Dear Dr. Chang:

It is a pleasure to accept your manuscript entitled "Route Planning and Cost Analysis for Travelling through the Arctic Northeast Passage Using Public 3D GIS" in its current form for publication in the International Journal of Geographical Information Science. The comments of the reviewers who reviewed your manuscript are included at the foot of this letter.

Thank you for your fine contribution. On behalf of the Editors of the International Journal of Geographical Information Science, we look forward to your continued contributions to the Journal.

Sincerely,
Prof. brian lees
Editor-in-Chief, International Journal of Geographical Information Science
b.lees@adfa.edu.au

Reviewers' Comments to Author:

Date Sent: 12-Mar-2015
**Route Planning and Cost Analysis for Travelling through the Arctic Northeast Passage Using Public 3D GIS**

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<tr>
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Route Planning and Cost Analysis for Travelling through the Arctic Northeast Passage Using Public 3D GIS

To plan undeveloped optimal routes between Asia and Europe via the Arctic Northeast Passages using a 3D geographic information system (GIS), voyage paths are simulated in a 3D visual form. This ensures that the distances are calculated accurately, and that other voyage data such as water depths, sea ice distribution, and seashore topology are also easily deciphered, giving a more direct and clear demonstration compared to simplified presentations on an Electronic Chart Display & Information System (ECDIS). This article also implements a higher-geometry maze router in ice zone areas to obtain the optimal path in relation to safety and costs. This paper compares the optimal Arctic Northeast Passages with traditional routes through the Suez Canal for dynamic analyses of the cost efficiency (including time costs, fuel costs, and other factors) of travel between major ports in Asia and Europe. The average benefit assessment is around 30%~45% in a bulk carrier comparison. Thus, a 3D GIS can easily obtain and demonstrate safe navigation routes, providing a very convenient tool for initial planning.

Keywords: Arctic Northeast Passage; route planning; route cost analysis; higher-geometry maze router

1. Introduction

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 (Polyakov et al. 2012). Therefore, the openings of the Arctic waterways are not as narrow as before, causing the countries that neighbor the Arctic Ocean to begin actively exploring these Arctic waterways and collecting information regarding Arctic waters and terrain for a new Arctic route.
The current exploration has focused on three Arctic waterways: the Northeast Passage, Northwest Passage, and a potential route through the center of the Arctic (Østreng et al. 2013). Because 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 possible Northeast Passage and Northwest Passage, respectively.

Figure 1. Depictions of possible Northeast Passage and Northwest Passage in 3D using Google Earth

The Northeast Passage has recently 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 (Wergeland and Østreng 2013, IMRF 2014). Although numerous ships have been dispatched from Asia to collect navigation information about the Arctic Ocean, there is still limited knowledge about such routes. A merchant ship of China recently sailed the Northeast Passage from Dalian to Rotterdam for the first time, which showed that this

Because of the increasing advancement and convenience of network information, new navigation routes presented using a 3D geographic information system (GIS) are more clearly understood (Steiniger and Hunter 2013). 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. There are many geographic information systems on the market. Representative products include ArcGIS, MapGIS, SuperGIS, GeoMedia, GeoStar, and MapInfo (Pang et al. 2013). When planning new routes, 3D GISs and network platforms can be integrated to analyze the various required costs and identify the most cost-efficient route, thereby offering users a collaborative problem-solving method. As mentioned in the IMO Polar Code, neither the IMO Performance Standard for ECDIS nor the IEC test standard for ECDIS (IEC 61174) specifically mentions the display of ENCs at high latitudes, and as most ECDISs display their charts in Mercator form, which cannot correctly show the polar regions (Anon. 2013). ECDIS uses gnomonic projection in polar areas (Andriani Skopeliti and Tsoulos 2014). Google Earth displays the earth in 3D, which is suitable for the polar region and arctic planning.

In this study, Google Earth was chosen as a network GIS 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. In 2009, it began providing a seafloor topography service that allows users to observe the terrain of the seafloor. The software also includes precise information about the depth, weather, sea ice, and other diverse layers to facilitate route planning. The development of visible routes is primarily focused on Arctic routes through the Arctic Ocean that link the three continents of Asia, Europe, and North America. This study adopted Google Earth route planning features, which are capable of 3D visual simulations (Patterson 2007, Britt and LaFontaine 2009). In addition, this study employed the elevation profile feature to determine water depths and Arctic Ocean sea ice distribution layers for the planning of the Northeast Passage (NEP). Next, the distance deviations were found between actual navigation routes and the routes using Google Earth to prove that Google Earth is accurate and capable. After the route planning was completed, this study compared the shipping costs between the Northeast Passage and the traditional Suez Canal route. Other than the time and distance costs, the percentage of costs generated by other uncertain factors were determined to factor in 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) has been 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, operation, training, search and rescue, and environmental protection matters relevant to ships operating in the inhospitable waters surrounding the two poles (IMO 2012). This paper is organized as follows: The procedure for planning the Arctic Northeast route is shown in section 2, and further cost functions and benefit assessments are presented in sections 3 and 4.

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

2.1 Distance Accuracy for Route Planning

The schematic diagram of the 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 traditional Suez Canal 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 the River Thames in the United Kingdom, and finally returning to the port of Kaohsiung through the original route (Evergreen 1999-2012).

![Figure 2. Schematic diagram of Evergreen CES navigation route](image)

Based on the statistics of the above routes obtained through Google Earth and the actual route data obtained through Evergreen, the greatest deviation between any two waypoints was calculated to be 0.01993, giving a maximum error of approximately 2%. This confirmed that Google Earth is good at approximating the path length as a planning tool.

2.2 Route Planning using Google Earth
To plan a feasible route, the water depths must also be considered. A tentative route was first planned by determining the ocean depth’s color 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 the risk of grounding was avoided. Based on the three climatic characteristics, the Northeast Passage was divided into four sections. The first and fourth sections comprise 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 a navigation area with a high possibility of fog (H-P fog) because of the high frequency of summer fogs in the region (Fett et al. 1993). Navigational speed should be reduced when travelling through this area. The third area was classified as the ice-zone navigation area and comprised the travel distance in the Arctic Ocean. It is advised that the travelling speed in this ice-zone area should be restricted to about 6–8 kn (Worby et al. 2008, Veritas 2009).

The Arctic icezone area is frequently covered with ice and fog during summer time (Tjernström et al. 2004, Andreas et al. 2002). Navigating in Arctic areas must take into account the distribution of the Arctic floating ice areas and must also be assisted by the elevation profile feature to determine the water depth. Information regarding the Arctic floating ice distribution can be obtained by referencing the Arctic Ocean sea ice distribution timeline provided by the U.S. National Snow and Ice Data Centre (as shown in Figure 6).

For the sea ice area, the costs of avoiding ice and breaking ice (icebreaker) are different. Therefore, it is necessary to map the ice sea area for further calculation to search for the minimum-cost or optimal route.

2.3 Route Planning by Higher-geometry Router in Sea Ice Area

The Arctic Ocean sea ice distribution diagram allows users to plan routes that avoid sea ice while maintaining sufficient water depth for safe passage. To optimize the planning route,
a higher-geometry maze router with weighted regions (Chang et al. 2003, Jan et al. 2008, Chang et al. 2013) is implemented as shown below. A detailed description of the algorithm is given in Appendix A.

Regarding the route planning for ice areas, areas where the ice is thinner than 1 m were assumed to be generally navigable with an icebreaker (Dichtel 1951). For an ice-strengthened ship, the navigable ice thickness could be 0.2 m to 1.0 m depending on the types of ice-class vessel (Veritas 2009, Timco et al. 2004). The information regarding ice thickness was obtained using satellites and detection by navigation instruments of the surrounding sea areas. Google Earth was used to calculate voyage distances, and the distance data of the initial planned routes were displayed in a window. Then, maze routing and turn penalties were adopted to seek the optimal path by the proposed method.

Nautical charts from Google Earth are color images that include data such as the water depth, and latitude and longitude coordinates. This route planning method determines navigability through wave propagation and marks the results using colors. Therefore, route planning can be completed by propagating a wave from the starting point to the terminal point to identify the water depth and area features. The Arctic Ocean was divided into five areas using different colors. Land was marked in yellow, and coastal areas not deep enough for navigation were marked in green. The Arctic ice was divided into thick and thin ice areas. The thin ice areas were presented in light blue, indicating navigability with icebreakers, whereas the thick ice areas unnavigable for icebreakers were marked in white. The other ice-free areas of sufficient water depth were marked in dark blue (Figure 3(a)).
The five ocean area types were converted to a grid plane with three area types for implementation of the higher-geometry maze router to optimize the planning route. The unnavigable land, shallow sea, and thick ice areas were assigned a weight of $\infty$ in black. Ships could break the ice and navigate through thin ice areas, but the incurred costs were relatively higher than the cost of sailing in the dark blue navigable areas. Therefore, the thin ice areas were assigned a weight of two in grey, and the dark blue of the ocean was assigned a weight of one in white, as shown in Figure 3(b). After assigning the weights of all the areas’ grid graphs, a higher-geometry maze router was employed to calculate wave propagations for determining the minimum-cost path. It should be noted that the propagation speed for the weight value of two was half that of the weight value of one. The calculation began from the starting point and expanded in all directions until all the grids of the navigable areas were calculated. The calculation ended when the target point was reached, and the path with the least costs was attained by backtracking (Figure 4(a)). Therefore, assigning a weight to the thin ice areas facilitated finding an optimal path through the ice areas and avoiding the obstacles in the unnavigable areas (Figure 4(b)).
2.4 Flow Chart of Northeast Passage Planning

For the initial planning of the Arctic Northeast route, four waypoint areas were determined if the reference water depth was navigable. The general navigation area involved sailing at normal speed and routing based on the designated water depths from Google. The ship speed could be reduced while sailing in the navigation area with (H-P fog). For the ice sea area, the minimum cost (optimal) path could be obtained using the algorithm of the higher-geometry maze router with weighted regions. Once the entire route path was obtained, the voyage cost function (calculated by Excel) was built-in for dynamic cost estimation. The visible simulation of the voyage was displayed, and the potential benefit was also shown in a webpage window for consideration. The flow chart of this study is shown in Figure 5.
2.5 Planning of Northeast Passage

To plan a feasible route, the water depths also had to be considered. A tentative route was first planned by determining the ocean depths based on the colors 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 the risk of...
grounding was avoided. The Northeast Passage was divided into four areas based on the climatic characteristics of the area. These areas comprised two general navigation areas at the start and end, a navigation area with H-P fog, and an arctic floating ice area, as shown in Figure 6. 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 6. Schematic of planned Arctic route and floating ice layers](image)

The depth profile in Figure 6 includes an overview of the NEP with the designated water depths for navigation to prevent the ship from grounding. In this study, the departure and destination ports were first selected, and routes were planned according to the water depth data provided by Google Earth. Regarding Arctic routes, different navigation speeds were set in various areas, and it was determined whether the areas were suitable for ice navigation.
according to the water depth data, sea ice thickness, and sea ice distribution areas. The sea ice had a piecewise distribution that was considered using weighted regions. Therefore, the ship routing model (Mannarini et al. 2013) was not suitable for this case. Maze routing and turn penalties are necessary route planning methods (Chang et al. 2003, Szlapczynski 2006, Chang et al. 2013) for ice navigation, identifying the optimal paths to enhance the accuracy of route planning. After planning the general navigation, fog, and ice areas, the latitude and longitude coordinates of the turning points were exported to Google Earth and the entire route was simulated by applying the Google Earth tour simulation. Subsequently, a voyage cost function was formulated to calculate the costs of the Northeast and traditional routes. The two costs were compared. Their benefits were assessed, and the results were expressed in benefit margins. Finally, the planned routes and outcomes of the benefit assessment were displayed on a webpage to present the results simultaneously.

Google Earth was used to simulate the navigation environment. In addition to water depth data, the planning process also employed the 3D seafloor topography (bathymetry), which could provide a better understanding of the water depth and underwater topography. The database of 3D seafloor depth is appropriately mapped along the Russian coastline waters since sea ice is melted during summer time. The downside of Arctic Ocean is only about 10% has been mapped with multibeam; the rest of its seafloor area is portrayed through mathematical interpolation using a very sparse depth sounding database (M. Jakobsson 2013). Therefore, a practical navigation trip should be implemented in a certified IMO ECDIS. A certified ECDIS needs to be approved by an officially authorized or flag state to enhance navigation safety and particularly to prevent ships from grounding (Hecht 2002). However, Google Earth is useful for route simulation planning using overall 3D images based on accurate voyage data.

This study created 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 Shanghai in China, port of Tokyo in Japan, port of Busan in South Korea, port of Hong Kong in China, and port of Kaohsiung in Taiwan. Additionally, three European ports were incorporated, namely, the port of Oslo in Norway, port of Rotterdam in the Netherlands, and port of Hamburg in Germany. Permutations of these eight ports generate 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 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 is shown below (Lin 2010).

\[
\text{Min. } C_{\text{Total}} = C_Tt + Exoil \times P_{mol} + Exch
\]  

where \(C_Tt\) represents the ship’s total time cost, \(Exoil\) represents the total voyage fuel cost, \(P_{mol}\) represents models of propulsion systems (the value is subject to a ship model), and \(Exch\) represents the discretionary costs generated by other uncertain factors (including negotiable icebreaker fees and extra environmental fees). \(C_{Total}\) 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 \(A\) added before the cost variable name is for the Arctic Northeast route, and the \(S\) added before the variable name is for the traditional Suez Canal route. It should be noted that all the cost variables (time cost, fuel cost, and discretionary costs) must be evaluated using an actual
ship voyage to obtain the required coefficients before they can be used to formulate the cost function.

3.1 Total Time Cost for Ship

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

\[ CT_t = T_t \times C_{day} \times Ship\_ty \]  

(2)

where \( CT_t \) represents the ship’s total time cost, \( T_t \) represents the voyage time, \( C_{day} \) represents the daily ship rental cost, and \( Ship\_ty \) represents the type of ship: bulk carrier, container, tanker, passenger ship, etc. (the value is subject to the ship type).

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, heavier ships or those 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:

\[ AT_t = \sum_{i=1}^{4} \frac{AD_i}{AV_i \times 24} \]  

(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 the 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 kn, but the ship velocity can be
reduced to 12 kn in \( AD_2 \) and only 6~8 kn in ice area \( AD_3 \).

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

\[
STt = \sum_{i=1}^{3} \frac{SD_i}{(SV_i \times 24)} \quad (4)
\]

where \( STt \) 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, and \( SV_i \) represents the service ship velocity for voyage \( SD_i \). A ship usually needs to spend at least 20 h travelling through the Suez Canal, not including the time waiting in the 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 section \( i \).

### 3.2 Fuel Cost for Ship

A ship’s fuel consumption 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 \((AC_F)_i\) represents the fuel consumption for voyage \(AD_i\), and \(AV_i^3\) represents the service ship velocity for voyage \(AD_i\).

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

\[
\text{Min. } AExoil = \sum_{i=1}^{4} (AC_F)_i \times (AT)_i \times 24 \quad (7)
\]

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 traditional Suez Canal route, the total fuel cost formula was established, as shown below.

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

### 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 a voyage period of only 6~8 weeks from July to September per year. The navigation season could be longer if icebreakers are available. The cost of employing an icebreaker for the Northeast Passage is regulated by the Russian Northern Sea Route Administration (NSR 2013). Thus, the theoretical cost saving of the NEP strongly depends on whether shipping companies are able to take advantage of this short period. For ships travelling the Northeast Passage, the protective and fragile ecology of the Arctic Ocean may demand 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 harbor 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.

\[
ACT_{\text{Total}} = ACT_t + AExoil \times P_{\text{mol}} + AExch
\]  
\[
SCT_{\text{Total}} = SCT_t + SExoil \times P_{\text{mol}} + SExch
\]

Here, (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 \(ACT_{\text{Total}}\) and \(SCT_{\text{Total}}\), respectively. \(ACT_t\) and \(SCT_t\) represent the total time costs for the Northeast and traditional routes, respectively. \(AExoil\) and \(SExoil\) denote the total fuel costs 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 of difference between the Northeast Passage total cost and the traditional route total cost was set as the benefit margin (Figure 7).
Figure 7. Difference between concepts of benefit schematic

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’s total cost and the Northeast Passage’s total cost by the traditional route’s total cost, the following assessment function was derived:

$$CBM = \frac{SCTotal - ACTotal}{SCTotal} \times \% \quad (11)$$

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 compared to the traditional Suez route. Thus, the benefit margin increases if the port is closer to northern 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 8. 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 route with the traditional route through the Suez Canal using a dynamic analysis of the cost efficiency (including the 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 and the right portion is a self-made evaluation program of the benefit assessment for users, directly showing the estimated CBM by inputting given ports and assessment cost values (Figure 8).

For example, one of the simulation routes from the Port of Shanghai to the Port of Rotterdam (with a ship velocity of 14 kn) is displayed in Figure 8. The blue line beginning on the right denotes the voyage from the port of Shanghai to the Bering Strait (AD₁), which measures approximately 2990 nautical miles. The yellow line denotes the voyage between the entrance and exit points of the Bering Strait (AD₂), which measures approximately 763 nautical miles. The red line denotes the voyage through the Arctic Ocean (AD₃), which measures approximately 2209 nautical miles, and finally, the blue line denotes the voyage from the Barents Sea to the port of Rotterdam (AD₄), which measures 1718 nautical miles. Because the ship travelled at the same velocity for AD₁ and AD₄, the same color is used to indicate its speed, and the remaining voyages are marked using various colors 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 traditional Suez Canal route. Figure 8 shows the Northeast Passage and traditional Suez Canal route planned using Google Earth.

A cost evaluation table that compares the Arctic Northeast routes with traditional routes via the Suez Canal from five different ports in Asia to a European port is given below.

Table 1 Cost evaluation of two competing routes

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<th>Arctic Northeast routes</th>
<th>Benefit</th>
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<td>Distance (N mi)</td>
<td>Time (day)</td>
<td>Fuel (ton)</td>
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<tr>
<td>TOK -&gt; ROT</td>
<td>12222</td>
<td>36.9</td>
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<tr>
<td></td>
<td>26</td>
<td>841</td>
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<tr>
<td></td>
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<tr>
<td>BSN -&gt; ROT</td>
<td>11833</td>
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<tr>
<td></td>
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<td>880</td>
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<tr>
<td></td>
<td>43.3%</td>
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<td>SHA -&gt; ROT</td>
<td>11486</td>
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<td></td>
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<tr>
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<td>1002</td>
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Notes: BSN, Busan; HON, Honk Kong; SHA, Shanghai; TOK, Tokyo; ROT, Rotterdam; Discr., Discretionary; N mi, Nautical mile; $, US dollar.

The cost of each item in the table 1 is calculated using the cost formulas in section 3. The details about the cost analysis for Tokyo to Rotterdam in the Table 1 are described in the following figures 9(a), 9(b), 9(c) and 9(d), where 9(a) is a calculation list for time cost, 9(b) for fuel cost, 9(c) for discretionary cost, and 9(d) is the total voyage cost & benefit margin.
In addition, the higher insurance rate, maintenance costs, crew costs can be considered as the discretionary cost; however, they are not yet included in this case. It will be added into dynamic cost estimate because the cost function and cost value may change with time (For instance, after 1st actual navigation trip). 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. Combining the five ports in Asia and three European ports generates 15 possible routes. As can be clearly evaluated and shown on our website, the average benefit assessment is around 30%~45% for the bulk carrier examples. The shipping costs of the various routes were assessed based on the voyage cost function including 11 formulas from (1) to (11). It is worth noting that the NEP is higher unit of goods transported than the classical route since the size/capacity of ships travelling through NEP is usually much smaller than the ships plying the classical route.

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 sea ice distribution data provided by Google Earth and a higher-geometry maze routing algorithm with turn penalties were also employed. The newly planned optimal routes comprised various routes that depart from major Asian 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 costs of some of these factors vary over time, dynamic costs must also be evaluated. In practice, the practical 3D Arctic route planning should be implemented in an accredited IMO ECDIS system to provide users an alternative method of clearly displaying and presenting the current navigational paths. In addition, before travelling these routes, assessments from environmental specialists are required. Currently, the use of icebreakers is regulated by the Russian Northern Sea Route Administration, which allows states to regulate maritime activities in Arctic ice-covered waters because crossing the Arctic Ocean is not merely a cost-benefit issue, but also involves the care and protection of the marine environment.

APPENDIX A

The input for the 4-geometry maze router is a cell map, the source (S) and destination (D) and the output path is a minimum cost value in weighted regions of cell map.

Algorithm: 4-geometry-maze-router (Cell-map, S, D, LL\textsubscript{path})

Input: Cell-map, S, D

Output: LL\textsubscript{path}

Step 0: Initialization:

For each cell $C_{i,j}$ ($RW_{i,j}$, $AT_{i,j}$, $Vis_{i,j}$) in an $m \times n$ cell map, the initial $RW_{i,j}$ value is 1 if the cell $C_{i,j}$ is in the free space or $\infty$ if $C_{i,j}$ is in the barrier. If the parameter $RW$ of any cell has a finite value between 1 and $\infty$, the cell belongs to one of the weighted regions. $AT_{i,j} = \infty$ and $Vis_{i,j} = false$ for all cells, $0 \leq i \leq m-1$, $0 \leq j \leq n-1$. The initial value of index is 0. $path-exists = FALSE$;

Step 1: Input the coordinates of a given-source, S. If $RW_{i,j}$ of the source cell is not equal to $\infty$, then update $AT_{i,j} = 0$, else return the error message “The source cell is in the barrier” and terminate.

Step 2: Compute the number of required buckets.

Step 2.1: Determine the required index number (buckets) of the linked list $LL_{index}$.

$$index\_no = (\sqrt{2} \times RW_{max}) / 10 + 2,$$

where $RW_{max}$ is the
maximum $RW$ in the weighted regions.

Step 3: Compute the time of arrival between the source cell and the remaining cells.

Step 3.1: Move the source cell into the temporary list $TL$ and update the source cell’s $Vis_{i,j}$ to true.

Step 3.2: Remove the source cell from the $TL$ into the bucket $LL_0$.

Step 3.3: For each cell in the $LL_{index}$, update the $AT_{i,j}$ of its neighboring cells.

Step 3.3.1: Remove the index of the first cell $C_{i,j}$ from the front end of the $LL_{index}$ and update this cell’s $Vis_{i,j}$ to true.

Step 3.3.2: Update the $AT_{i',j'}$ value of the 4-geometry neighbors of cell $C_{i,j}$.

Case 1: If $|i' - i|^2 + |j' - j|^2 = 1$,

then $New\_AT_{i',j'} = AT_{i,j} + 1 \times (RW_{i,j} + RW_{i',j'}) / 2$

Case 2: If $|i' - i|^2 + |j' - j|^2 = 2$,

then $New\_AT_{i',j'} = AT_{i,j} + \sqrt{2} \times (RW_{i,j} + RW_{i',j'}) / 2$

If $New\_AT_{i',j'} < AT_{i',j'}$, then $AT_{i',j'} = New\_AT_{i',j'}$.

Step 3.3.3: Iterations

If $LL_{index}$ is not empty, then go back to steps 3.3.

Step 3.4: Move the cells’ indices in the $TL$ into their corresponding buckets.

Step 3.4.1: For all the indices in the $TL$, move $(i,j)$ from $TL$ into $LL[AT_{i,j}]_{mod\_index\_no}$

Step 3.4.2: If the $TL$ is empty, then update the $index$ value

$$index = (index + 1) \mod index\_no.$$ 

Step 3.5: Iterations
if $D$ cell in $LL_{index}$ then

    {
        $path-exists =$ TRUE;
        break Step 3;
    }

If rest of buckets is not empty, then repeat steps 3.3.

if ($path-exists =$ TRUE) then    RETRACE ($Cell$-map($AT_D$), $LL_{path}$);
else path does not exist;

6. References


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