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Concept of Route Planning and Cost Analysis for Travelling through the Arctic Northeast Passage Using a 3D Geographic Information System

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To plan undeveloped theoretically new optimal routes between Asia and Europe via the Arctic Northeast Passages, using a 3D geographic information system, voyage paths are simulated in a 3D visual form. This ensures that the distances are calculated accurately, and that other voyage data is also easily deciphered and presented in a manner familiar to users. This study compares the optimal Arctic Northeast Passages with traditional routes through the Suez Canal for dynamic analysis of the cost efficiency of major ports between Asia and Europe. Although some routes are greatly benefited by travel through the Arctic, the environmental impact and seasonal opening of the waterway should also be considered. It is noted that the current 3-D GIS used in this paper is not suitable for practical route planning, this work only brings out that such 3D presentation can be implementable within an official accredited ECDIS for future use.

KEYWORDS

1. Arctic Northeast Passage. 2. Route planning. 3. Route cost analysis.

4. 3D geographic information system (GIS).

1. Introduction
Because of the increasing advancement and convenience of network information, new navigation routes presented using 3D geographic information systems (GIS) are more clearly understood. Reflecting the phrase “a picture is worth a thousand words,” a 3D GIS provides users with simulated environmental images of the routes desired, increasing the ease of comprehension and route planning. When planning new routes, 3D GISs and network platforms can be integrated to analyse the various required costs and identify the most cost-efficient route, thereby offering users a collaborative problem-solving method.

In this study, the choice of network GIS is Google Earth because it is free to access and commonly used. This application software is a virtual globe software program developed by Google that uses satellite imagery, aerial photography, and GISs to map a 3D model of the earth. Since 2009, it began providing a seafloor topography service that enabled users to observe the terrain of the seafloor, the software has also included precise information of depth, weather, icebergs, and other diverse layers to facilitate route planning. The development of new routes is primarily focused on Arctic routes through the Arctic Ocean that link the three continents Asia, Europe, and North America. The Arctic Ocean has been covered by ice for thousands of years, with the ice areas narrowing the opening of the Arctic waterway; however, global warming in recent years has caused the Arctic ice to melt. Therefore openings of the Arctic waterway are not as narrow as before, causing the countries that neighbour the Arctic Ocean to begin actively exploring the Arctic waterways and collecting information regarding Arctic waters and terrain for a new Arctic route.

Current exploration has focused on three Arctic waterways; the first is the Northeast Passage, the second is the Northwest Passage, and the third is a potential route through the centre of the Arctic. As the central area of the Arctic Ocean has been covered by a thick ice layer for many years, this route would be the last to open and
the reason this route has not yet been exploited. The yellow and red routes shown in Figure 1 illustrate the Northeast Passage and Northwest Passage.

![Figure 1](image.png)

**Figure 1.** Mapping the Northeast Passage and the Northwest Passage in 3D using Google Earth

Currently, the Northeast Passage has attracted the attention of numerous Asian countries, such as China, South Korea, and Japan, who have begun to build ships with superior ice-breaking capabilities to explore Arctic regions and understand the geographic environment. Although a number of ships have been dispatched from Asia to collect navigation information of the Arctic Ocean, there still remains limited knowledge of such routes. Merchant ships of China recently for the first time have practically sailed the Arctic Northeast Passage from Dalian to Rotterdam, the results show that this voyage can save about 9 navigational days when compared to the Suez Canal traditional route. (Gannicus, 2013). Arctic Routes has been studied for several years (Somanathan et al., 2009, Ren and Chen, 2011, Khon et al., 2010, Ge and Jiang,
This study adopts Google Earth route planning features which are capable of 3D visual simulations. In addition, this study employs the elevation profile feature to determine water depths and Arctic Ocean iceberg distribution layers for the planning of the Northeast Passage. Next, comparisons of the distance deviations between actual navigation routes and the routes using Google Earth to prove that Google Earth is accurate and capable in this study. After route-planning was completed, this study compares the shipping costs between the Northeast Passage and the Suez Canal traditional route. Other than time and distance costs, the percentage of costs generated by other uncertain factors were determined to factor the cost benefit margins between the two routes and provide decision makers with additional information to select the most profitable route. Recently, the IMO (International Maritime Organization) is developing a draft International code of safety for ships operating in polar waters (Polar Code), which would cover the full range of design, construction, equipment, operational, training, search and rescue and environmental protection matters relevant to ships operating in the inhospitable waters surrounding the two poles (IMO, 2012).

2. Route Planning

Before route planning, the deviations between planned routes using Google Earth and actual routes were examined. The actual navigation route data were obtained by referencing the Evergreen China-Europe Shuttle Service (CES) actual data, which when inputting corresponding waypoint values into Google earth and obtaining Google earth distances of such routes, the differences between them are negligible, proving that Google earth is accurate and suitable for route planning.

2.1 References Evaluated for Route Planning

The schematic diagram of European shipping route taken by Evergreen CES from the Port of Kaohsiung in Taiwan to the Port of Rotterdam in the Netherlands was adopted
to reflect the Suez Canal traditional route. As shown in Figure 2, the red line denotes the route from the Port of Kaohsiung to the Port of Rotterdam, and the blue line denotes the return route from the Port of Rotterdam through Hamburg in Germany and River Thames in the United Kingdom, finally returning to the Port of Kaohsiung through the original route (Evergreen, 1999-2012).

Figure 2. Schematic diagram of Evergreen CES navigation route

Based on the statistics of the above routes obtained through Google earth and actual route data obtained through Evergreen, between each two waypoints, the farthest deviation was calculated at 0.01993, approximately giving a maximum 2% error. This confirms that Google Earth is a viable route planning tool.

2.2 Route-Planning Using Google Earth

To plan a feasible route, water depths must also be considered. A tentative route was first planned by determination of the ocean depth’s colour in Google earth’s display. Next, slight adjustments to the route were further implemented using the Google Earth elevation profile feature to ensure that the ocean depth remained constant and risk of grounding was avoided. The Northeast Passage was divided into three areas based on the climatic characteristics of the area. These areas comprised a general navigation area at the start and end, a fog-zone navigation area, and an arctic floating ice area (Ren and Chen, 2011), as shown in Figure 3. When travelling the traditional Suez route, ships must reduce their speed upon entering the Suez Canal,
causing the route to be divided into two areas, namely, a general navigation area and the Suez Canal area.

Figure 3. Schematic of the planned Arctic route and floating ice layers

Google Earth was used to simulate the navigation environment. The planning process employs not only water depth data, but also the 3D seafloor topography, enhancing better understanding of the water depth. Google Earth in flight model is currently available, allowing users to follow and view aerial routes from airports to a desired destination. However, at present, this feature is only available for routes between airports. If this feature can be applied to navigational planned routes, visual effects can be added to the simulation, providing a clearer illustration of the planned route.

Applying the touring feature of Google Earth to route planning is also a feasible
option for simulation. Currently, many website designers use the maps provided by Google Earth and 3D buildings developed by other designers to simulate 3D navigation images (Figure 4). Therefore, by applying the Google Earth touring feature to the navigation process, ships can be displayed as they travel from port to port, ensuring that the planned routes are in coordinate with the actual routes (Ships, 2011).

Figure 4. Image of simulated navigation routes

Google earth disclaims all warranties in connection with the content and the products, and is not reliable for any damage or loss resulting from the use of the product. Also, Google earth is not a certified official ECDIS. Therefore, Google earth is not suitable for practical navigation route. (Google, 2013)

2.3 Planning of the Northeast Passage

Based on the three climatic characteristics, the Northeast Passage was divided into four sections. The first and fourth section composes the route from the departure port to the Bering Strait and from the Barents Sea to the port of destination, respectively; these two sections were classified as the general navigation areas. The second area, which spanned the distance between the entrance and exit points of the
Bering Strait, was classified as the fog-zone navigation area because of the high frequency of summer fogs in the region, navigational speed should be reduced when travelling through this area. The third area was classified as the ice-zone navigation area and composes the travel distance in the Arctic Ocean, the travelling speed in the ice-zone area is advised to be restricted to 5 knots.

Navigating in the Arctic areas must take into account of distribution of the Arctic floating ice areas and in addition, must also be assisted by the elevation profile feature to determine water depth. Information regarding the Arctic floating ice distribution can be obtained by referencing the Arctic Ocean iceberg distribution timeline provided by the U.S. National Snow and Ice Data Centre (as shown in Figure 3). The Arctic Ocean iceberg distribution diagram allows users to plan routes which avoid icebergs while maintaining sufficient water depth for safe passage. To optimize the planning route, higher-geometry maze routing algorithm (Chang and Jan, 2003) is implemented. But, to avoid multiple direction changes for little benefit gains in travelling cost, path routing requires a turn penalty in the area of numerous barriers (Szlapczynski, 2006, Chang et al., 2013). Therefore, the total distance between the optimal route and the plan route has no much difference in this study.

This study has made a route planning website for readers. The method used to plan the routes from the Port of Shanghai in China to the Port of Rotterdam in the Netherlands was also used to plan other routes. Google Earth was embedded into a self made website for route planning. A total of five ports in Asia were included, namely, the Port of Kaohsiung in Taiwan, Port of Hong Kong in China, Port of Shanghai in China, Port of Tokyo in Japan, and Port of Busan in South Korea. Concerning European ports, three ports were incorporated, namely, the Port of Oslo in Norway, Port of Rotterdam in the Netherlands, and Port of Hamburg in Germany.
Permutation of these eight ports generated 15 possible routes. The shipping costs of the various routes were assessed based on the cost variations. Therefore, 15 possible routes and their estimated costs could be established and presented to the reader.

3. Formulating the Voyage Cost Function

Concerning trip-time costs for charters, charterers must bear fixed costs such as the cost of renting the ship. The rental cost of the ship is typically determined according to current market conditions. Regarding variable costs, charterers must cover the voyage distance, fuel consumption, and discretionary costs generated by other uncertain factors. The objective function of the minimum voyage cost for the carrier is shown below (Lin, 2010).

\[ \text{Min. } C_{\text{Total}} = C_{\text{Ti}} + E_{\text{oil}} + E_{\text{ch}} \]  

(1)

Where, \( C_{\text{Ti}} \) represents the ship’s total time cost, \( E_{\text{oil}} \) represents the total voyage fuel cost, and \( E_{\text{ch}} \) represents the discretionary costs generated by other uncertain factors. \( C_{\text{Total}} \) represents the sum of the ship’s total time cost, total voyage fuel cost, and discretionary costs. By establishing this function, the voyage cost can be determined. The cost variable added \( A \) before the variable name is for the Arctic Northeast route and added \( S \) before the variable name is for the Suez Canal traditional route.

3.1 Total Time Cost for the Ship

The ship’s total time cost includes the costs of capital and depreciation the ship operators incur. The relationship between voyage costs and navigation time is expressed as follows:

\[ C_{\text{Ti}} = T_{\text{i}} \times C_{\text{day}} \]  

(2)

Where, \( C_{\text{Ti}} \) represents the ship’s total time cost, \( T_{\text{i}} \) represents the voyage time, and \( C_{\text{day}} \) represents the daily ship rental cost.
Carriers that do not own a ship can rent one using the trip-time charter method, where the daily rental cost is used to calculate the time cost for the ship. Generally, ships heavier in weight or featuring special equipment (i.e., ships with ice-breaking capabilities) are more expensive to construct, and thus possess a higher ship time cost. Because of the change in the daily ship rental cost resulting from variations in the ship weight, equipment, global economic environment, and charter time, carriers must limit the voyage time to minimize voyage costs (Lin, 2010). To calculate the Northeast Passage navigation time, the following formula was employed:

\[ AT_t = \sum_{i=1}^{4} \frac{AD_i}{AV_i \times 24} \]  \hspace{1cm} (3)

Where, \( AT_t \) represents the total voyage time, \( AD_1 \) represents the voyage distance from the port of departure to the Bering Strait, \( AD_2 \) represents the voyage distance between the entrance and exit points of the Bering Strait, \( AD_3 \) represents voyage distance travelled in the Arctic Ocean, \( AD_4 \) represents the voyage distance from the Barents Sea to the destination, and \( AV_i \) represents the service ship velocity for voyage \( AD_i \). For example, the regular navigation speed (\( AD_1 \) and \( AD_4 \)) for a bulk carrier ship is 14 knots, the ship velocity can be reduced to 12 knots in \( AD_2 \) and only 6~7 knots in ice area \( AD_3 \).

To calculate the time cost for the Suez Canal traditional route, the following formula was employed:

\[ ST_t = \sum_{i=1}^{3} \frac{SD_i}{SV_i \times 24} \]  \hspace{1cm} (4)

Where, \( ST_t \) represents the total voyage time, \( SD_1 \) represents the voyage distance from the port of departure to the Suez Canal entrance, \( SD_2 \) represents the voyage distance through the Suez Canal, \( SD_3 \) represents the voyage distance from the Suez Canal exit to the destination, \( SV_i \) represents the service ship velocity for voyage \( SD_i \). For a ship, travelling through the Suez Canal usually need spend at least 20 hours, not
including waiting queue.

The time spent at sea can be estimated by using the voyage distance and service ship velocity. In the formula, 

\[ T_i = \frac{D_i}{(V_i \times 24)}, \]

24 is included in the denominator to enable conversion of the solution into days for easier calculation. \( D_i \) denotes the voyage distance (in nautical miles) and \( V_i \) is the ship velocity (knots per hour) for \( i \) section.

3.2 Fuel Cost for the Ship

Fuel consumption for ship is directly proportional to \( V^3 \) if the ship displacement is fixed, the following fuel consumption formula was established:

\[ C_F = a \times V^3 \quad (5) \]

Where \( C_F \) represents the hourly fuel consumption (in tonnes) of the ship, \( a \) represents the ship type-dependent coefficient, and \( V \) represents the ship velocity (in knots). However, revisions to this formula are required based on the results of a comparison with actual ship navigation data.

The fuel consumption for the four areas of the Northeast Passage was determined using the following formula:

\[ (AC_F)_i = a \times AV_i^3, \quad i = 1 \sim 4 \quad (6) \]

Where, \( AC_F \) represents the fuel consumption for the voyage \( AD_i \), \( AV_i^3 \) represents the service ship velocity for voyage \( AD_i \).

The Northeast Passage total fuel cost formula derived was as follows:

\[ \text{Min. } AE_{\text{Exoil}} = \sum_{i=1}^{4} (AC_F)_i \times (AT)_i \times 24 \quad (7) \]
The total fuel consumption was determined by summing the fuel consumed for the four voyages of the route. The unit for Exoil was fuel consumed per hour (in tonnes); thus, the value of Exoil was multiplied by the voyage navigation time (in hours). Referencing the fuel costs of the Suez Canal traditional route, the total fuel cost formula was established, as shown below.

\[
\text{Min. } SExoil = \sum_{i=1}^{3} (SC_i) \times (ST) \times 24 \quad (8)
\]

### 3.3 Discretionary Costs

The discretionary costs included the cost of travelling through the Suez Canal and employing an icebreaker ship through the Northeast Passage. The discretionary costs (i.e., Suez Canal tolls) for the traditional route were calculated based on the ship weight and toll rates for the selected ship type. The Northeast Passage has only 6 ~ 8 weeks voyage period from July to September per year. The cost of employing an icebreaker for the Northeast Passage was referenced from a Korean study regarding the daily cost of renting an icebreaker for exploration activities, which totalled approximately KR₩800 000 (Ren and Chen, 2011); this equates to approximately US$720. Furthermore, the traditional route involves travelling through the Strait of Malacca and the Somalia Seas, where pirates are rampant. For this reason, pirate insurance must be considered for voyages through these areas (Ren and Chen, 2011). Although pirates have seldom threatened ships travelling the Northeast Passage, the simple and fragile ecology of the Arctic Ocean may demand even higher insurance standards compared to other sea regions. Insurance companies may also be reluctant to provide insurance for fear of ice-related calamities.

Because the departure and destination ports of both routes are identical, and the
voyage time of Arctic shipping routes is limited by weather conditions (Zhang, 2009), this study set the route navigation period in seasons when the Arctic routes are accessible. In addition, because the total ship weight and ports of call were identical, assessments of the harbour costs and voyage suspension costs were not included in this study.

After assessing all items, the time cost, fuel cost, and discretionary costs for the traditional route and the Northeast Passage were summed. The objective function of the minimum voyage cost for the carriers was determined, as listed below.

\[
ACT_{Total} = ACT_t + AExoil + AExch \quad (9)
\]

\[
SCT_{Total} = SCT_t + SExoil + SExch \quad (10)
\]

(9) represents the objective function of the minimum voyage cost for the Northeast Passage, and (10) represents the objective function of the minimum voyage cost for the traditional route, which are referred to as \( ACT_{Total} \) and \( SCT_{Total} \), respectively. \( ACT_t \) and \( SCT_t \) represent the total time cost for the Northeast and traditional routes, respectively. \( ACT_t \) and \( SCT_t \) denote the total fuel cost for the Northeast and traditional routes, respectively.

4. Benefit Analysis and Simulation Result

The objective cost function for the two routes was obtained using the cost estimates explained above. Because the Northeast Passage navigation data were relatively deficient, only known portion factors that affect the shipping costs could be included in the assessment. Therefore, the percentage difference between the Northeast Passage total cost and the traditional route total cost was set as the benefit margin (Figure 5).
Using the benefit margin, ship carriers can estimate the cost generated by other uncertain factors. The benefit margin also reflects the discretionary costs for the Northeast Passage. Dividing the difference between the traditional route total cost and the Northeast Passage total cost by the traditional route total cost, the following assessment function was derived:

\[
CBM = \left( \frac{SCTotal - ACTotal}{SCTotal} \right) \times 100\% \quad (11)
\]

Where, \( CBM \) represents the benefit margin, \( SCTotal \) represents the minimum voyage cost for the traditional route and \( ACTotal \) represents the minimum voyage cost for the Northeast Passage. The Northeast Passage has a shorter distance when compared to the traditional Suez, thus the benefit margin is increased if the port is closer north in Asia.

A greater difference in the benefit margin indicates a larger cost from factors not included in the assessment. Conversely, a smaller difference in the benefit margin signifies a smaller cost from factors not included in the assessment. Therefore, when selecting departure and destination ports for ships that travel the Northeast Passage, ship carriers may assess the benefit margin using this model. Furthermore, when the
benefit margin is less than a certain set value, ship carriers may consider dismissing the voyage option.

Figure 6. Route Planning and dynamic cost estimate of benefit

The results of this study are shown in the self made website for route planning, comparing the optimal Arctic Northeast Passages with traditional routes through the Suez Canal with dynamic analysis of the cost efficiency (includes time costs, fuel costs and other factors) of major ports between Asia and Europe, in which the left portion of the website features an embedded Google Earth diagram of the planned route, the right portion is a self made evaluation program of the benefit assessment for users, directly showing the estimated CBM by imputing given ports and assessment cost values (Figure 6).

For example, one of the simulation routes from the Port of Shanghai to the Port of Rotterdam (with ship velocity 14 knots) is displayed in Figure 6. The blue line beginning on the right denoted the voyage from the Port of Shanghai to the Bering Strait (AD₁), which measures approximately 2990 nautical miles. The yellow line denoted the voyage between the entrance and exit points of the Bering Strait (AD₂), which measures approximately 763 nautical miles. The red line denoted the voyage...
through the Arctic Ocean (AD₃), measures approximately 2209 nautical miles, and finally, the blue line denoted the voyage from the Barents Sea to the Port of Rotterdam (AD₄), measures 1718 nautical miles. Because the ship travelled at a same velocity for AD₁ and AD₄, the same colour was used to indicate their speed, and the remaining voyages were marked using various colours representing different speeds.

For the Northeast Passage, the water depth of the total voyage ranged between 15 and 9000 m, and the total voyage distance measured approximately 7680 nautical miles. The distance is 3860 nautical miles shorter than the Suez Canal traditional route. Figure 6 shows the Northeast Passage and the Suez Canal traditional route planned using Google Earth.

The planning route can display zoom and rotation angles to the user’s desired location. The route simulation from Asia to Europe is available in simulated 3D navigation images. Combinations of five ports in Asia to 3 European ports generated 15 possible routes and can be clearly evaluated and shown in our website, the average benefit assessment is around 30%~ 45% for these examples. The shipping costs of the various routes were assessed based on the voyage cost function.

5. Conclusion

This study uses the online GIS Google Earth as the theoretical route planning and visualization software. According to statistical comparisons, the distance deviation between the actual route and the planned route in Google earth is within 2%. To plan the optimal routes, the water-depth and Arctic iceberg distribution data provided by Google Earth and higher-geometry maze routing algorithm with turn penalties were also employed. The newly planned optimal routes comprised various routes that depart from major Asia ports through the Arctic Northeast Passage to ports in Europe. The fuel costs, voyage time, and ship rental costs for each route were estimated.
However, because the cost of some of those factors varies over time, dynamic costs must also be evaluated. In practice, the practical 3D Arctic route planning should be implemented in an accredited official ECDIS system. In addition, before traveling these routes, assessments from environmental specialists are required. Currently, although no laws or regulations govern the hired icebreakers employed to guide the exploratory navigation, in the future, icebreakers and ships should conform to the International Maritime Organization’s Polar Code and relevant provisions, because crossing the Arctic Ocean is not merely a cost-benefit issue, but also involves the care and protection of the marine environment.

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