

University of Transport Ho Chi Minh City
[*]Corresponding author: hoangpt@ut.edu.vn

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Abstract:

The transportation of goods and people between islands poses distinctive logistical hurdles due to the geographical remoteness and varied infrastructure prevalent in island settings. This study introduces a theoretical framework designed to improve the efficiency of selecting and routing hub islands in an inter-island logistics network by utilizing the hub-and-spoke model. The process of identifying potential hub islands involves an initial assessment of several criteria, encompassing geographical, economic, and equipment-related factors. The utilization of Floyd's algorithm was employed in the computation of the shortest distance matrices between islands, with consideration given to the avoidance of ship collisions. The identification of the required hubs is determined by employing a location set covering model, which includes a constraint on the maximum distance for service provision. The p-Median model was employed to ascertain the most efficient hub locations to minimize transportation expenses. The framework provides a quantitative approach to designing efficient logistics networks for inter-island transportation. It considers important factors, such as shipping routes, hub locations, and collision avoidance. The utilization of this methodology holds promise for augmenting connectivity and streamlining resource accessibility in geographically isolated island areas with limited infrastructure.

Keywords: Inter-islands logistics; Hub-and-spoke; Ship collision avoidance; Maritime routing; Location problem.

1. Introduction

The transportation of commodities from the mainland to remote islands presents logistical challenges. It might be argued that islands located at a considerable distance from major population centers tend to possess less developed infrastructure. Ports may vary in size, with some being tiny or even non-existent. The geographical characteristics of the islands exhibit significant variations, with some islands possessing naturally occurring deep-water ports, while others have shallow reefs or lack docking facilities altogether, hence necessitating the use of shallow draft barges or amphibious sealift ships [1]. The process of loading and unloading requires meticulous consideration of factors such as tidal patterns, prevailing weather conditions, and the presence of cranes or other pertinent equipment at respective ports [2].

The strategic planning of shipping routes requires meticulous consideration of factors such as the scarcity of refueling stations and potential navigational obstacles, including reefs and shallow waterways, and optimization of the total navigation time [3]. In the event of weather-related delivery delays, it is important to maintain reserves of essential resources, such as gasoline and replacement parts [4]. Perishable food and pharmaceuticals require transportation methods that maintain temperature control conditions and minimize the duration of transfer from mainland warehouses as well as expedited handling [5].

The coordination of inter-island logistics requires a comprehensive understanding of sea transportation, optimal routing strategies, and the ability to adapt to the distinct infrastructure present on each island. Companies that handle these factors effectively play a crucial role in island economies by facilitating the connection between resources and communities. By establishing efficient logistical networks, islands have the capacity to facilitate the sustainable exchange of products, people, and cultural elements beyond their maritime boundaries [6].

In this research, due to natural difficulties, this study investigates the applicability of the standard spoke-and-hub model for inter-island logistics. Cargo is only carried from the mainland to hub islands, where hub warehouses are situated. Subsequently, in response to the demand emanating from tiny islands, cargoes are transported to these locations using smaller vessels. The authors proposed a methodology for the identification and selection of suitable sites for the establishment of hub islands. Hub islands should possess convenient accessibility via maritime vessels and demonstrate efficient capability in meeting diverse demands. Nevertheless, the establishment of an optimal number of hub islands and their appropriate locations lacks a definitive foundation. Hence, this study presents a decision-making framework for the selection of hub islands using the principles of the scientific method.

2. Literature review

2.1. Short sea shipping and an extension, inter-islands logistics

There is a plethora of terminologies pertaining to marine services that do not include the act of traversing vast seas. The majority of the discourse revolves around intra-regional shipping, coastal-wise shipping, or inland waterway transportation, but with subtle variations in meaning. The concept of “short sea shipping” (SSS) was formally introduced by the European Commission in 1992 [7]. It refers to the transportation of goods and individuals via sea routes, specifically between ports located within geographical Europe or between ports in non-European nations that have coastlines along the enclosed seas adjacent to Europe. Therefore, the concept is established within a distinct regional framework, with the term SSS mostly used in Europe.

Nevertheless, this phenomenon is not limited to Europe. According to the proposal put out by Brooks et al. [8], a broader interpretation of SSS might be considered, including "transportation services by sea that do not involve transoceanic voyages." Various factors contribute to the occurrence of SSS, including the geographical proximity of population centers and industries to coastal areas, the presence of water bodies that need diversions or restrict land-based transportation modes, and the existence of inhabited islands. These circumstances may be seen in several regions around the globe, and inter-island logistics in Southeast Asia, considering short and medium domestic navigation distances, exemplifies a geographically and demographically representative case study for extensive SSS.

The field of inter-island logistics has received very little scholarly attention, mostly from scholars based in Indonesia and the Philippines, both of which comprise thousands of islands. Palconit and Abundo [9], [10] introduced an electric ferry ecosystem designed to address the issues of sustainability and safety in inter-island transportation within the Philippines. The logistics performance indicators of time, cost, and distance were analyzed by Widodo and Kurniawan [11] across several segments within the supply chain. Additionally, they examined the breakdown of pricing and costs, specifically within the perishable commodities supply chain in Indonesia. The study by Ansar et al. [12] included face-to-face interviews as a methodological approach to examine the inter-island trading practices of Bugis merchants. Alamsjah and Asrol [13] investigated the correlation between ambidextrous, agile, and lean supply chains and their impact on supply chain performance. Additionally, they explored the potential moderating influence of inter-island logistics on this connection. Alamsjah and Asrol [14] explored the influence of supply chain ambidexterity on supply chain performance (SCP) under uncertainty.

2.2. Automated manner in ship collision avoidance and generation of optimum navigation routes

Maritime routing difficulties exhibit distinct characteristics compared to the terrestrial routing problems that are often encountered. In terrestrial environments, a network of roadways exists, and the task at hand pertains to the selection of the most efficient route. In maritime environments, the absence of a predetermined route necessitates consideration of the routing issue, which is often intertwined with the challenge of collision avoidance. The first assessment of ship collision avoidance was proposed by Calvert [15]. Subsequent investigations have focused on using computational techniques to provide suitable recommendations for mitigating collisions in distinct approach scenarios, such as situations involving two ships heading in opposing directions, intersecting, or overtaking maneuvers. The authors addressed the issue of avoiding collisions with several ships in a single region using a strategy that involves the selection of ships with the greatest collision risk as a means to mitigate the occurrence of such incidents. This technology will autonomously identify the vessel posing the highest risk and initiate collision avoidance measures accordingly. The study of marine routing problems may be categorized into two distinct groups: one using analytical techniques and the other utilizing optimum search methods via the use of route-finding algorithms within the domain of computer science (heuristic algorithms). The analytical technique incorporates various rules and calculation procedures to identify a suitable solution to the problem, whereas the optimal search method exclusively identifies gaps and cautiously generates potential routes, comparing them to hypothetical routes to determine an acceptable route that fulfills the design requirements. The latter methodology is characterized by its simplicity and the relative proximity of its outputs to the optimal outcomes. Numerous analytical research studies have been conducted in the field. Notable previous works include those by Iijima and Hagiwara [16], Miele et al. [17], Hwang et al. [18], Szlapczynski [19], and Dinh and Im [20]. The use of heuristics algorithms has been widely employed in several academic investigations due to its straightforwardness and efficacy. Examples of such algorithms include Genetic Algorithms (GA), the A* algorithm, the Particle Swarm Optimization Algorithm (PSO), and various other derivative approaches. Several notable investigations have been published, such as the work of Tsou et al. [21], Blaich et al. [22], Pham and Nguyen [23-24].

2.3. Location problem

The groundbreaking work of Hakimi [25] marked a significant turning point in the field of location problems during the early 1960s. Since then, several approaches to location modeling have been used in both public sectors, such as police stations, ambulances, homeland defense, and humanitarian responses, as well as in commercial sectors, including warehouses and bank branches. The solutions typically consist of two components: the first involves the reduction of the number of candidate sites via the application of the covering problem, whereas the second entails the determination of optimum locations by using the *p*-Median problem. The covering problem was first introduced in Hakimi's seminal work [26]. Toregas et al. [27] made enhancements to the mathematical model known as the Location Set Covering Problem (LSCP) by mitigating the impact of problem size expansion. Church and ReVelle [28] established the Maximal Covering Location Problem (MCLP) to identify the location that maximizes coverage. These two investigations served as the basis for subsequent location models. Over the last four and a half decades, several scholars have made efforts to formulate new concepts and methods pertaining to location difficulties. The probabilistic LSCP for emergency facilities was developed by ReVelle and Hogan [29]. In the context of the new supply chain system, Hwang [30] introduced a stochastic set-covering problem specifically tailored for warehousing and distribution facilities. In their study, Straitiff and Cromley [31] provided insightful expansions of the set coverage approach to ascertain the most ideal sites for emergency warning sirens within the vicinity of Dublin, Ohio. Curtin et al. [32] used the maximum coverage problem as a methodology to determine the most efficient spatial allocations for police patrol zones in Dallas, Texas.

The *p*-Median issue was first proposed by Cooper [33] prior to the covering problem. The primary goal of the *p*-Median model is to determine the optimal placement of p facilities to effectively service n demand points. This is achieved by minimizing the total weighted distance or cost associated with the selected facilities and the demand points they serve. Subsequently, Hakimi [25], [26] used the p-median model to determine the most ideal sites for switching centers in telephone interconnection networks and police stations along highways. Ceselli and Righini [34] proposed the use of a branch-and-price algorithm as the preferred approach for addressing the capacitated p-Median problem. Beltran et al. [35] introduced the use of semi-lagrangian relaxation as a method for solving the *p*-Median problem. Bell et al. [36] integrated the LSCP with the *p*-Median model to determine the optimal placement of aviation alert stations. Park et al. [37] used a *p*-Median methodology to ascertain the optimal locations for bike parking facilities.

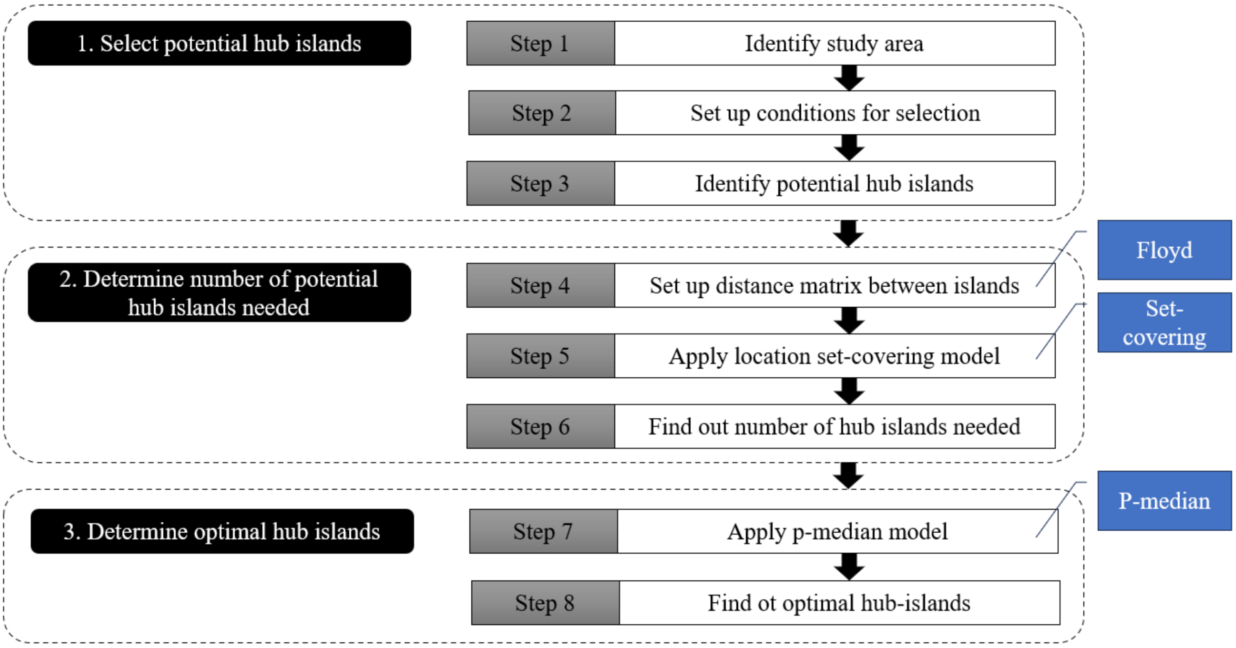

Figure 1. Decision-Making System for Selecting hub islands.

2.4. Research demand

In general, the analysis revealed that previous research on inter-island studies mostly focused on economic models or examined and analysed factors/indicators using qualitative design methods. To date, no empirical research has been conducted on the use of algorithms for the purpose of optimizing models, including routing, avoiding ship collisions,… In this study, the authors provide a conceptual framework for an optimized routing model that takes into account both the hub-and-spoke system and ship collision avoidance. First, the identification of marine networks and distances between islands is crucial in ensuring ship collision avoidance because there is no set path on the sea. Subsequently, algorithms were used to ascertain the optimal quantity of hub islands required and their respective locations.

3. Conceptual framework for the decision-making system

The process of finding hub islands involves many steps, including the selection of prospective sites, identification of maritime networks and distance matrices connecting islands, determination of the number of locations, and selection of optimal locations. The steps are described as follows.

3.1. Selecting potential hub islands

When contemplating the selection of a hub island, there are several criteria that must be taken into account, as belows:

Geographical prerequisites: The identification of suitable hub islands necessitates their positioning among satellite islands, while also possessing sufficient dimensions to accommodate the placement of warehouses. Furthermore, it is essential that they exhibit accessibility via marine boats. The berth depths must be appropriate to accommodate the drafts of the ships. The decision-maker has the option to include other geographic considerations, such as the absence of shallow reefs or coral reefs in the vicinity.

Economic prerequisites: Prospective islands must possess characteristics that make them appealing from an economic standpoint, such as large population and abundant resources. The primary purpose of warehouses situated on the island should be to cater to the local requirements of that specific island while also serving as a reserve center for neighboring satellite islands.

Equipment prerequisites: The port located on the selected hub island requires the presence of appropriate equipment to effectively simplify the process of loading and unloading cargo to and from maritime vessels. Furthermore, it is essential that the warehouse system implemented on the island has the necessary capacity to adequately cater to the additional demand for product storage from the surrounding islands.

Population and economic prerequisites: The selection of an island hub is frequently influenced by its economic development level. An island is a desirable location for a central hub if it has a robust economy with prospects for investment and flourishing businesses. Furthermore, the population size is also important. A densely populated hub can offer several advantages, including a sizable consumer base and a varied labor pool with top-notch employees.

3.2. Determining number of potential hub islands

3.2.1. Distance matrices between islands

After the potential locations are selected, distance matrices from these potential hub islands to the small surrounding islands are set up based on Floyd's algorithm as follows:

Consider a directed graph $G = (V,E)$ with n vertices and m edges. The objective is to determine the shortest distance, $d(u,v)$, between vertex u and vertex v in the given graph. The method computes the expenses associated with various routes and determines $c[u,v]$, which represents the route with the lowest cost from vertex u to v. For every vertex k in the graph, there exists a set of paths ranging from 1 to n. The calculation of the route with the lowest cost $c[u,v]$ is determined by using the following formula:

$$c[u,v] = min(c[u,v], c[u,k] + c[k,v]) \quad (1)$$

The method for determining the path with the lowest cost:

For $k:=1$ to n do

```
For $u := 1$ to $n$ do
    For $v := 1$ to $n$ do
        $c[u,v] = min(c[u,v], c[u,k] + c[k,v])$(2)
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$c^k[u,v]$ is considered as the cost associated with the shortest route from vertex u to vertex v, which includes all vertices in the collection $\{1,2, ..., k\}$. When the value of k is equal to zero, it is evident that:

$$c^0[u,v] = c[u,v] \tag{3}$$

The most direct path from vertex u to vertex v only traverses intermediate vertices $\{1, 2, ..., k\}$, however, there are some conditions that need to be considered. If the path does not traverse vertex k, but instead traverses vertices $\{1, 2, 3, ..., k-1\}$, then:

$$c^k[u,v] = c^{k-1}[u,v] \tag{4}$$

When traversing vertex k, the shortest route can be obtained by combining two segments: one from u to k and other from k to v:

$$c^k[u,v] = c^{k-1}[u,k] + c^{k-1}[k,v] \tag{5}$$

The objective is to identify the value of $c^k[u,v]$ in order to ascertain the minimum cost:

$$c^k[u,v] = min(c^{k-1}[u,v], c^{k-1}[u,k] + c^{k-1}[k,v]) \tag{6}$$

This research uses the findings of Dinh and Im [20], who conducted calculations to determine the dangerous area around the ship (domain). The waypoint network is constructed using points that are uniformly distributed at intervals of 0.5 nautical miles in both the horizontal and vertical directions. The operational concept may be described as follows: during the moving process, objects (islands, shoals, corals, dangerous water areas, etc.) will cover the points it overlaps in the network (Figure 1), the system will recognize them as dangerous spots, then remove them from the surrounding area. Floyd's algorithm uses the remaining points in the network to find the shortest path leading the owner ship (OS) to the destination.

Once the route from the prospective hub island to a small island has been established, the corresponding distance between the two islands can be determined.

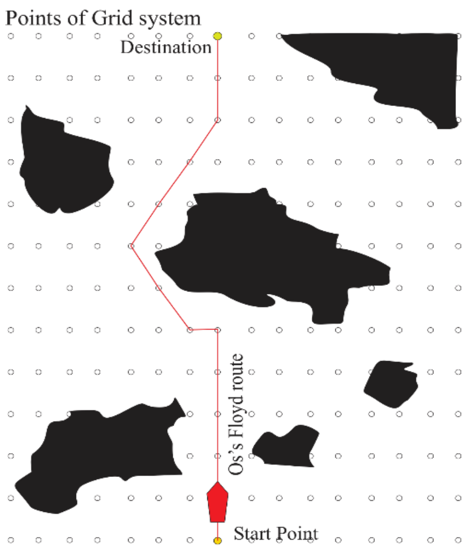

Figure 2. Principle of routing based on Floyd's algorithm.

3.2.2. Determining the number of hub island needed

The number of hub islands is determined using the location set-covering model, utilizing the distance matrices generated via Floyd's method. The location set-covering model establishes a constraint on the greatest permissible distance between a hub island and satellite islands, while simultaneously minimizing the number of hub islands within this range that fulfill the specified requirements. The underlying assumption of this location model is that the value of a service remains relatively constant within the maximum allowable distance but experiences a sharp decline after that distance is surpassed. A predetermined optimal arrival time was established for travel between a satellite island and its closest hub island. The hub island is strategically positioned within a distance, enabling it to provide a comparable level of service to all prospective satellite islands. The location set-covering model used in this investigation is as follows:

Indices

j = Hub inlands ($j \in J$)

i = Satellite islands ($i \in I$)

Data

d_{ij} = the shortest distance between nodes i and j

S_{ij} = the service area (S is defined by decision maker, for example, 100NM)

$N_i=\{j\ /\ d_{ij} \leq S_{ij}\ \}$ is the set of hub islands j within the critical distance S_{ij} of area of satellite i

Decision variable

If hub island j is installed, X_j=, otherwise, 0

Objected function

Minimize $\sum_{j\in J} X_j$ (7)

Subject to $\sum_{j\in N_i} X_j \geq 1\ \forall i \in I$ (8)

$X_j \in \{0.1\}\ \forall j \in J$ (9)

Equation (Eq.) (7) is an objective function that aims to minimize the total number of hub islands j. Eq. (8) is the constraint that satellite i is serviced by at least hub island j. Eq. (9) is the constraint that the decision variable *Xj* is a binary variable that has a value of 0 or 1.

3.3. Determining the optimal location

The number of hub islands required, as determined by the aforementioned set-covering model, is referred to as the p-value. The *p*-Median model was used to determine the precise optical position for each hub island. The transportation distance between each hub island and satellite is calculated, and the installation location of p or fewer hub islands that meet the need of all satellite islands with the lowest transportation cost is determined.

Indices

j = hub islands ($j \in J$)

i = Satellite islands ($i \in I$)

Data

h_i = Demand of satellite island i

d_{ij} = Distance between hub island j and satellite island i

p = The number of hub islands

Decision variable

If hub island j is installed, $X_j = 1$, otherwise, $X_j = 0$, $Y_{ij} = 1$ if area of interest, demand location.

Objected function

Minimize $\sum_{i\in I}\sum_{j\in J} h_i d_{ij} Y_{ij}$ (10)

Subject to $\sum_{j\in J} Y_{ij} = 1\ \forall i \in I$ (11)

$\sum_{j\in J} X_j = P$ (12)

$Y_{ij} \leq X_j\ \forall i \in I, \forall j \in J$ (13)

$X_j \in \{0,1\}\ \forall j \in J$ (14)

$Y_{ij} \in \{0,1\}\ \forall i \in I, \forall j \in J$ (15)

The goal function represented by Eq. (10), reduces the spatial separation between hub island j and satellite island i. The demand of each satellite island is assigned a weight based on the demand from transportation on the satellite island. The constraints expressed in Eq. (11) ensure that every service point is consistently attended to by a hub island and that there are no instances of overlapping or missing service areas. Eq. (12) represents the requirement that the quantity of hub islands is denoted by p. The restriction expressed in Eq. (13) states that hub island j must be open while satellite i is being supplied by hub island j. Eqs.(14) and (15) provide the constraints that govern the choice variables *Yij* (allocation variables) and *Xj* (location variables), respectively, which are binary variables that can only take values of 0 or 1.

4. Conclusion

This research presents a conceptual framework aimed at enhancing the efficiency of inter-island logistics networks through the systematic identification of hub island locations and the establishment of efficient shipping routes. The selection criteria for potential hub islands encompassed essential geographical, economic, and infrastructural factors. In order to ascertain the most efficient routes, Floyd's algorithm computes matrices that represent the shortest distances between islands, taking into consideration the need to avoid ship collisions. The location set covering model was utilized to ascertain the minimum number of hub islands required for the provision of services to all islands within a specified maximum distance. The *p*-Median model ultimately determines the number of optimal hub islands.

This framework offers a quantitative and algorithmic approach to address significant logistical obstacles in inter-island environments, such as restricted infrastructure, extensive distances, and navigational hindrances. The methodical procedure for identifying central nodes and determining secure and effective pathways has the potential to improve connectivity and enhance the availability of resources for remote island communities. Subsequent investigations may encompass the implementation and validation of models using authentic case studies pertaining to groups of islands. The optimization process could also consider additional factors, such as weather conditions, capacity constraints, and traffic congestion. With additional advancements, this framework has the potential to serve as a significant decision-support tool for the design and management of sustainable inter-island logistics networks.

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