8-23-2020

Navigation risk evaluation of the Northeast Passage based on the Entropy Weight TOPSIS Model

Fengde Qu

WORLD MARITIME UNIVERSITY

Dalian, China

NAVIGATION RISK EVALUATION OF THE NORTHEAST PASSAGE BASED ON THE ENTROPY WEIGHT TOPSIS MODEL

By

Qu Fengde

A dissertation submitted to the World Maritime University in partial Fulfillment of the requirements for the award of the degree of

MASTER OF SCIENCE

In

MARITIME SAFETY AND ENVIRONMENT MANAGEMENT

2020

DECLARATION

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

Signature:

Date:

Supervised by: Professor Wang Fengwu

Dalian Maritime University

ACKNOWLEDGEMENTS

First of all, I would like to extend my heartfelt gratitude to DMU for providing me such a valuable opportunity. As a matter of fact, I participated the ESSP of WMU in 2017, and I was deeply attracted by this university. At that time, I had made my decision that I would obtain my master degree here. Today, my dream has come true.

This dissertation cannot be completed without the careful guidance from Professor Wang Fengwu. I want to express my sincere thanks to him, who offered me critical guidance and constructive suggestions when I was writing this dissertation. His profound scientific knowledge and rigorous academic spirit have deeply influenced me, and he will always be my model for my future work and study.

I wish to show my special appreciation to my DMU colleagues and classmates, especially Mr. Zhao Jian and Mrs. Zhao Lu. In this 14 months, something happened in my family. It is them who gave me great help and support when I was in trouble.

Moreover, I am profoundly grateful to my families. Thanks to my parents for raising me up and teaching me how to be an upright man. Special thanks would go to my wife and my newborn son. You are the propeller of my life and you make my life more meaningful. Your selfless love and care will urge me to keep on striving.

ABSTRACT

Title of Dissertation: **Navigation Risk Evaluation of the Northeast Passage Based on the Entropy Weight TOPSIS Model**

Degree: **Master of Science**

With the continuous warming of the global climate, the Arctic sea ice is melting at an accelerating speed, which makes the opening of the Arctic Passages become reality. As one of the most important Arctic Passages, the opening of the Northeast Passage (NEP) will greatly shorten the distance between China and Europe, which will bring great strategic value and commercial benefits to China. Therefore, since M/V “Yongsheng” successfully transited the NEP in 2013, more and more Chinese ships have chosen this route. By now, COSCO SHIPPING, China, has taken the majority of the portion of the transit shipments of the NEP. However, due to the special geographical location, the navigation environment is a significant factor affecting its commercial use and navigation safety. Therefore, this dissertation will analyze and evaluate the navigation environment of the NEP.

As a crucial part of the NEP, the Northern Sea Route (NSR) determines whether the NEP can be realized to navigate. Hence, this dissertation introduces the NSR briefly, based on analyzing the factors that affect the navigation environment, the risk evaluation system is established, and in the end the Entropy Weight TOPSIS Model is used to evaluate the risk extent. In order to make the evaluation results more scientific and reasonable, the whole chosen route will be divided into 9 Legs, the navigation environment of each Leg will be analyzed, and the navigation environment of different Legs will be compared, so as to find out the main Leg that restricts navigation of the NSR.

KEY WORDS: Navigation Risk Evaluation, Northeast Passage, Entropy Weight TOPSIS Model

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATION

AFoPS	Asian Forum for Polar Sciences
AIS	Automatic Identification System
ANSR	Northern Sea Route Administration
ARCDEV	Arctic Demonstration and Exploratory Voyage
AREOP	Arctic Operational Platform
CCS	China Classification Society
CNARC	China-Nordic Arctic Research Center
CNIMF	Central Marine Research & Design Institute of Russia
ECDIS	Electronic Chart Display and Information System
FNI	Fridt of Nansen Institute of Norway
GMDSS	Global Maritime Distress and Safety System
GPS	Global Positioning System
HEL-L	International Association of Classification Societies
IACS	Light Helicopter
IASC	International Arctic Science Committee
IMO	International Maritime Organization
INSROP	International Northern Sea Route Programme
LRG	Long-range aircraft
MEPC	Maritime Environmental Protection Committee
MRCC	Maritime Rescue Coordination Centre
MRSC	Maritime Rescue Subcenters
MSC	Maritime Safety Committee
NASA	National Aeronautics and Space Administration
NEP	Northeast Passage
NIS	Negative Ideal Solution
NSR	Northern Sea Route
NWP	Northwest Passage
PIS	Positive Ideal Solution

RB	Rescue boat
RV	Rescue vessel
SAR	Search and rescue
SOF	Ship & Ocean Foundation of Japan
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution
TSR	Transpolar Sea Route
TSS	Traffic Separation Scheme
UN	United Nations
UNCLOS	Convention on the Law of the Sea
VTS	Vessel traffic service
WMO	World Meteorological Organization

CHAPTER 1: INTRODUCTION

1.1 Background

At present, the global climate continues to become warmer, according to the World Meteorological Organization (WMO) (2019), all 20 of the warmest years on global temperature record have occurred in the past 22 years. In the last four years, they have occupied the top four positions, both the global highest temperatures and the high-temperature durations in the north of the Arctic Circle hit the record. As a result of climate warming, sea ice coverage and thickness in the Arctic waters continue to decrease, since 1979, the annual average sea ice in Arctic waters has seen a dramatic decline, with a rate of 3.5 to 4.1% per decade, while 9.4 to 13.6% per decade of summer sea ice (Intergovernmental Panel on Climate Change, 2014). All ten of the lowest Arctic sea ice extent minimal have occurred in the last 11 years (2006 - 2016) (Catherine, 2016). On the basis of the observed trend, it is estimated that 20 years later, the Arctic shelf seas will be ice-free periodically, and the seasonally ice-covered waters will extend further south, by the 2050s, it will be ice-free all year round (Onarheim, Eldevik & Smedsrud, 2018). Besides the observed changes, several sea-ice prediction algorithms have been developed, such as the National Aeronautics and Space Administration (NASA) Team algorithm, all of which give such similar prediction results (AMAP, 2017). Therefore, nowadays, the Arctic shipping routes have become the focus of the world's attention, and people are having a heated discussion on them.

According to satellite images taken by NASA, at the end of summer 2008, both the Northeast Passage (NEP) and the Northwest Passage (NWP) had become navigable for the first time (*Both Routes,* 2008). This historical event had led to the realization that the Arctic shipping routes would become commercially navigable in the near future. In late July 2009, two German heavy-lift ships, M/V “Beluga Fraternity” and M/V “Beluga Foresight”, departed from Ulsan, South Korea, along Russia’s Arctic coast to Siberia, Russia, successfully passed through the NEP, and finally arrived at the Port of

Rotterdam, Netherlands (Matt & Seth, 2009). The successful completion of this voyage marked the successful transition from theory to the practice of Arctic navigation researches. With the continuous melting of sea ice in the Arctic Ocean, the navigation environment in the Arctic waters is gradually improving, and the number of commercial ships passing through the NEP is increasing as well. According to statistics, only two ships had transited the NEP in 2009 as introduced above, four transit voyages were made in 2000, and there was a significant increase to 34 voyages in 2011, even though there was a slight decrease in 2014 and 2015 subsequently (Alexei, 2019), it can be seen that there was still a rising tendency in ships transiting the NEP.

The opening of the NEP is of strategic significance to the shipping industry of China. In 2013, M/V "Yongsheng", which was owned by COSCO SHIPPING, started her voyage from Dalian, China, transited the NEP and arrived at the port of destination Rotterdam, Netherlands, with a total of 7,931 nautical miles travelled in 27 days. Compared with the traditional shipping routes passing through the Strait of Malacca and the Suez Canal, as shown in Figure 1, the voyage was shortened by about 2,800 nautical miles and nine days in time spent on the voyage. Therefore, this new route will dramatically reduce CO_2 emission, save much more fuel and transportation time for shipowners (*NSR 2010*, 2010). It is also the reason why Chinese company COSCO SHIPPING has taken the majority of the portion of the transit shipments in recent years (Atle, 2019). From 2013 to 2017, there were a total of ten ships that had been dispatched by COSCO SHIPPING to complete 14 voyages that transited the NEP. Compared with the traditional shipping routes, the voyages were shortened by approximately 67,390 nautical miles, saving 220.7 days of sailing dates and 6,948 tons of fuel, and the total cost saving was nearly $9.367 million.

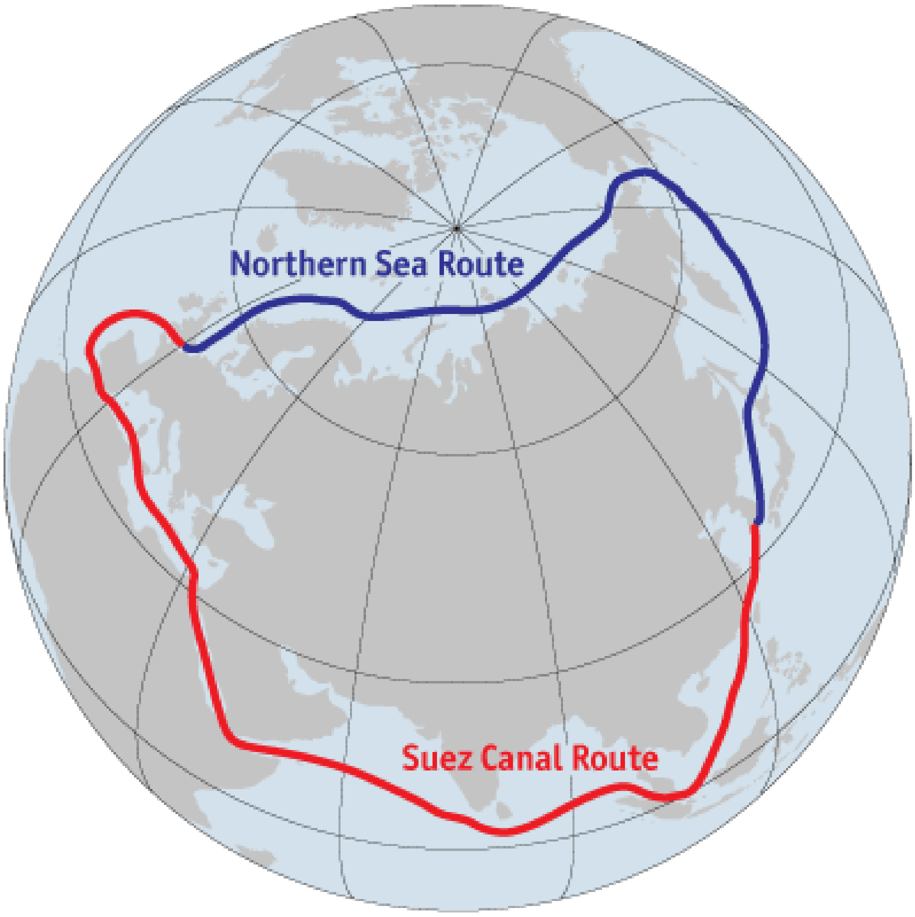


Figure 1 - The Northeast Passage and the Suez Canal Route

Source: The Northern Sea Route, 2014

Even though more and more ships choose the NEP, the harsh climatic conditions, poor navigational facilities and infrastructures, complex geographical environment, lack of navigation experiences, etc. make it difficult and dangerous to navigate in the Arctic waters. In this paper, based on analyzing several significant factors that will influence the safe navigation in the NEP, an evaluation index system will be established, and the safety extent of navigating in the NEP will be evaluated further, which will provide a reference for navigation and the development of the NEP in the future.

1.2 Literature Review

Research on Arctic navigation began in the 1990s, which was started by eight Arctic countries, namely Canada, the United States, Russia, Sweden, Denmark, Norway, Iceland and Finland. The governments and organizations undertook collaborative research, which involved political status, strategic significance, and environmental protection and the like. In 1990, the International Arctic Science Committee (IASC), a non-governmental, international scientific organization, was founded in Canada, which aimed to encourage and facilitate the cooperation of Arctic research, and guide and coordinate Arctic expeditions of each country (*About IASC*. n.d.). From 1993 to 1999, the International Northern Sea Route Programme (INSROP) was jointly developed and coordinated by Central Marine Research & Design Institute of Russia (CNIMF), Ship & Ocean Foundation of Japan (SOF), and the Fridt of Nansen Institute of Norway (FNI). The INSROP included four sub-programmes, which analyzed factors such as natural conditions, environment, politics, laws and regulations, etc. relating to the Northern Sea Route (NSR) of Russia, and carried out the economic analysis of bulk carrier of 25,000 DWT, 35,000 DWT and 50000 DWT as well (Brubaker & Ragner 2010). In September 1996, the Arctic Council was established in Ottawa, Canada, by the USA, Canada, Russia and five Nordic countries, whose aim is to protect the Arctic environment and promote sustainable development in the economy, society and welfare in the region. By now, besides the eight Arctic States, additional six permanent participants, six working groups and 38 observers are in the Arctic Council (*ARCTIC COUNCIL*, n.d.). In 2015, China became one member of the 38 observers. One of the most significant tasks of the Arctic Council is to assess the Arctic marine shipping. In 2009, the Arctic Marine Shipping Assessment - 2009 Report was published, which introduced the current situations including geography, climatic, history, governance and the like of Arctic marine shipping, forecasted the development prospects of 2020, analyzed the impacts of Arctic marine shipping on the environment (AMSA, 2009). The Arctic Council also published reports relating to sustainable development, Arctic marine environment protection and so on.

In April 1998, in order to demonstrate the technical feasibility of transporting petroleum and natural gas from Russia Arctic to Western Europe by sea, the Arctic Demonstration and Exploratory Voyage (ARCDEV) project was funded by European Commission and achieved by the leading European industry and research institutes. In this project, escorted by two icebreakers, the tanker “M/T Uikku” transported gas condensate from the Port of Murmansk in Russia to Rotterdam in the Netherlands, more than 70 scientists from 7 countries aboard the research platform “Kapitan Dranitsyn” evaluated the ship performance, the ice parameters and navigational aids in the Arctic and concluded that even with very severe ice conditions, transporting by sea is still feasible in this area (*Final public report*, 1999). In December 2002, a three-year research project: Arctic Operational Platform (AREOP) was commenced by seven countries including Finland, Netherlands, Germany, UK, Italy, Russia and Norway, which studied the means of collecting and forecasting the ice information of sea routes, discussed relevant marine insurance, traffic laws and regulations, assessed impacts on the environment and emergency response, etc., and came to a conclusion that transporting oil and gas through the Russia Arctic was technologically possible and economically feasible (Juurmaa, 2006). In the following years, with increasing attention to Arctic activities, a number of organizations and research institutes were established all around the globe. For instance, the Asian Forum for Polar Sciences (AFoPS) that was established in 2004, the Arctic Institute of South Korea that was founded in 2011, the China-Nordic Arctic Research Center (CNARC) that was set up in 2013 and so forth.

The International Maritime Organization (IMO), as a specialized agency within the United Nations which is responsible for the safety of shipping and the prevention of marine pollution by ships, performs a significant role in guiding activities of ships in Arctic waters. In 2002, guidelines for ships operating in Arctic ice-covered waters were published by IMO, which described that for the sake of the safety of ships navigating in Arctic ice-covered waters as well as pollution prevention, some specific rules had to be followed from aspects on construction, equipment, operational, environmental protection and damage control (IMO, 2002). However, they were only recommendatory guidelines rather than mandatory. According to the requirements of the guidelines, the International Association of Classification Societies (IACS) organized researches and prepared corresponding uniform requirements, ten of the world's leading classification societies including China Classification Society (CCS) were involved. In 2006, the unified Requirements concerning POLAR CLASS were issued (IACS, 2006). In December 2009, the Guidelines for ships operating in polar waters (IMO, 2009) were adopted by IMO on the Assembly 26th sessions. In addition to the existing requirements of the SOLAS Convention and the MARPOL Convention, safety and pollution prevention-related measures have been developed to address the adverse navigation conditions and environmental challenges in polar waters. Still, these guidelines were recommendatory rather than mandatory. With the increasing demand of the shipping industry in the polar waters and the increasingly fierce competition among the countries around the polar region for the polar natural resources, IMO realized that it was necessary to introduce a law with a strong force to regulate the shipping activities in the polar waters as well as protect the ecological environment. As a result, IMO adopted the Polar Code, short for the International Code of Safety for Ships Operating in Polar Waters by Resolution MSC.385 (94) of the Maritime Safety Committee (MSC) (IMO, 2014a) and Resolution MEPC.264 (68) of the Maritime Environmental Protection Committee (MEPC) (IMO, 2015a) respectively. Furthermore, in order to strengthen the Polar Code, two amendments were adopted respectively towards the SOLAS Convention (IMO, 2014b) and the MARPOL Convention (IMO, 2015b). Ultimately, the Polar Code went into effect on January 1st, 2017, marking a milestone on navigational safety of ships and protecting the polar environment.

In addition to countries and organizations, experts and scholars from various countries have done researches in different fields and achieved certain achievements in the study of Arctic shipping. These research data and results play a guiding role in the future application of Arctic shipping routes and the guarantee of navigation safety. By now, numerous feasibility studies of shipping along Arctic Passage have been carried out. Such studies are often centered on the Arctic sea ice changes (Smith & Stephenson, 2013; Polyakov, Walsh & Kwok, 2012) and predictions (Calla et al., 2016; Reid &

Tarantino, 2014), this is because the sea ice is the biggest problem for navigating in the Arctic waters. From the perspective of economic feasibility, some scholars have identified the situations on what type of ships will be economically viable, especially for containers (VERNY & GRIGENTIN, 2009; Cariou et al., 2019). Moreover, plenty of safety evaluation studies of shipping along the Arctic Passage have been conducted. Such studies are focused on the evaluation methods, such as fuzzy comprehensive evaluation (Yao, 2015), Cloud Model (Ding, 2014), Rough Set theory (Wang et al., 2017) and the like. These methods can be used to systematically analyze the navigation conditions of the Arctic Passages and conclude the main factors affecting the navigation environment, and then establish the evaluation index system to find out the evaluation results, which enriches the related theoretical research on the Arctic shipping. Furthermore, the governance of Arctic shipping is as well a heated discussed issue. The rich natural resources, huge business value and important military strategic position in the Arctic region have been highlighted, and the dispute over rights and interests in the Arctic has become increasingly fierce, both of which make it complicated to governance (AMSA, 2009; Robert et al., 2017).

CHAPTER 2: ARCTIC PASSAGES

2.1 Introduction of the Arctic Passages

The Arctic Passages are sets of shipping routes that connect the Atlantic and the Pacific Ocean via the Arctic Ocean. As stated in AMSA (2009), the Arctic Passages comprise two main routes, to be more specific, they are NEP and NWP.

The NEP is the name given to "the set of sea routes from northwest Europe around North Cape (Norway) and along the north coast of Eurasia and Siberia through the Bering Strait to the Pacific" (AMSA, 2009). Most of the NEP is in Russian waters, as is shown in Figure 2. The NWP is described as "various marine routes between the Atlantic and Pacific oceans along the northern coast of North America that span the Canadian Arctic Archipelago" (AMSA, 2009), as is shown in Figure 3.

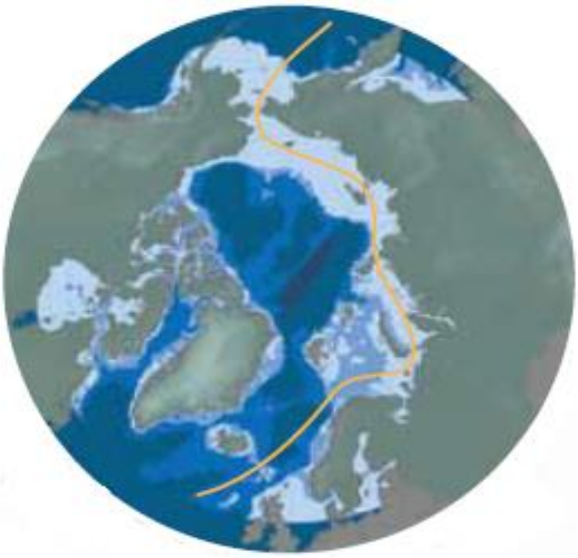


Figure 2 - The Northeast Passage

Figure 3 - The Northwest Passage

In addition, Transpolar Sea Route (TSR) has been proposed after the opening up navigation of the NEP and the NWP (Malte & Andreas, 2012), which is defined as a future Arctic shipping route running from the Atlantic Ocean to the Pacific Ocean across the center of the Arctic Ocean ("Transpolar Sea Route", n.d.). It is the most direct route to transit the Arctic, hence, it is also called Trans-Arctic Route at times, as is shown in Figure 4. The TSR is located on the high seas, which does not need to pass through the NEP that is controlled by Russia and the NWP that is controlled by Canada. Currently, the TSR is mainly used in scientific research and tourism.

Figure 4 – The transpolar Sea Route
Source: The Arctic Portal, 2012

Compared with the harsh navigation environment of the NWP and the TSR, the ice conditions and geographical conditions along the NEP are more suitable for navigation, in the meantime, supporting facilities such as the port infrastructures, supply, icebreakers, and other aids to navigation are relatively complete (Østreng et al., 2013), the navigable window is much longer all year round as well (Ma et al., 2019). Besides, the NEP is the shortest sea route connecting China and Europe.

2.2 Differences between the NEP and the NSR

People are having a long time confusing between the NEP and the NSR. In the 1930s, the NSR Administration was set up by the Soviet Union (Hunt, 2016). However, it did not attract the attention of the international community. After the collapse of the Soviet Union, the NSR was generalized by Russia. As described in AMSA which is the most authoritative explanation (2009),

> The NSR is defined in Russian Federation law as a set of marine routes from Kara Gate (south of Novaya Zemlya) in the west to the Bering Strait in the east. Several of the routes are along the coast, making use of the main straits through the islands of the Russian Arctic; other potential routes run north of the island groups, as is shown in Figure 5.

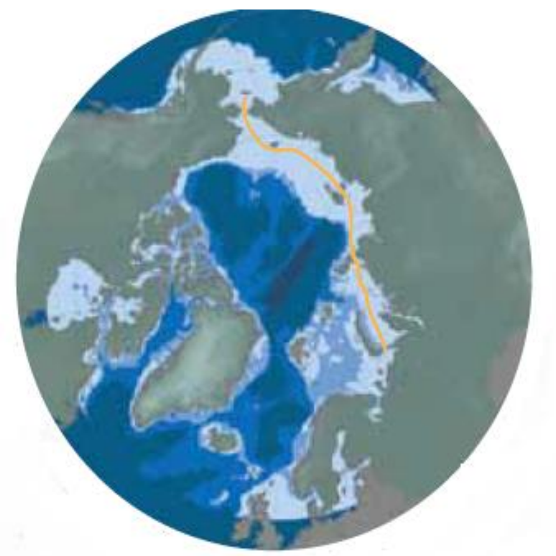


Figure 5 - The NSR

Figure 6 - The NEP and the NSR

Thus it can be seen that technically speaking, the NSR is a part of the NEP, as is shown in Figure 6. At present, the NEP has realized year-round navigation from Northern Europe to the Barents Sea. In contrast, due to the harsh navigation environment in the NSR, the navigation time is mainly concentrated in the summer, and it is not suitable for navigation in other seasons. Therefore, it follows that the navigation through the NEP mainly depends on the conditions of the NSR. This dissertation will mainly analyzes from the perspective of the navigation environment.

2.3 Introduction of the NSR

Geographically, the NSR spans across five Arctic Seas from Siberia and the Far East. To be more specific, they are the Barents Sea, the Kara Sea, the Laptev Sea, the East Siberian Sea and the Chukchi Sea (Arctic Bulk, n.d.), as is shown in Figure 7.

Figure 7 - The sketch plan of the NSR

Source: Freight week, 2016.

2.3.1 The Barents Sea

The Barents Sea is the westernmost part, which is 1,300 km long and 1,050 km wide, and covers 1,405,000 square km, as shown in Figure 8. Its average depth is 229 m, maximum depth is 600 m near the Bear Island Trench. The climate is subarctic, with the mean summer temperature 0° C in the north and 10° C in the south; and the mean winter temperature -25° C and -5° C respectively. Influenced by the warm currents that are brought by the North Cape and Spitsbergen branches of the Norway Current, even though located at higher latitude, the seawater temperature of the Barents Sea is relatively higher. Ice will form every year, but the ice layer is relatively thin, which is mostly fresh ice. The southwest part of the Barents Sea can achieve year-round ice-free, where can be navigable throughout the year. The current amplitude and direction change significantly (Barents Sea, 2019).

Figure 8 - The sketch plan of the Barents Sea

Source: Worldatlas.com

2.3.2 The Kara Sea

The Kara Sea is located off western Siberia, which is connected with the Barents Sea and the Laptev Sea. The overall length is about 1450 km, and the width is about 970km, and it covers 880,000 square km, as is shown in Figure 9. The average depth is 127 m, and the maximum depth is 620 m. The winter temperature averages are from -28° to -20°, and the summer averages are from -1° to 6° C. In winter there are frequent gales and snowstorms, in summer there are snow, snow squalls, and fogs. For most of the year, the sea is covered with ice (Kara Sea, 2014). Overall, it is navigable from the beginning of August to the end of October each year, still in extreme circumstances, the navigation time can be advanced to the end of July and extended to the beginning of November, even possible in June with the help of icebreakers.

Figure 9 - The sketch plan of the Kara Sea

Source: Worldatlas.com

3.3.3 The Laptev Sea

The area of the Laptev Sea is about 714,000 square km, the average depth 578 m, and the greatest depth 2,980 m, as is shown in Figure 10. There are around 11 months in the north and nine months in the south that the air temperature is below 0° C. The winter air temperatures averages vary from -31° C to -34° C and the mean temperatures in summer vary from 0° C - 6° C. Winter brings frequent gales, blizzards, and snowstorms; and summer brings snow squalls and fogs. For most of the year, the sea is covered with ice. In the winter, the sea temperature is just below the freezing point, about -0.8° C to -1.7° C. In the summer the sea temperature warms to above 0° C (Laptev Sea, 2012). On the whole, the Laptev Sea is usually ice-free in August and September, which allows ships to navigate freely. However, due to the melting of large pieces of sea ice, a large amount of floating ice accumulates in the northwest, which has a certain impact on the safe navigation of ships. Ice begins to form in mid-September or early October, but the ice is thin, and ships can make short voyages with the assistance of icebreakers.

Figure 10 - The sketch plan of the Laptev Sea

Source: Worldatlas.com

2.3.4 The East Siberian Sea

The East Siberian Sea is the marginal sea of the Arctic, with approximately 936,000 square km, which is covered by ice much of the year, as is shown in Figure 11. Since the sea is almost entirely on the continental shelf, the overall depth of the water is relatively shallow, with the average depth about 45 m, and the greatest depth 155 m, but in some places, it is as shallow as 9 to 20 m (East Siberian Sea, 2011). The climate in this area is quite variable. The southeastern sea is affected by low pressure frequently, which leads to shorter winter and earlier melting of sea ice. The western sea is largely ice-free in summer, while the eastern part has always floating ice. Generally speaking, as the temperature rises from May, the ice sheet in the East Siberian Sea begins to melt. July to September is the best navigation period, but sometimes the icebreaker is still needed. It starts to freeze in October. At the same time, fog often occurs in summer.

Figure 11 - The sketch plan of the East Siberian Sea

Source: Worldatlas.com

2.3.5 The Chukchi Sea

The Chukchi Sea covers around 582,000 square km. The average depth is 77 m and 56% of the sea area is less than 50 m in depth, as is shown in Figure 12. The sea is navigable between July and October both eastward and westward from the shallow Bering Strait, and often the sea is foggy in summer (Chukchi Sea, 2018). Normally, the Chukchi Sea is the most difficult section of the NEP (Roucek, 1983).

Figure 12 - The sketch plan of the Chukchi Sea

Source: Worldatlas.com

2.4 The Main Straits in the NSR

As many as 58 straits are connecting the seas in the NSR, owing to the different climatic characteristics of different sea areas, the geographical features, ice conditions, navigability, etc. vary greatly among of the straits. Four of the mains straits will be analyzed below.

2.4.1 The Kara Strait

The Kara Strait is a very significant shipping strait between the Barents Sea and the

Kara Sea, which separates Novaya Zemlya and Vaygach Island, as is shown in Figure 9. The total length is about 18 nautical miles, 56 km wide, and a minimum depth 21 m. The northeast entrance is scattered with islands, and the coastal entrance is covered with rocks, so a Traffic Separation Scheme (TSS) had been set up (AMSA, 2009). Strong tidal waves, fog, lots of drifting ice and other harsh conditions make navigation pretty difficult. The sea ice usually begins to melt in late June and enters an ice-free period in early August. As the weather gets colder, ice floes began to appear in late October.

2.4.2 The Vilkitsky Strait (Vilkitshogo Strait)

The Vilkitskiy Strait is the northernmost and the shortest strait between the Kara Sea and the Laptev Seas, as is shown in Figure 10, with 60 nautical mile length, 100-200 m depths, and minimum width 54 km (AMSA, 2009). The strait freezes in winter, but ice is rarely encountered during the navigable window. Summer brings fog often. Generally speaking, the sea area near the Zemlya Peninsula is suitable for navigation.

2.4.3 The Sannikov Strait

The Sannikov Strait connects the Laptev Sea and the East Siberian Sea, as shown in Figure 10, with a total length of 160 nautical miles, minimum depths of 13 m, minimum width 57 km (AMSA, 2009). It is not hard to navigate eastbound while navigating westbound is difficult because offshore winds move the ice floes. In late July, the shore ice begins to break up and melt, and strong easterly winds often bring large amounts of sea ice into the strait, which has an influence on safe navigation. September is the best time for navigation, and by early October, the Sannikov Strait begins to freeze.

2.4.4 The Long Strait

The Long Strait is the only strait between the East Siberian Sea and the Chukchi Sea, which has a 120-nautical mile southern route along the coast with 20 m minimum depths; and a 160-nautical mile northern route with 33 m minimum depths (AMSA, 2009), the total width is approximate 139 km. All ships passing through the NSR have to pass through it. Influenced by the ice floe, the ice in the Strait is harsh and complex. Therefore, ships shall proceed cautiously along the coast under the guidance of aids to navigation. In some years, there will be no ice sheets in the Strait.

CHAPTER 3: INTRODUCTION OF ENTROPY WEIGHT TOPSIS

3.1 The Rationale of TOPSIS

The Technique for Order Preference by Similarity to an Ideal Solution, or TOPSIS, was first proposed by Hwang and Yoon (1981), which is a multi-criteria decision analysis method of ranking a finite number of objects according to how similar they are to an ideal solution. It can effectively achieve the order preference of a multi-object comprehensive evaluation.

TOPSIS is based on the rationale that the order preference is carried out by calculating the distance between the evaluation object and the Positive Ideal Solution (PIS) or the Negative Ideal Solution (NIS). If the evaluation object has the shortest distance from the PIS and the longest distance from the NIS, it is the chosen solution (Assari, Mahesh & Assari, 2012). Otherwise the versa. The PIS comprises all the best criteria values attainable, which means that all the indicators of the PIS reach the optimal value of each evaluation indicator; and the NIS comprises all the worst criteria values attainable, which means that all the indicators of the NIS reach the worst value of each evaluation indicator. (Aref, Javadian & Kazemi, 2012).

3.2 The Characteristics of TOPSIS

As one of the widely used method, TOPSIS has several advantages. The original data has to be standardization in the process of TOPSIS. It can eliminate the influences of different indicator dimensions, and make full use of the information of the original data, which could fully reflect the gap between the various alternatives, and objectively reflect the actual situation. Besides, the method of TOPSIS is simple, rational, comprehensive, and reliable, and it has no special requirements for sample data (Roszkowska, 2011). In addition, compared with single indicator mutual analysis, TOPSIS can reflect the overall situation, and analyze comprehensively, which is universally applicable. Inevitably, the disadvantages do exist as well. There are different problems in evaluating the risks of different types of issues. For instance, the weight information is given in advance, so the result has certain subjectivity. Furthermore, rank reversal problems exist due to adding a new alternative or changing the original data structure (Aires & Ferreira, 2019), which needs more in-depth analysis and research.

3.3 Introduction of Entropy Weight TOPSIS

In the process of multiple-objective comprehensive evaluation when using TOPSIS, one of the significant steps is to determine the weight. In order to reduce the subjectivity in this process, in the meanwhile, the advantages of the TOPSIS are retained, information entropy is put forward for weighting in this paper, and that is the reason why this method is called improved entropy weight TOPSIS. Improved entropy weight TOPSIS has become one of the most widely used methods of multi-criteria decision-making, which plays a great role in optimizing and improving risk management and control.

In the beginning, entropy is just a state parameter in thermodynamics. As is stated in Encyclopedia Britannica, it is the measure of a system's thermal energy per unit temperature that is unavailable for doing useful work (Gordon, 2018). Shannon (1948) introduced entropy into information theory, it could be used to measure the uncertainty degree of information emitted by the information source, and thus the theoretical basis of information measurement and transfer model was generated. The smaller the information in a message, the larger its uncertainty, and the larger its entropy. In a similar way, with the increase of the information in a message, its uncertainty and its entropy will decrease.

3.4 Evaluation Steps of the Entropy Weight TOPSIS Method

In the actual evaluation process, suppose there are m evaluation objects ($m=1,2,\cdots,m$), and there are n evaluation indicators ($n=1,2,\cdots,n$), based on the principle of combining qualitative and quantitative indicators, the original decision matrix A' of risk evaluation can be obtained as follow,

$$\mathrm{A}' = \begin{bmatrix} a_{11}' & a_{12}' & \cdots & a_{1n}' \\ a_{21}' & a_{22}' & \cdots & a_{2n}' \\ \vdots & \vdots & \vdots & \vdots \\ a_{m1}' & a_{m2}' & \cdots & a_{mn}' \end{bmatrix}$$

(1) Standardization of the original data of evaluation indicators

Owing to different dimensions and orders of magnitude of each indicator in the original matrix, to ensure the results of risk evaluation, it is necessary to standardize the original matrix, which could further establish the standardized decision matrix $A = \{a_{ij}\}$ ($0 < i \le m, 0 < j \le n$), in which a_{ij} is the standardized value of the j evaluation indicator of the evaluation objects i , $a_{ij} \in [0,1]$.

$$\mathrm{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}$$

The indicators in the original decision matrix A' include the benefit indicators and the cost indicators. To be more specific, a benefit indicator means the higher the indicator value, the better the evaluation result, and it is a positive indicator. On the contrary, a cost indicator means the smaller the indicator value, the better the evaluation result, and it is a negative indicator. The standardized formula of the original data of the benefit indicator can be described as:

$$a_{ij} = \frac{a_{ij}' - \min(a_{1j}', a_{2j}', \cdots, a_{mj}')}{\max(a_{1j}', a_{2j}', \cdots, a_{mj}') - \min(a_{1j}', a_{2j}', \cdots, a_{mj}')} \quad i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \quad (3.1)$$

The standardized formula of the original data of the cost indicator can be described as:

$$a_{ij} = \frac{\max(a_{1j}', a_{2j}', \cdots, a_{mj}') - a_{ij}'}{\max(a_{1j}', a_{2j}', \cdots, a_{mj}') - \min(a_{1j}', a_{2j}', \cdots, a_{mj}')} \quad i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \quad (3.2)$$

(2) Define the entropy of each evaluation indicator

After getting the standardization decision matrix $A = \{a_{ij}\}_{m \times n}$, define the weight is the ratio f_{ij}, which is the j indicator of the evaluation object i

$$f_{ij} = a_{ij} \Big/ \sum_{i=1}^{n} a_{ij} \tag{3.3}$$

(3) Calculation of the entropy of the indicators

$$H_j = -k \sum_{i=1}^{m} f_{ij} \ln(f_{ij}) \tag{3.4}$$

Here, k is the Boltzmann constant which is related to the sample number m, $k > 0$

Normally, $k = 1 \big/ \ln m$, $0 \le H_j \le 1$

(4) Calculation of entropy weight of evaluation indicators

Assumed that ω_j is the entropy weight of the evaluation indicator j, n is the total number of the indicators. Then

$$\omega_j = (1 - H_j) \Big/ (n - \sum_{j=1}^{n} H_j) \tag{3.5}$$

(5) Establish a weighted standardized decision matrix

Depending on the importance of each indicator, comprehensively considering the entropy weight of each indicator, a weighted standardized decision matrix can be obtained by

$$Z=(Z_{ij})_{m\times n}=(\omega_j a_{ij})_{m\times n} \quad (i\in m,\ j\in n) \tag{3.6}$$

(6) Establish the PIS and the NIS

The PIS and the NIS of risk evaluation indicators are calculated, which respectively establishes the PIS vector and the NIS vector.

$$S_j^+=\left\{\max_i Z_{ij}\right\} \quad j\in T_1; S_j^+=\left\{\min_i Z_{ij}\right\} \quad j\in T_2 \tag{3.7}$$

$$S_j^-=\left\{\min_i Z_{ij}\right\} \quad j\in T_1; S_j^-=\left\{\max_i Z_{ij}\right\} \quad j\in T_2 \tag{3.8}$$

Here T_1 is the benefit indicator and T_2 is the cost indicator.

(7) Calculate the distance from evaluation indicators to the PIS and the NIS

$$D_i^+=\sqrt{\sum_{j=1}^{n}(Z_{ij}-S_j^+)^2} \quad (i=1,2,\cdots,m) \tag{3.9}$$

$$D_i^-=\sqrt{\sum_{j=1}^{n}(Z_{ij}-S_j^-)^2} \quad (i=1,2,\cdots,m) \tag{3.10}$$

(8) Calculate the similarity to the ideal solution

$$P_i=\frac{D_i^-}{D_i^+ + D_i^-} \quad (i=1,2,\cdots,m) \tag{3.11}$$

After calculating the similarities of all the evaluation objects, the order preference can be built, and the larger the value of P_i, the better. Concerning the evaluation model of multi-level indicators, the evaluation results of the previous level indicators need to be composed into the initial matrix of the next level, then repeat the above steps, and further get the evaluation result of the next level.

CHAPTER 4: ANALYSIS OF FACTORS AFFECTING NAVIGATION SAFETY ALONG THE NEP

4.1 Introduction of the Human - Machine (Ship) - Environment System

Identifying the indicators is the most significant step of establishing the TOPSIS network. By analyzing the factors, it is found that there are many factors that impact the safe navigation of a ship passing through the NSR. The reasonable selection of these factors will directly affect the size of the network. Therefore, the principles of representativeness, reliability, comprehensiveness and independence will be followed when selecting these factors, all of which are the network indicators (Wang et al., 2017; Banu & Santhiyavalli, 2019).

When a ship is navigating along the NEP, it will encounter various threats brought by the severe environment. If one or some certain underlying factors are shown, serious consequences will occur, threatening the safety of the seafarers, cargo, and even leading to the loss of the ship.

A ship is a human - machine (ship) - environment system (Anghel & Belu, 2015), in which human is the operator of the ship, the ship is the object to be manipulated, and the environment is the various factors that affect human and the ship. They interact and influence each other, as shown in Figure 13. Therefore, in studying the risk evaluation of a ship navigating through the NEP, normally, the analysis will be made from three main aspects: human, ship and environment.

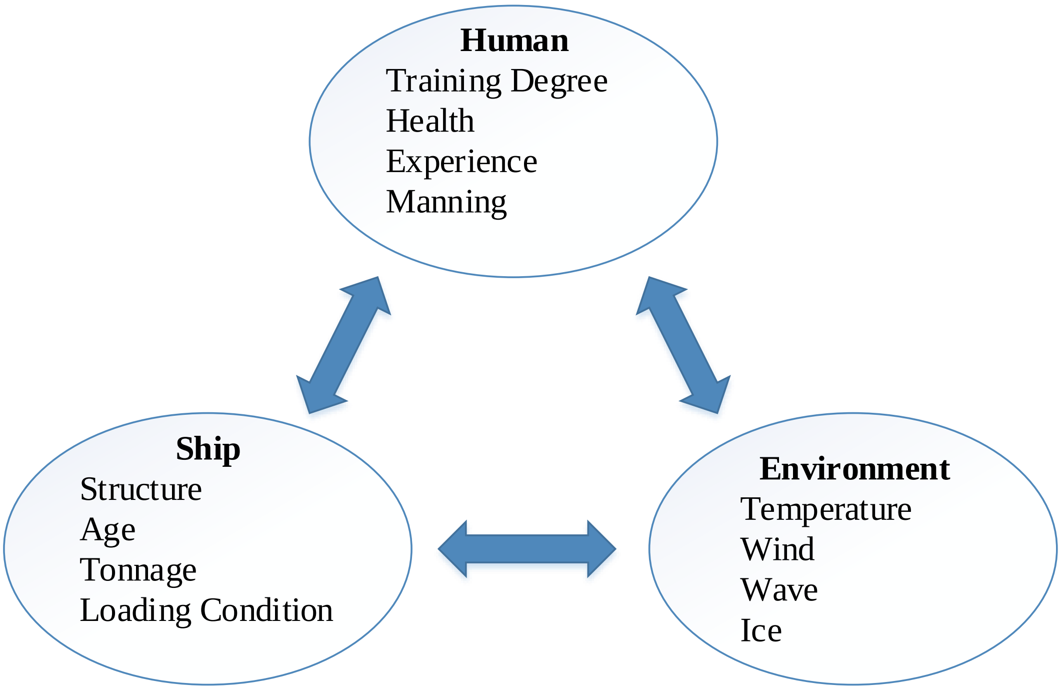


Figure 13 - The human- ship-environment system

Source: Author

However, as discussed above, the NEP is a newly developed route, in which the ship has to encounter the most hostile environment. To guarantee the navigation safety, the best trained and experienced seafarers will be manned, and in the meanwhile, the ship construction has to meet the strictest construction standards. Hence, in this dissertation, the human and ship factors will be left aside, that is, assume that the human and ship factors are 100% safe. More attention will be paid to environmental factors.

4.2 The Analysis of Environmental Factors

The environmental factors will be divided into four parts. To be more specific, they are meteorological factors, hydrology factors, geographical environments and other related factors.

4.2 1 Meteorological factor

Temperature

When navigating in the Arctic region, the temperature has the most impacts on the ship, which mainly reflects in the following three aspects. In the first place, low temperature causes the sea to freeze and further form ice, which directly affects navigation safety. In the second place, when the ship is navigating, the accumulate ice onboard the ship, which is caused by the waves, rain or snow in low temperature, will indirectly affect the ship's manoeuvrability. Lastly, it will bring inconvenience to the normal life and work of the seafarers, the poor state of the seafarers will affect the ship's operation. As can be seen from Figure 14 that from mid-June to late August, the mean temperature of the Arctic region can reach above 0 ℃.

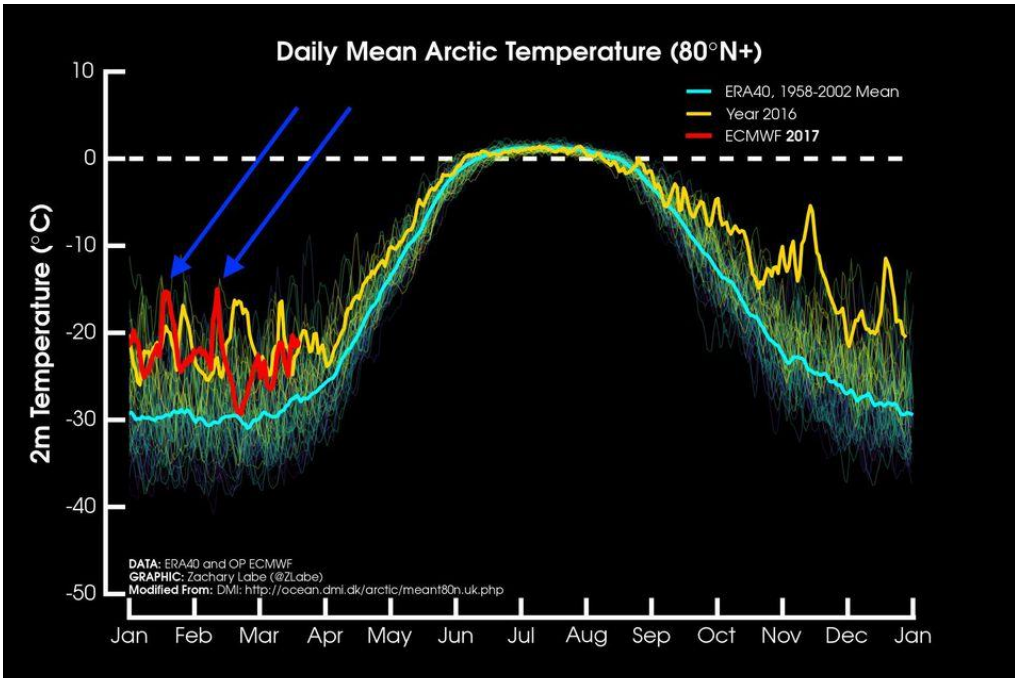


Figure14 - Daily mean Arctic temperature

Source: Freedman, 2017

Visibility

Visibility is a very significant factor affecting the navigation safety of ships in the Arctic region. It is easily affected by fog, sunlight duration, rain, snow, etc., especially when snowstorms together with wild winds and heavy snowfall approaches, the visibility will decrease sharply (Pastusiak, 2016, p.54). Fog is a major factor that gives rise to low visibility in the Arctic region. In summer when ships could pass through the

NSR, like July and August, advection fog is the most common type, which is caused by warm, moist air blows over the cooler sea surface. Besides, poor color contrast is another factor that should be taken into account. This is especially true when the surfaces of the objects are covered with snow, it is not easy to identify.

Wind

The wind has a great influence on the safe navigation of ships, especially in the case of a strong wind, it is easy to cause a ship to deviate from the original route, and grounding or other accidents may happen. When navigating in the NSR, wind can also move ice floes, posing a potential threat to ships. Moreover, when there is a strong wind at sea, the snow will fly and result in reduced visibility. Usually, the wind above 7 Beaufort scale will have effects on the safe navigation of ships. In Arctic waters, there are seldom stormy days, and the data from drifting ice stations shows that the average wind is about 3 Beaufort scale (NATO, 2007). Figure 15 shows the monthly mean wind speed of May 2020 in the Arctic region.

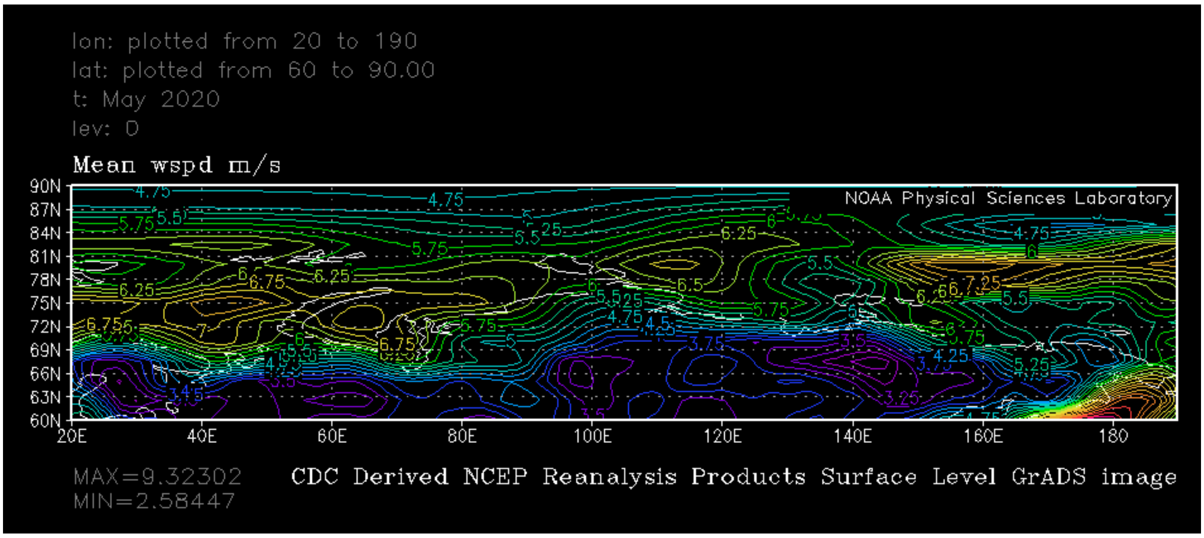


Figure15 - Monthly mean wind speed of May 2020

Source: NCEP Reanalysis Derived Products

4.2.2 Hydrology factor

Current

When floating at sea, ships are affected by current all the time. In the open water, current shall influence navigation efficiency, but it will not endanger the ship's safety. While in the restricted water, current may involve the ship into danger and even cause the risk of collision and grounding (Hong & Yang, 2012, p.83). Current has effects on ship speed over ground, stop distance, ship drifting movement and turning motion.

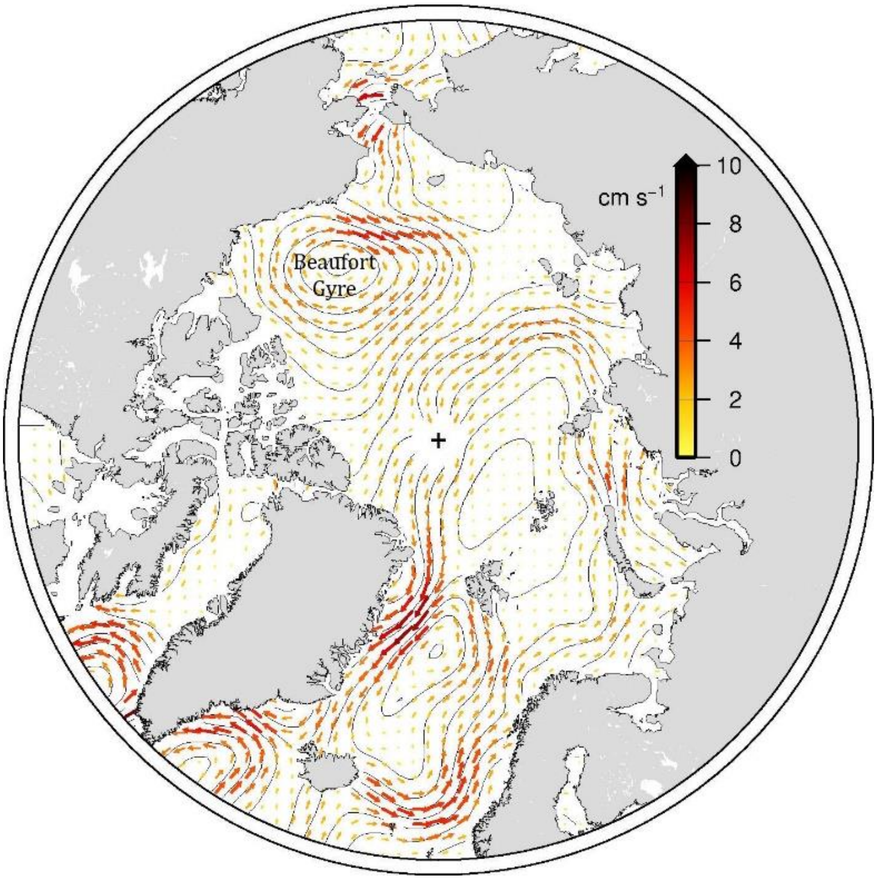


Figure 16 - Distribution of the Arctic current

Source: Armitage, 2020

As is shown in Figure 16, by and large, the current along the NSR flows from west to east. The strongest currents occur in the northwest of the Kara Sea and north of the Laptev Sea, approximately 3 knots.

Sea ice

Sea ice is one of the most primary features of Arctic waters. Among the factors affecting the navigation safety on the NSR, sea ice has a tremendous influence. According to the formation and development stage of sea ice, it can be divided into five types, as is shown in Table 1.

Table 1 - The features of different types of sea ice

Type of sea ice	Features
New Ice	Newly formed ice including frazil ice, grease ice, slush and so on.
Nilas	The thickness is no more than 10 cm and could be comprised of dark nilas and light nilas.
Young Ice	The thickness is around 10-30 cm, including grey ice (10-15 cm) and grey-white ice (15-30 cm).
First-year Ice	Less than a winter's growth, more than 30 cm but less than 2m, including thin first-year ice (30-70 cm), medium first-year ice (70-120 cm) and thick first-year ice (120-200 cm).
Old Ice	The formation period is greater than a summer's melt, including second-year ice and multiyear ice without thickness limited.

Source: *Sea ice: types and forms,* 2013

(1) Sea ice extent

Under normal circumstances, when sea ice extent is less than 15%, ships are able to navigate successfully, while when sea ice extent is larger than 15%, it will affect the navigation of the ship.

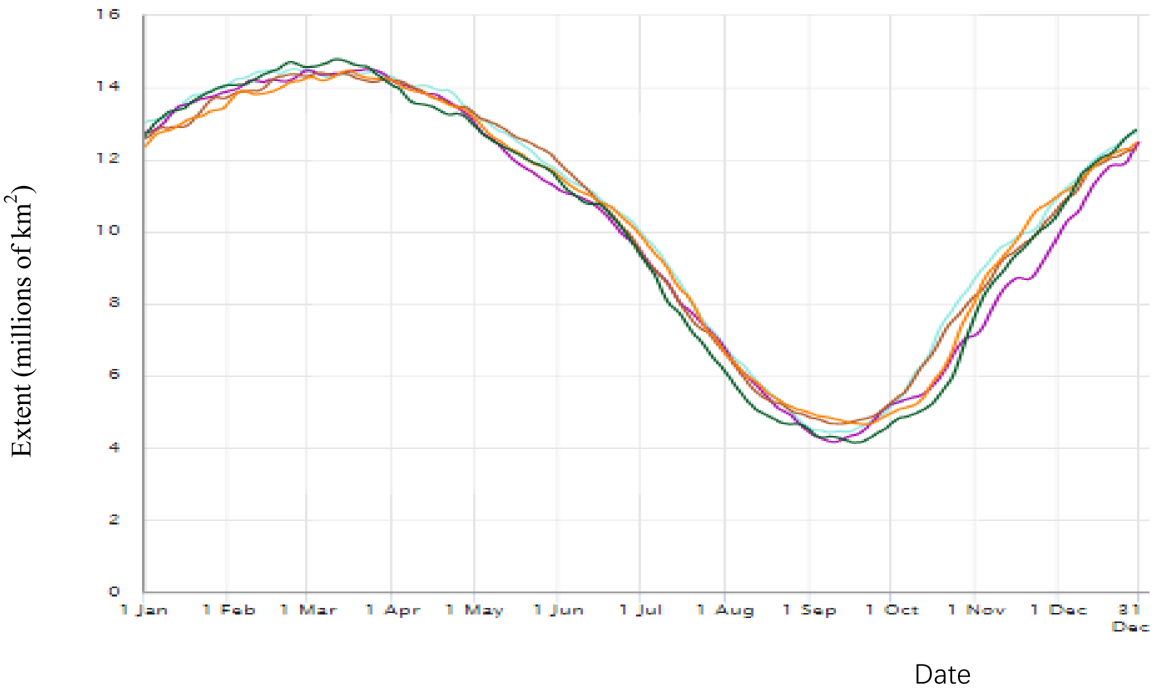


Figure17 - Arctic Sea Ice Extent from 2015-2019

Source: National Snow & Ice Data Centre.

The Arctic sea ice changes with the seasons remarkably. As is shown in Figure 17, which is the area of ocean with at least 15% sea ice. It is clear that every year, the maximum Arctic sea ice extent typically occurs around mid-March. After that, with the gradual rise of the temperature, the sea ice extent begins to decrease, especially after June when summer arrives in the northern hemisphere. By mid-September, the sea ice extent recedes to its lowest level of the year. This is the best time for navigation. As Arctic temperatures drop after September, the extent of sea ice begins to increase month by month.

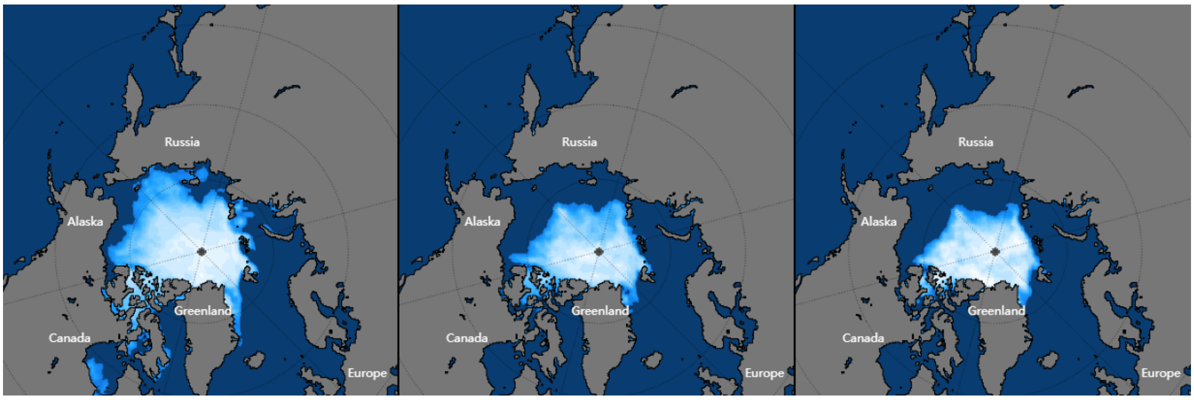


Figure 18 - A comparison of ice extent between July, August and September in 2019

Source: National Snow & Ice Data Centre

Figure 18 describes the comparison of the ice extent during the navigable window. In July, the ice extent is pretty large in the northeast of the Kara Sea, northwest of the Laptev Sea and the East Siberian Sea, which has negative impacts on safe navigation. September is the best time to pass through the NSR, nearly all the sea ice has melted.

(2) Sea ice thickness

Under normal circumstances, when sea ice thickness is less than 30 cm, ships are able to navigate successfully, while when sea ice thickness is larger than 30 cm, it will affect the navigation of the ship. Of the five seas through which the NEP passes, the sea ice in the Barents Sea is the weakest. While the sea ice in the other four seas is mainly the first-year ice, which basically can melt during the navigable window, and has little effects on safe navigation. Figure 19 shows the mean sea ice thickness conditions of the Arctic Ocean in October 2019. At this time, the ice has already begun to form and accumulate, the ice thickness is larger than the former months.

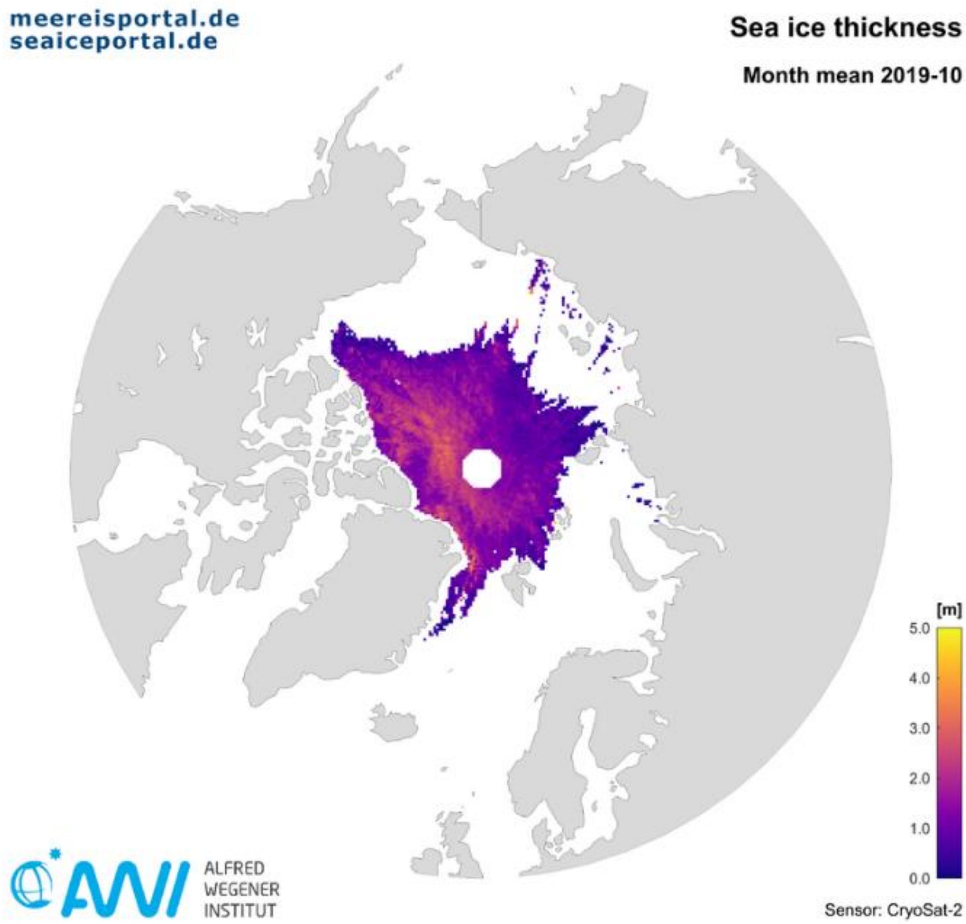


Figure 19 - The mean sea ice thickness in October 2019

Source: Grosfeld et al., 2016

4.2.3 Geographical environment

The conditions of the strait

As is known to all that a strait is a navigable waterway that connects two seas. Due to the different meteorological and hydrological conditions of the seas, in most cases, a strait is affected by a variety of factors. Consequently, the navigation environment is more complex than other sea areas.

(1) The length of the strait

To some extent, the length of the strait is a factor that affects safe navigation. In the strait, the hydrological conditions normally are a little more complicated. For example, due to the reasons like temperature differences, salinity differences, the current will be swifter. In the meanwhile, the longer the strait, the more sea ice will be encountered when a ship passes through the strait.

(2) The width of the strait

The width of the strait directly affects the navigation safety of ships. When a ship is navigating in a narrow strait, it is easy to have the phenomenon of shore suction or shore push, it may even cause ground or collide. For instance, as is stated in Chapter 2, the minimum widths of the Kara Strait, the Vilkitsky Strait, the Sannikov and the Strait Long Strait are 56 km, 54 km, 57 km and 139km respectively.

(3) The minimum depth of the strait

The minimum depth of a strait determines if the strait can be navigable and also the sizes of the ships that can pass. Some straits cannot be navigable because there are unnavigable shores, reefs or archipelagoes, which can result in the grounding of the ship. As introduced in Chapter 2, the minimum depth of the Kara Strait is about 21 m, the Vilkitsky Strait more or less 6-8 m, the Sannikov Strait round 13 m and the Long Strait approximate 20 m. When passing through the straits, the passage plan should be kept away from these sites.

Distance from the shore

Distance from shore is another factor that should be taken into consideration. The farther away from the shore, the closer to the Arctic pole, the more complex of the meteorological and hydrology conditions, the more uncertainties exist, the more dangerous for the ships. Therefore, as long as all the conditions meet the requirements, under the premise of ensuring navigation safety, it is recommended to choose an inshore route.

4.2.4 Other related factors

Aids to navigation and supporting facilities

Aids to navigation and supporting facilities are crucial for the safe navigation of ships. The NSR is located in the high latitude area, plenty of aids to navigation cannot normally work like the compass and Global Positioning System (GPS), the data in Electronic Chart Display and Information System (ECDIS) is not very accurate, even the Global Maritime Distress and Safety System (GMDSS) cannot find the satellite signal. Moreover, as the NSR is a special route, several sea areas are lack of supporting facilities such as beacons, lighthouses and Vessel Traffic Service (VTS), which cannot satisfy the needs of navigation. Last but not least, the ports along the NSR should have the capacity to tackle all the unexpected circumstances, such as ship maintenance and repair, water and oil supply. The number of ports plays a vital role.

Navigable window

" The navigable window means the start date, the end date, and the navigable period of the passage sailing by one ship without the sea ice affecting the safety of navigation" (Ma, 2019, p.244). The only factor that affects the navigable window is sea ice. The sea ice cannot melt in a day. The longer the navigable window means the higher temperature or the thinner ice thickness, both of which are benefits for safe navigation. In addition, some cases may happen that a ship enters the NSR within the navigable window, but comes out from the NSR beyond the navigable window. Hence, a longer navigable window can guarantee that the ship will pass through the NSR within the navigable window.

Search and rescue (SAR) capacity

Maritime Rescue Coordination Centre (MRCC) is responsible for the organization, coordination and command of the emergency response, such as pollution accidents caused by ships, SAR operation of lives at sea and clearance of obstacles in important navigable waters. The more MRCCs and available SAR facilities along with the NSR, the better guarantees of safety of ships. At present, there is an MRCC in DIKSON port which has SAR facilities of rescue boat (RB), rescue vessel (RV) and long-range aircraft (LRG). Another two Maritime Rescue Subcenters (MRSC) exist in PEVEK port and TIKSI port, both of which have SAR facilities of RB, RV, LRG and light Helicopter (HEL-L), as is shown in Figure 20.

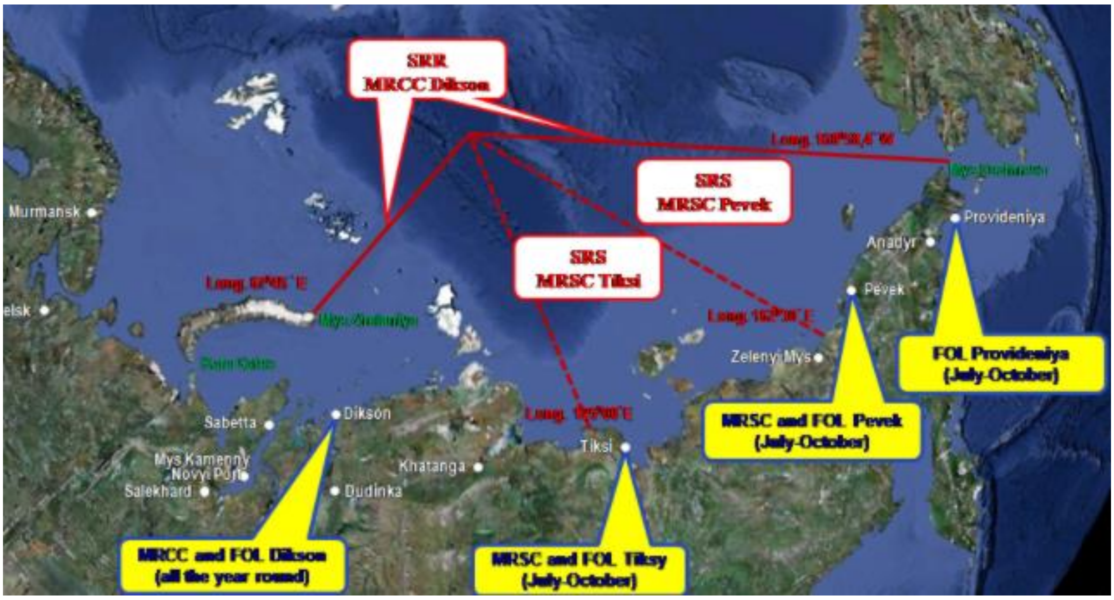


Figure 20 - Locations of MRCC along the NSR

Source: The Northern Sea Route Administration

Moreover, 10 SAR centers along the NSR were planned to establish in 2009, by now, Dudinka, Naryan-Mar, and Arkhangelskhas already come into use, and the schedule for the others delayed to this year, 2020 (Sakhuja, 2015).

Icebreakers available

Icebreakers are indispensable tools when ships are navigating in the NSR, according to the Rules of navigation in the water area of the Northern Sea Route (2013), icebreaker assistance is compulsory for foreign ships transiting the NSR. Besides, icebreakers can also be used in operations such as channel maintenance, SAR and the like. Russia has the most icebreakers in the world. Nevertheless, since many of the icebreakers are too old to meet the requirements, Russia is now accelerating the construction of new icebreakers. Up to now, there are a total of 40 icebreakers in the fleet, and another 11 more is planned or under construction (Gady, 2019). In mid-January, 2020, Russia signed another contract that the world's most powerful new-generation nuclear-powered icebreaker "*Lider*" would be built (ROZIN, 2020). Table 2 is the list of part of the icebreakers in the fleet.

Table2 - List of part of icebreakers in the fleet

Vessel name	**Year of construction**	**Age (by 2019)**
Kapitan Babichev	1983	36
Kapitan Borodkin	1994	25
Kapitan Evdokimov	1983	36
Dikson	1983	36
Dudinka	1970	49
Kapitan Khlebnikov	1981	39
Krasin	1976	43
Tor	1964	55
Moskva	2008	11
Novorossiysk	2016	3
Kigoriak	1979	33
Andrey Vilkitskiy	2018	1
Alexander Sannikov	2018	1
50 let Pobedy	2007	12
Taimyr	1989	30
Vaygach	1990	29
Yamal	1992	27

Source: CHNL Information Office

VTS coverage

VTS is a marine traffic monitoring system, which is very important to safe navigation. As is stated by IMO (1997),

> "VTS is designed to improve the safety and efficiency of vessel traffic and protect the environment. The service shall have the capability to interact with the traffic and respond to traffic situations developing in the VTS area".

If the VTS coverage is not wide enough, many marine traffic accidents cannot be prevented and handled, which is not conducive to the navigation safety of ships in the NSR. In other words, within the VTS area, the ship will be much safer.

CHAPTER 5: THE FLOW PATH OF ESTABLISHING THE TOPSIS NETWORK

5.1 The Process of Establishing the TOPSIS Network

In practice, a great many factors need to be considered. The process to establish the TOPSIS network should be treated as an overall flow. This is mainly because numerous problems will be encountered during the process of defining variables, choosing mathematical algorithms, and establishing networks, etc. Figure 21 shows the typical process of establishing the TOPSIS network.

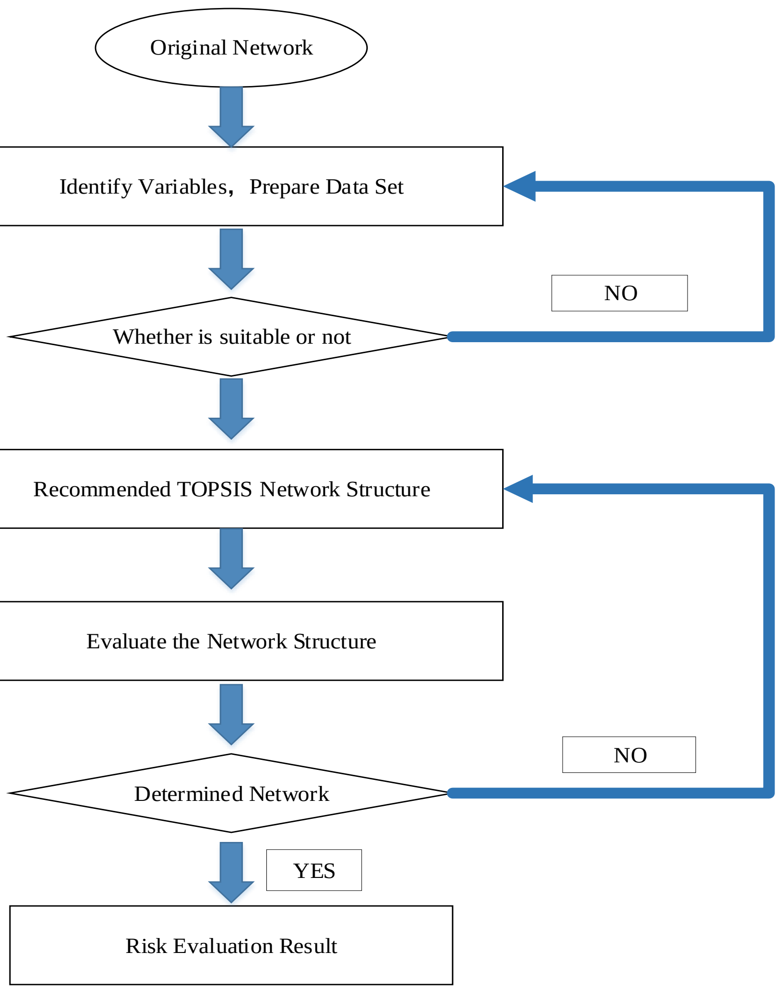


Figure 21 - The process of establishing the TOPSIS network

Source: Author

5.2 Navigation Risk Evaluation in NEP Based on Entropy Weight TOPSIS Model

On the basis of the evaluation indicator analysis above, after consulting several experts and professors, the final navigation risk evaluation system of ships navigating in the NEP is set as follows:

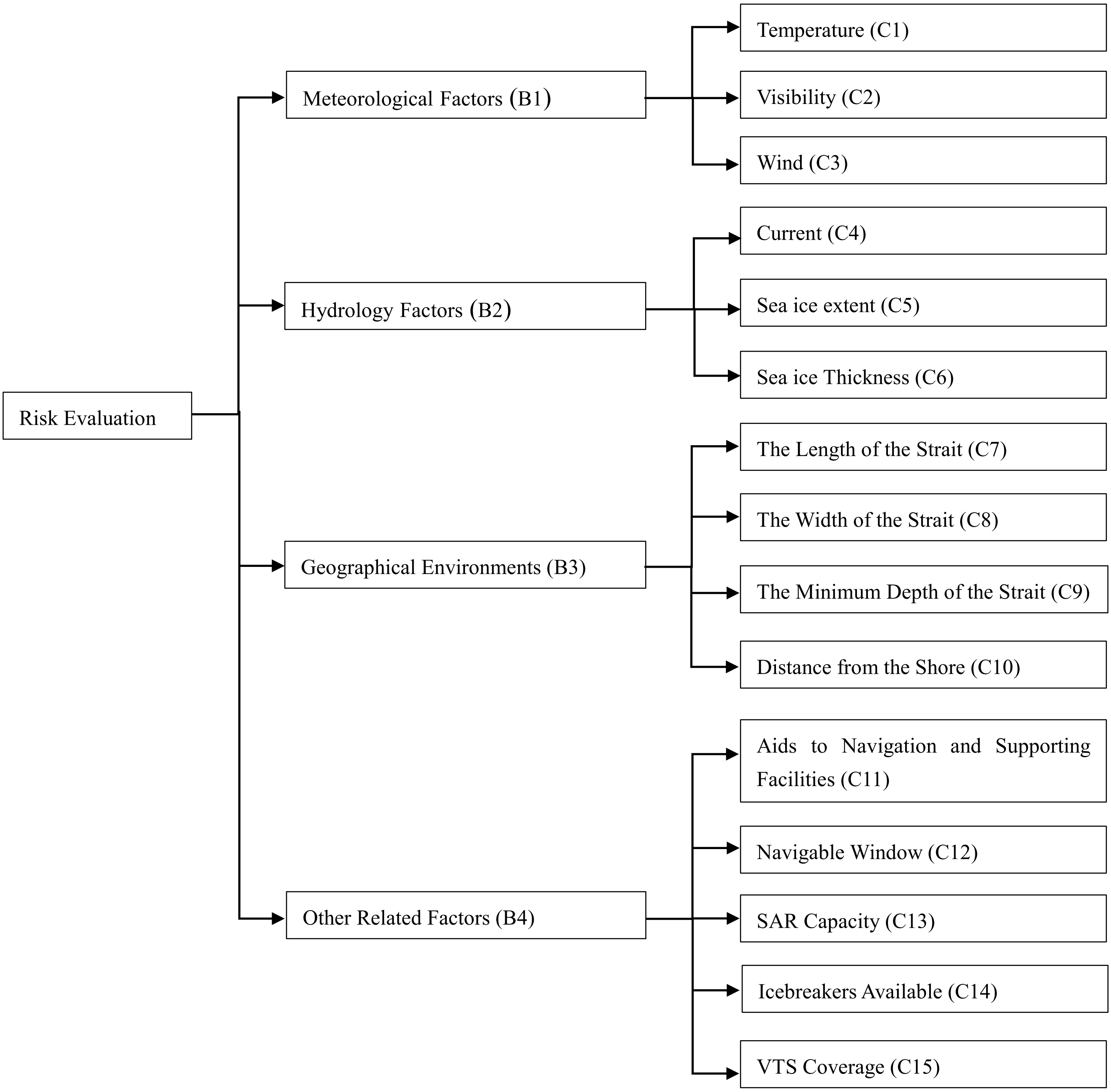
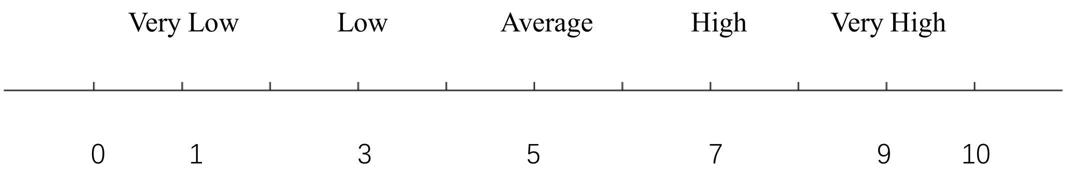


Figure 22 - The TOPSIS risk evaluation system of ships navigating in the NEP

Source: Author

Of all the indicators in the risk evaluation system, there are 12 quantitative indicators and three qualitative indicators; nine benefit indicators and six cost indicators. The actual data of the quantitative indicators will be derived from research institutes or organizations that study the Arctic, such as the National Snow & Ice Data Centre, the NASA, the International Arctic Research Center, the Online sea-ice knowledge and data platform and so forth; While the values of the qualitative indicators will be assigned in the light of a bipolar scale. A bipolar scale indicates an expert or professor to balance two different qualities, determining the relative proportion of those qualities, which has two polar opposites from 0 to 10 (Talikoti, n.d.), in which 0 represents extremely low, 5 represents the average and 10 represents extremely high for the benefit indicators. The cost indicators are just the other way round, show as follow:

The interval scale of the benefit indicators



The interval scale of the cost indicators

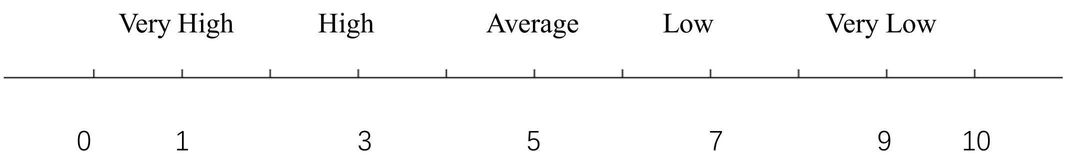


Figure 23 - Quantization of the qualitative indicators in the bipolar scale

Source: Author

Different evaluation risk should consider different indicators. The risk evaluation system introduced above is just an example. In other cases, some of these indicators may be removed and others will be added.

5.3 Empirical Analysis

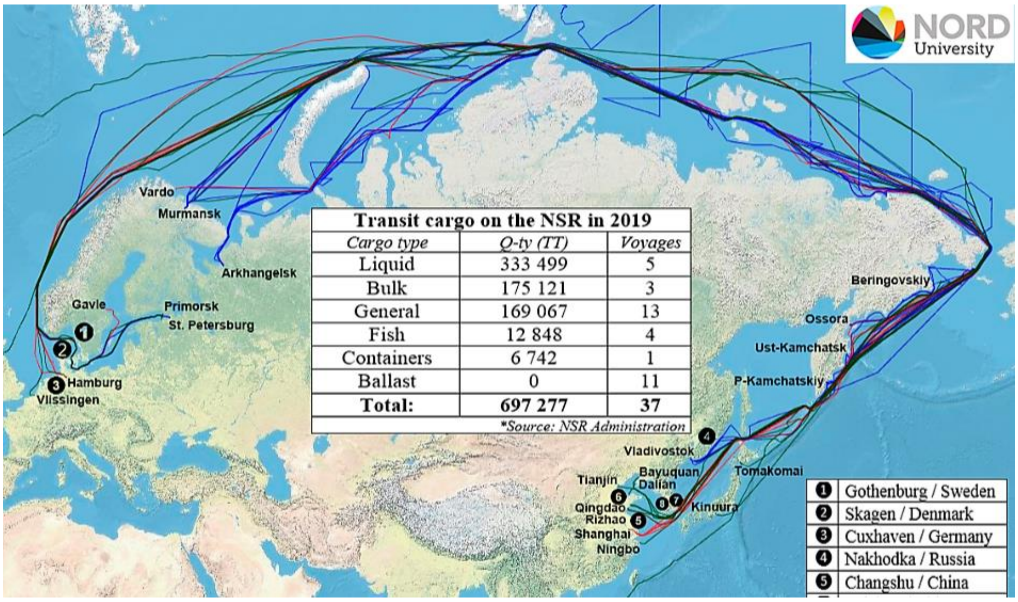


Figure 24 - NSR Shipping traffic – Transits in 2019

Source: CHNL Information Office

Figure 24 shows the Automatic Identification System (AIS) information of all the transits statistics in 2019. The red lines represent westbound ship routes, the dark green lines represent eastbound ship routes, and the blue lines represent transiting routes inside Russia. It can be found that three ship routes have been adopted that transit the NEP, as is shown in Table 3.

Table 3 - The adopted routes transiting the NEP

Route 1	Chukchi Sea --- Long Strait --- East Siberian Sea --- Sannikov Strait --- Laptev Sea --- Vilkitsky Strait --- Kara Sea --- Kara Strait --- Barents Sea
Route 2	Chukchi Sea --- Long Strait --- East Siberian Sea --- Sannikov Strait --- Laptev Sea --- Vilkitsky Strait --- Kara Sea --- North of Novaya Zemlya --- Barents Sea
Route 3	Chukchi Sea --- North of Wrangel Island--- East Siberian Sea --- North of New Siberian Island --- Laptev Sea --- Vilkitsky Strait --- Kara Sea --- North of Novaya Zemlya --- Barents Sea

Source: Author

For the sake of better evaluating the risk extent of the routes, each route will be divided into several Legs in this dissertation. The Leg represents each part of the route in Table 3. The final result is to find out which leg is much safer and much more attention should be paid to the much more dangerous Leg when passing through it, take Route 1 as an example, the detailed information of all the Legs is shown in Table 4.

Table 4 - The detailed information of each Leg of the route 1

Leg 1	The Chukchi Sea
Leg 2	The Long Strait
Leg 3	The East Siberian Sea
Leg 4	The Sannikov Strait
Leg 5	The Laptev Sea
Leg 6	The Vilkitsky Strait
Leg 7	The Kara Sea
Leg 8	The Kara Strait
Leg 9	The Barents Sea

Source: Author

Assume that one ship made a voyage passing the NEP in July 2019. The original data of each indicator are shown in Table 5. In order to make sure the consistency of all the indicators, as well as all the chosen indicators are meaningful, some indicators will be removed. For example, some Legs contain strait, while others cross the ocean, so the indicators of “the width of the Strait” and “the minimum depth of the Strait” will be removed, and the indicator of “the length of the Strait” will be changed to “the length of the Leg”. Moreover, the indicator of “Navigable Window” and “Icebreakers Available” will be removed. According to different situations, the indicators could be changeable.

Table 5 - The original data of each indicator

Indicator3	Leg 1	Leg 2	Leg 3	Leg 4	Leg 5	Leg 6	Leg 7	Leg 8	Leg 9
Temperature C1 (+)	6.6	7.7	2.7	6.6	2.4	2.8	2.1	4.8	3.9
Visibility C2 (-)	10.5	4.5	12	4	10.5	5.9	9	10	6
Wind C3 (-)	6.5	4.3	5.3	6.6	7.4	6.7	6.6	8.7	6.7
Current C4 (-)	3	13	3.8	1	4	4.3	5	1	1
Sea ice extent C5 (-)	0	0	58%	22%	32%	50%	9%	0	0
Sea ice thickness C6 (-)	0	0	0.94	0.62	0.48	0.74	0.17	0	0
The Length of the Leg C7 (-)	326	120	589	160	477	60	801	18	576
Distance from the Shore(max) C8 (-)	16	29	165	127	149	14.6	101	15.1	218
Aids to Navigation and Supporting Facilities C9 (+)	8	8	7	6	6	7	9	9	9
SAR Capacity C10 (+)	8	10	8	9	8	7	7	7	6
VTS Coverage C11 (+)	100%	100%	29%	100%	24%	100%	35%	100%	30%

Source: Author

The original decision matrix A' can be established as follows:

$$A' = \begin{bmatrix} 6.6 & 7.7 & 2.7 & 6.6 & 2.4 & 2.8 & 2.1 & 4.8 & 3.9 \\ 10.5 & 4.5 & 12 & 4 & 10.5 & 5.9 & 9 & 10 & 6 \\ 6.5 & 4.3 & 5.3 & 6.6 & 7.4 & 6.7 & 6.6 & 8.7 & 6.7 \\ 3 & 13 & 3.8 & 1 & 4 & 4.3 & 5 & 1 & 1 \\ 0 & 0 & 0.58 & 0.22 & 0.32 & 0.5 & 0.09 & 0 & 0 \\ 0 & 0 & 0.94 & 0.62 & 0.48 & 0.74 & 0.17 & 0 & 0 \\ 326 & 120 & 589 & 160 & 477 & 60 & 801 & 18 & 576 \\ 16 & 29 & 165 & 127 & 149 & 14.6 & 101 & 15.1 & 218 \\ 8 & 8 & 7 & 6 & 6 & 7 & 9 & 9 & 9 \\ 8 & 10 & 8 & 9 & 8 & 7 & 7 & 7 & 6 \\ 1 & 1 & 0.29 & 1 & 0.24 & 1 & 0.35 & 1 & 0.3 \end{bmatrix}$$

As can be seen from Table 4, four of the chosen indicators are benefit indicators and others are cost indicators, in the light of formula (3.1) and (3.2), the standard decision matrix A can be obtained as follows:

$$A = \begin{bmatrix} 0.8 & 1 & 0.11 & 0.8 & 0.05 & 0.13 & 0 & 0.48 & 0.32 \\ 0.19 & 0.94 & 0 & 1 & 0.19 & 0.76 & 0.38 & 0.25 & 0.75 \\ 0.5 & 1 & 0.77 & 0.48 & 0.3 & 0.45 & 0.48 & 0 & 0.45 \\ 0.83 & 0 & 0.77 & 1 & 0.75 & 0.73 & 0.67 & 1 & 1 \\ 1 & 1 & 0 & 0.62 & 0.45 & 0.14 & 0.84 & 1 & 1 \\ 1 & 1 & 0 & 0.34 & 0.49 & 0.21 & 0.82 & 1 & 1 \\ 0.61 & 0.87 & 0.27 & 0.82 & 0.41 & 0.95 & 0 & 1 & 0.29 \\ 0.99 & 0.91 & 0.04 & 0.29 & 0.15 & 1 & 0.45 & 1 & 0 \\ 0.67 & 0.67 & 0.33 & 0 & 0 & 0.33 & 1 & 1 & 1 \\ 0.5 & 1 & 0.5 & 0.75 & 0.5 & 0.25 & 0.25 & 0.25 & 0 \\ 1 & 1 & 0.07 & 1 & 0 & 1 & 0.14 & 1 & 0.08 \end{bmatrix}$$

After getting the standardization decision matrix $A = \{a_{ij}\}_{m \times n}$, the weight f_{ij} can be calculated based on the formula (3.3).

$$f_{ij} = \begin{bmatrix} 0.099 & 0.106 & 0.038 & 0.113 & 0.015 & 0.022 & 0 & 0.06 & 0.054 \\ 0.023 & 0.1 & 0 & 0.141 & 0.058 & 0.128 & 0.076 & 0.031 & 0.127 \\ 0.062 & 0.106 & 0.269 & 0.068 & 0.091 & 0.076 & 0.095 & 0 & 0.076 \\ 0.103 & 0 & 0.269 & 0.141 & 0.228 & 0.123 & 0.133 & 0.125 & 0.17 \\ 0.124 & 0.106 & 0 & 0.087 & 0.137 & 0.024 & 0.167 & 0.125 & 0.17 \\ 0.124 & 0.106 & 0 & 0.048 & 0.149 & 0.035 & 0.163 & 0.125 & 0.17 \\ 0.075 & 0.093 & 0.094 & 0.115 & 0.125 & 0.16 & 0 & 0.125 & 0.049 \\ 0.122 & 0.097 & 0.014 & 0.041 & 0.046 & 0.168 & 0.089 & 0.125 & 0 \\ 0.083 & 0.071 & 0.115 & 0 & 0 & 0.055 & 0.199 & 0.125 & 0.17 \\ 0.062 & 0.106 & 0.175 & 0.106 & 0.152 & 0.042 & 0.05 & 0.031 & 0 \\ 0.124 & 0.106 & 0.024 & 0.141 & 0 & 0.168 & 0.028 & 0.125 & 0.014 \end{bmatrix}$$

The entropy of the indicators H_j and the entropy weight of the indicators ω_j can be acquired as follow on the basis of the formula (3.4) and (3.5).

Table 6 – The Calculated results of H_j and ω_j

Indicators	H_j	ω_j
C1	0.548	0.15
C2	0.662	0.112
C3	0.742	0.085
C4	0.954	0.015
C5	0.805	0.065
C6	0.793	0.069
C7	0.771	0.076
C8	0.663	0.112
C9	0.703	0.098
C10	0.68	0.106

C11	0.66	0.113

Source: Author

A weighted standardized decision matrix can be constructed as follows:

$$Z=(Z_{ij})_{m\times n}=(\omega_j a_{ij})_{m\times n}=\begin{bmatrix} 0.12 & 0.15 & 0.016 & 0.12 & 0.007 & 0.019 & 0 & 0.072 & 0.048 \\ 0.021 & 0.105 & 0 & 0.112 & 0.021 & 0.085 & 0.043 & 0.028 & 0.084 \\ 0.043 & 0.085 & 0.066 & 0.041 & 0.026 & 0.038 & 0.041 & 0 & 0.038 \\ 0.013 & 0 & 0.012 & 0.015 & 0.011 & 0.011 & 0.01 & 0.015 & 0.015 \\ 0.065 & 0.065 & 0 & 0.04 & 0.029 & 0.009 & 0.067 & 0.08 & 0.08 \\ 0.069 & 0.069 & 0 & 0.023 & 0.034 & 0.014 & 0.056 & 0.069 & 0.069 \\ 0.046 & 0.066 & 0.02 & 0.062 & 0.031 & 0.072 & 0 & 0.076 & 0.022 \\ 0.11 & 0.102 & 0.004 & 0.032 & 0.017 & 0.112 & 0.05 & 0.112 & 0 \\ 0.066 & 0.066 & 0.032 & 0 & 0 & 0.032 & 0.098 & 0.098 & 0.098 \\ 0.053 & 0.106 & 0.053 & 0.08 & 0.053 & 0.027 & 0.027 & 0.027 & 0 \\ 0.113 & 0.113 & 0.008 & 0.113 & 0 & 0.113 & 0.016 & 0.113 & 0.009 \end{bmatrix}$$

The PIS and the NIS of risk evaluation indicators can be calculated on the basis of the formula (3.7) and (3.8)

$$S_j^+=\left\{0.15,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0.098,\ 0.106,\ 0.113\right\}$$

$$S_j^-=\left\{0,\ 0.112,\ 0.085,\ 0.015,\ 0.065,\ 0.069,\ 0.076,\ 0.112,\ 0,\ 0,\ 0\right\}$$

In the end, the distance from evaluation indicators to the PIS and the NIS and the similarity to the ideal solution can be obtained according to the formula (3.9), (3.10) and (3.11).

Table 7 - The PIS, the NIS and final evaluation results

Legs	D_j^+	D_j^-	P_j
Leg 1	0.174	0.212	0.549
Leg 2	0.207	0.226	0.522
Leg 3	0.202	0.202	0.5
Leg 4	0.181	0.211	0.539
Leg 5	0.223	0.168	0.43
Leg 6	0.233	0.154	0.4
Leg 7	0.225	0.165	0.423
Leg 8	0.201	0.206	0.506
Leg 9	0.171	0.174	0.504

Source: Author

5.4 Analysis of the Navigation Risk Evaluation Results

As discussed above, the smaller of the entropy weight, the smaller impacts of this indicator towards the navigation risk evaluation results; and vice versa. Figure 25 shows the entropy weight of all indicators, it can be seen that temperature attaches the most importance. This is mainly because the low temperature is the main feature of the Arctic region, it is also the root causes of other indicators such as sea ice. Visibility and distance from the shore (Max) follow next. Current, sea ice extent and sea ice thickness hold the least importance. This is mainly because at present, icebreaker assistance is compulsory for foreign ships transiting the NSR, which can greatly improve navigation safety.

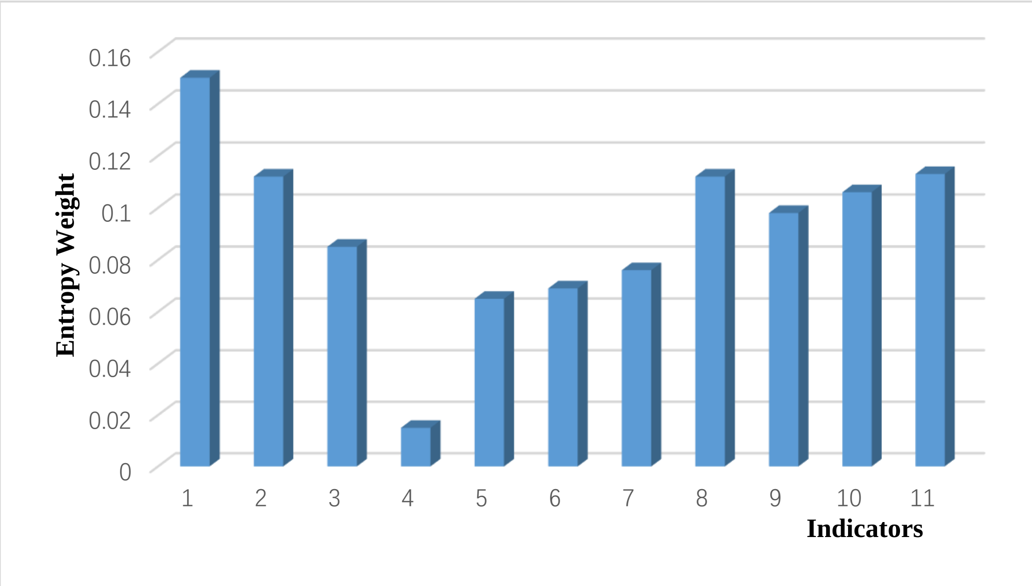


Figure 25 - Entropy weight of Indicators

Source: Author

As can be seen from Table 7, the final evaluation results in ascending order are Leg 6, Leg 5, Leg 7, Leg 3, Leg 9, Leg 8, Leg 2, Leg 4 and Leg 1. The conclusion can be drawn that Legs in lower latitude are much safer than that in higher latitude, which is consistent with the former conclusion that temperature attaches the most importance towards navigation risk in the NSR. Furthermore, compared with navigating in the Seas on the same latitude, navigating in the Straits is much safer.

In addition, this entropy weight TOPSIS model can be used on other circumstances as well. For instance, there are three straits connecting the Barents Sea and the Kara Sea. To be more specific, they are the Youngor Strait, the Kara Strait and the Matochkin Strait, all of which could allow ships to navigate successfully in the navigable window. When planning a passage from the Barents Sea to the Kara Sea, it is necessary to determine which one is much safer due to different conditions. At this time, the entropy weight TOPSIS model can be applied. Another example which could best illustrate this model is it can be used to decide which month of the navigable window is much safer to transit the NSR. When considering different situations, the chosen indicators should be changed. Furthermore, as the temperature rises with each passing year, there will be more routes along the NEP, rather than the three introduced above. Due to the vast and large span sea areas of the Arctic region, the environmental factors will differ. The entropy weight TOPSIS model can be used to weigh the best route.

CHAPTER 6: SUGGESTIONS FOR IMPROVING SAFE NAVIGATION ALONG THE NEP

6.1 The Preparatory Work of the NEP Navigation

6.1.1 Collect and study necessary information and data

Ice data

When planning a passage of Arctic voyage, carefully search the ice data from the Sailing Direction, the Guide to Port Entry, and the Mariner's Handbook, etc., understand and study distribution of ice area, navigation methods and precautions in detail, collect the latest charts of ice conditions, ice and weather forecast, continuously accept NAVTEX warnings and forecasts of ice conditions. This kind of information can also be obtained from the website of Northern Sea Route Administration (ANSR) who is an organization of the Russian Federation. Coastal warning east, coastal warning west, types of ice conditions, charts of ice conditions, daily hydrometeorological information, synoptic forecast, weekly weather bulletin and long-term forecasts are provided to the public, but only limited to the NSR.

Relevant laws and regulations

When transiting the NEP, several Federal Laws that were issued by the Russian Federation shall be abided by. For instance, Rules of navigation on the water area of the Northern Sea Route (2013); Rules of the repeatedly crossing by foreign ships the State Border of the Russian Federation (2014) and the like. In addition, some other laws have to be complied with as well, such as the Convention on the Law of the Sea (UNCLOS) that was published by the United Nations (UN) and the Polar Code (2014a, IMO) that were formulated by IMO, etc..

Application of the admission to navigate in the NSR

Navigation in the NSR is organized, controlled and managed by ANSR. According to the Rules of navigation on the water area of the Northern Sea Route, permission which is issued by ANSR needs to be applied by foreign vessels sailing within or transiting the NSR. In practice, in deciding whether to issue this permission, ANSR will mainly consider whether the ship has the appropriate ice class and the ability to pass safely during the season when the NSR is applied for.

6.1.2 Checks or inspections before entering the NEP

Before entering the NEP, plenty of checklists should be finished by all departments of ships. For example, in the bridge checklist, the items contain content such as close all watertight doors, check the hull structure, especially the bow, and check the life-saving appliance to make sure they are in good conditions and so forth. Similarly, in the engine room checklist, there are items such as piping and valves in the double bottom that should be maintained in normal condition, check piping, valves and pumps of the cooling system and clean all inlet filters, etc.

Besides, for the ships that will pass through the NSR, a delegate will be assigned by ANSR to inspect onboard ships. This work can be done at the port of Murmansk (eastbound ships), the port of Provideniya (westbound ships) or other port that the shipowner considers convenient for inspection. The inspection is only limited to confirming whether the ship is safe to pass the NSR.

Adjust draft and trim of ships

To ensure that the ship has a good icebreaking ability and maneuverability, and meanwhile to protect the ship’s hull, rudder and propeller which are the most vulnerable parts of the ship (*Ice navigation*, 2019), in general, it is better to keep the trim between 0.5 m to1.0 m. When the thickness of the ice reaches 30 cm, the propeller should be kept more than 1.5 m below the waterline. Moreover, with regard to the ships of ice-class B, if possible, the forward draft should be kept greater than l.0 m above the Ballast Water Line and greater than 0.5 m below the Load Water Line (Hong & Yang, 2012, p.188).

Freeze protection work

When navigating in the NEP, the navigational lights, the lights of the open-air compass and repeaters of gyros should be opened round the clock. The water in all the pipes outdoors, such as freshwater pipe, should be drained. It is a good practice to keep the water in the wing tanks and fore and aft peak tanks no more than 85% full and the water in the double bottom no more than 95% full.

6.2 Ship Handling in the NEP

6.2.1 Before entering the ice-covered waters

Extra vigilant lookouts must be posted (Singh, 2019) when entering into the ice-covered waters. Besides, in practice, if ice concentrations are 5/10 or less and the thickness of the sea ice is less than 30 cm, ships are generally able to navigate without any assistance; while ice concentrations are 6/10 or more and the thickness of the sea ice is greater than 30 cm, it is hard for a ship to navigate by herself, and this is the time when the icebreakers are needed (Hong & Yang, 2012, p.189). Moreover, the bow of the ship should be at right angles to the edge of the pack ice to avoid glancing blows (Chauhan, 2018). In the meanwhile, on account of the irregular edge of the ice, the site of entering the ice-covered waters must be chosen carefully, preferably in a flatter position of less ice concentration from leeward, it is much better if there is a slower flow or no flow.

6.2.2 Passing through the NEP

It is vital for safe navigation to choose the correct speed according to different situations. If ice concentrations are 4/10 - 5/10 or less, ships can proceed with normal speed; while ice concentrations are 6/10 – 7/10 or more, navigation should always be done at low speeds. (Hong & Yang, 2012, p.188). When navigating at night or in reduced visibility, the ship should slow down the speed. Furthermore, it is better to alter course less when navigating in ice-covered waters. If the course alteration is inevitable, it is forbidden to have a hard over, use a small rudder order between 5 ~10 degrees each time to slowly alter the course, which will benefit for preventing damage to the rudder and propeller. What's more, if the ship is blocked by heavy ice concentration, the rudder should be put amidships and the engines should be kept turning slowly ahead, which will be conducive to fall back (Singh, 2019).

6.2.3 Help of icebreakers

For foreign ships that navigate within the NSR, icebreaker assistance is compulsory. When joining the escort operation, some considerations should be kept in mind. First of all, the distance between the escorted ships is generally maintained 2~3 times the length of the ship or determined by the commanding officer of the icebreaker (Canadian Coast Guard, 2012) or the pilot. In the second place, the ship in the afterwards should closely keep a watchful eye on the movement of the ship in her front, and timely adjust the distance between. Last but not least, in general, the speed of the escorted ship can be maintained at about 8 knots when the concentration of ice is less than 4/10. Every 1/10 increase in ice concentration slows down the speed by l knot. In the meantime, the speed of the escorted ship is also decided by the distance from the ships in her front.

6.3 Manning Adequate Qualified Seafarers

According to statistical data, approximately 80% of maritime accidents are caused by human factors (European Maritime Safety Agency, n.d.). Therefore, effectively eliminating human factors can significantly improve navigation safety, which is especially true for navigating in the NEP. One of the best solutions is to man adequate qualified seafarers (OCIMF, 2017). When navigating in the NEP, besides the professional quality of ship navigation, it is also necessary to master the ability to know and identify ice, the navigational experience and skills in the ice-covered waters. What's more important is to have good psychological quality. At present, plenty of institutions, universities and shipping companies have launched ice navigation courses, such as Simulator Course of Odessa Maritime Training Centre, FURUNO Maritime

Training, Professional Maritime Competence Indonesia (PT Promacindo) and the like, which can cultivate qualified seafarers.

CHAPTER 7: CONCLUSION AND PROSPECT

7.1 Conclusion

With the global climate getting warmer, the opening of the Arctic shipping routes has come true, especially the opening of the NEP, which will bring huge benefits and development prospects to China's shipping industry and import and export trade. Therefore, in recent years, China has continuously increased the exploration and research of the NEP, actively participating in the development of the NEP, and has established China's power of discourse in the Arctic region. This is especially true when the “Arctic Silk Road” Initiative of China advances step by step and strategic partnership between China and Russia become closer (Zerohedge, 2017). By now, the investment orientation of China is mainly focused on shipping, energy and science (Zhang, 2020).

This dissertation mainly studied the NSR which is a part of the NEP, and main factors affecting the safe navigation of the NSR are analyzed. In the light of the previous AIS information, three main Arctic routes were identified. On the basis of the above, the risk evaluation system of navigation environment is constructed and in the end, the entropy weight TOPSIS method is used to evaluate the navigation environment of the NSR. In order to make the evaluation result more scientific and reasonable, the selected route is divided into several Legs, the navigation environment of each Leg is evaluated, and the navigation environments of different parts are compared, and then which Legs are much safer and which Legs are much more dangerous are finally found.

7.2 Prospect

A few limitations still exist in the dissertation, for example, of all the indicators discussed, some of them are quantitative indicators and others are qualitative indicators. The actual data of some of the quantitative indicators were derived from research institutes or organizations. However, some quantitative indicators cannot be obtained temporarily, historical statistical data are used, which may not be very convincing.

Moreover, a bipolar scale is used to weigh the qualitative indicators, and it needs experts or professors to decide, which has certain subjectivity. Furthermore, only the environmental factors of the NSR are analyzed, which is only a part of the human - machine (ship) - environment system. The human and ship factors are presumed 100% safe. This is because only the environmental factors have real data, and the real data of the human and ship factors should be aimed at a specific ship and her manning. Whether a specific ship can safely navigate through the Arctic waters, in future studies, on the basis of the data and conclusion of this dissertation, a more comprehensive and systematic risk evaluation will be realized with the help of other mathematical models.

In the future, with the global climate getting warmer, the environment will become less hostile, the navigable window will become longer and the navigable waters will become wider. At that time, more NEP routes will appear. The entropy weight TOPSIS method will prove much more significant in choosing the best NEP routes.

Reference

About IASC. (n.d.). Retrieved from https://iasc.info/iasc/about-iasc

Aires, R. F. D. & Ferreira, L. (2019). A new approach to avoid rank reversal cases in the TOPSIS method. *Computers & Industrial Engineering, 132,* 84-97.

Alexei Bambulyak. (2019). *Shipping and the Northern Sea Route*. Retrieved February 28, 2019, from https://www.kbnn.no/en/article/shipping-and-the-northern-searoute

AMAP (2017). *Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017*. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

AMSA. (2009). *Arctic Marine Shipping Assessment 2009 Report*. Arctic Council, April 2009.

Anghel, D. C. & Belu, N. (2015). Contributions to Predict the Malfunction Probability of the Human-Machine-Environment System, Using Artificial Neural Networks. *Applied Mechanics and Materials, 760*, 771-776.

Aref, M. A., Javadian, N. & Kazemi, M. (2012). A New Fuzzy Positive and Negative Ideal Solution for Fuzzy TOPSIS. *WSEAS TRANSACTIONS on CIRCUITS and SYSTEMS, 11*(3), 92-103.

Arctic Bulk. (n.d.). *NORTHERN SEA ROUTE- the shortcut between Asia and Europe.* Retrieved from http://arcticbulk.com/article/186/NORTHERN_SEA_ROUTE

ARCTIC COUNCIL -- The leading intergovernmental forum promoting cooperation in the Arctic. (n.d.). Retrieved from https://Arctic-council.org/en/

Armitage, T. (2020). *Glimpsing under the ice: measuring the ice-covered Arctic Ocean from space.* Retrieved March 22, 2020, from https://cpom.org.uk/glimpsing-under-the-ice-measuring-the-ice-covered-arctic-ocean-from-space/

Assari, A., Mahesh, T., & Assari, E. (2012). Role of public participation in sustainability of historical city: usage of TOPSIS method. *Indian Journal of Science and Technology, 5*(3), 2289-2294.

Atle Staalesen. (2019). *China's COSCO to stay course on Arctic shipping*. Retrieved May 16, 2019, from https://www.Arctictoday.com/chinas-cosco-to-stay-course-on-Arctic-shipping/

Banu, A. R. R. & Santhiyavalli, G. (2019). A TOPSIS Approach to Evaluate the Financial Performance of Scheduled Commercial Banks in India. *Journal of Business and Management*, *21*(1), 24-33.

Barents Sea. (2019). In *Encyclopedia Britann*ica. Retrieved March 05, 2019 from https://www.britannica.com/place/Barents-Sea

Both Routes around Arctic Open at Summer's End. (2008). Retrieved from *https://earthobservatory.nasa.gov/images/9078/both-routes-around-Arctic-open-at-summers-end*

Brubaker R. D. & Ragner C. L. (2010). A review of the International Northern Sea Route Program (INSROP) – 10 years on. *Polar Geography*, *33*(2), 15-38.

Calla, O., Singhal, S., Mathur, S., Kumar, A. & Gadri, K. L. (2016). Expected Arctic Sea Ice extent as on 2036. *International Conference on Recent Advances and Innovations in Engineering (ICRAIE)* (pp. 1-3). Jaipur.

Canadian Coast Guard. (2012).*Ice Navigation in Canadian Waters*. Ottawa: Author.

Cariou, P., Cheaitou, A., Faury, O. et al. (2019). The feasibility of Arctic container shipping: the economic and environmental impacts of ice thickness. Maritime Economics & Logistics. https://doi.org/10.1057/s41278-019-00145-3

Catherine Jex. (2016). *When will the Arctic be ice free?* Retrieved October 05, 2016 from https://sciencenordic.com/Arctic-climate-change-denmark/when-will-the-Arctic-be-ice-free/1437677

Chauhan, A. (2018). *Ice Navigation- Things a Navigator Should Know*. Retrieved April 6, from https://chirpybrains.com/ice-navigation/

Chukchi Sea. (2018). In *Encyclopedia Britann*ica. Retrieved March 16, 2018 from https://www.britannica.com/place/Chukchi-Sea

Ding, Q. (2014). The Evaluation Research on the Navigation Environment of Arctic Northeast Route Based on Cloud Model. Master Thesis. Dalian Maritime University, China.

East Siberian Sea. (2011). In *Encyclopedia Britann*ica. Retrieved December 15, 2011 from https://www.britannica.com/place/East-Siberian-Sea

European Maritime Safety Agency. *BLACK AND CASBIN SEA PROJECT*. Retrieved Jaunary from http://emsa.europa.eu/bcsea-project/component-4-protection-of-the-marine-environment-2.html.

Final public report of the ARCDEV project. (1999). Retrieved from https://trimis.ec.europa.eu/sites/default/files/project/documents/arcdev.pdf

Freedman, A. (2017). *Arctic sea ice plunges to record winter low after freak polar 'heatwaves'.* Retrieved March 23, 2017, from https://mashable.com/2017/03/22/arctic-sea-ice-melt-record-low-winter/

Freight week. (2016). GAC and Russia to develop Northern Sea Route. Retrieved December April 14 from https://www.freightweek.org/index.php/en/latest-news/90-government/2008-gac-and-russia-to-develop-northern-sea-route

Gady, F. S. (2019). Russia Launches New Nuclear-Powered Icebreaker. Retrieved May 27, 2019, from https://thediplomat.com/2019/05/russia-launches-new-nuclear-powered-icebreaker/

Geir B. Honneland. (1997). Navigating the Straits of the Northern Sea Route, INSROP.

Gordon W.F. Drake. (2018). Entropy .In *Encyclopedia Britann*ica. Retrieved June 07, 2018 from https://www.britannica.com/science/entropy-physics

Grosfeld, K., Treffeisen, R., Asseng, J., Bartsch, A., Bräuer, B., Fritzsch, B., et al. (2016). Online sea-ice knowledge and data platform. *Alfred Wegener Institute for Polar and Marine Research & German Society of Polar Research*, 85 (2), 143-155.

Hong, B. G. & Yang, L. J. (2012). Ship *Handling*. Dalian: Dalian Maritime University Press.

Hunt, J. (2016). *A Brief History of the Northern Sea Route in the 1930s*. Retrieved December 26, 2016 from http://greatwhitecon.info/2016/12/a-brief-history-of-the-northern-sea-route-in-the-1930s/

Hwang, C.L. & Yoon, K. (1981). Multiple Attribute Decision Making: Methods and Applications. Springer-Verlag, New York.

Ice Navigation. (2019). Retrieved November 28, from https://knowledgeofsea.com/ice-navigation/

Intergovernmental Panel on Climate Change [IPCC]. (2014). Climate Change 2013 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

International Association of Classification Societies (IACS). (2006). *Requirements concerning POLAR CLASS*. Retrieved from http://www.engr.mun.ca/~cdaley/9093/UR_I_pdf410.pdf

International Maritime Organization [IMO]. (1997). RESOLUTION A. 857(20), *GUIDELINES FOR VESSEL TRAFFIC SERVICES*. London: Author.

International Maritime Organization [IMO]. (2002). GUIDELINES FOR SHIPS OPERATING IN ARTCTIC ICE - COVERED WATERS: MSC.1/Circ.1056 & MEPC/Circ.399, London: Author.

International Maritime Organization [IMO]. (2009). Resolution A. 1024(26), *GUIDELINES FOR SHIPS OPERATING IN POLAR WATERS*, London: Author.

International Maritime Organization [IMO]. (2014a). Resolution MSC. 385 (94), *INTERNATIONAL CODE FOR SHIPS OPERATING IN POLAR WATERS (POLAR CODE)*, London: Author.

International Maritime Organization [IMO]. (2014b). Resolution MSC. 386 (94), *AMENDMENTS TO THE INTERNATIONAL CONVENTION FOR THE SAFETY OF LIFE AT SEA*, *1974*, *AS AMENDED*, London: Author.

International Maritime Organization [IMO]. (2015a). Resolution MEPC. 264(68), *INTERNATIONAL CODE FOR SHIPS OPERATING IN POLAR WATERS (POLAR CODE)*, London: Author.

International Maritime Organization [IMO]. (2015b). Resolution MEPC. 265(68), *AMENDMENTS TO THE ANNEX OF THE PROTOCOL OF 1978 RELATING TO THE INTERNATIONAL CONVENTION FOR THE PREVENTION OF POLLUTION FROM SHIPS*, *1973*, London: Author.

Juurmaa, K. (2006). *Arctic Operational Platform: Integrated Transport System. ARCOP Final Report*. Aker Finnyards Inc., Helsinki.

Kara Sea. (2014). In *Encyclopedia Britann*ica. Retrieved November 19, 2014 from https://www.britannica.com/place/Kara-Sea

Laptev Sea. (2012). In *Encyclopedia Britann*ica. Retrieved April 13, 2012 from https://www.britannica.com/place/Laptev-Sea

Ma, L., An, L., Zhang, X. H., Zheng, Z. Y., Li, Z. H. & Chen, G. W. (2019). Navigable Window Dataset of the Arctic Northeast Passage (2006–2015). *Journal of Global Change Data & Discovery*. *3*(3), 244-251.

Malte H. & Andreas R. (2012). *The Future of Arctic Shipping Along the Transpolar Sea Route.* Arctic Yearbook 2012. (pp. 281-307). Retrieved from https://arcticyearbook.com/arctic-yearbook/2012

Matt, M. &Seth, B. (2009). *Two German merchant ships conquer famed Arctic passage*. Retrieved September 12, 2009, from http://archive.boston.com/news/world/europe/articles/2009/09/12/two_german_merchant_ships_conquer_famed_Arctic_passage/

North Atlantic Treaty Organization (NATO). (2007). *ATP 17(C), NAVAL ARCTIC MANUAL*. Retrieved April 2, 2014, from Navy Warfare Library.

NSR 2010 - Historic sea route opens through the Arctic to China. (2010). Retrieved from http://Arcticbulk.com/page/242/NSR_2010

Oil Companies International Marine Forum (OCIMF). (2017). *Northern Sea Route Navigation—Best Practices and Challenges* (1st ed.).[Brochure]. London: Author.

Onarheim, I. H., Eldevik, T., & Smedsrud, L. H. (2018). Seasonal and Regional Manifestation of Arctic Sea Ice Loss. *JOURNAL OF CLIMATE*, 31, 4917-4932.

Østreng, W., Eger, K. M., Fløistad, B., Jorgensen-Dahl, A., Lothe, L., Mejlænder-Larsen, M., & Wergeland, T. (2013). *Shipping in Arctic Waters: A comparison of the Northeast, Northwest and Trans Polar passages*. Berlin: Springer.

Pastusiak, T. (2016). *The Northern Sea Route as a Shipping Lane--Expectations and Reality*. Switzerland: Springer International Publishing.

Polyakov, I.V., Walsh, J.E., & Kwok, R. (2012). Recent changes of Arctic multiyear sea ice coverage and the likely causes. *American Meteorological Society*, pp. 145-151.

Reid, T. G. R. & Tarantino, P. M. (2014). Arctic Sea Ice Extent Forecasting Using Support Vector Regression. *13th International Conference on Machine Learning and Applications* (pp. 1-6). Detroit.

Robert, C. B., Tore, H., Kristine, D. K., Erik, J. M. & J. Ashley R. (2017). *Governance of Arctic Shipping*. Brill | Nijhoff. https://doi.org/10.1163/9789004339385

Roszkowska, E. (2011). MULTI-CRITERIA DECISION MAKING MODELS BY APPLYING THE TOPSIS METHOD TO CRISP AND INTERVAL DATA. *Multiple Criteria Decision Making, 6*, 200-230.

Roucek, J. (1983). The geopolitics of the Arctic. *American Journal of Economics and Sociology*, 42(4).

ROZIN, I. (2020). *Russia to build the world's most powerful icebreaker.* Retrieved February 23, 2020, from https://www.rbth.com/science-and-tech/331738-worlds-most-powerful-icebreaker

Rules of navigation in the water area of the Northern Sea Route, Ministry of Transport of Russia, (2013).

Rules of the repeatedly crossing by foreign ships the State Border of the Russian Federation, GOVERNMENT OF THE RUSSIAN FEDERATION, (2014).

Sakhuja, V. (2015). *Search and Rescue in the Northern Sea Route*. Retrieved February 20, 2015, from http://www.iecca.ru/en/legislation/strategies/item/363-search-and-rescue-in-the-northern-sea-route

Sea ice: types and forms. (2013). Retrieved July 23, 2013, from https://www.canada.ca/en/environment-climate-change/services/ice-forecasts-observations/latest-conditions/educational-resources/sea/types-forms.html

Shannon, C.E. (1948). A Mathematical Theory of Communication**.** *Bell System Technical Journal*, *27*(2), 379-423.

Singh, B. (2019). *5 Important Points for Ice Navigation of Ships.* Retrieved October 11, from https://www.marineinsight.com/marine-navigation/5-important-points-for-ice-navigation-of-ships/

Smith, L.C., & Stephenson, S.R. (2013). New Trans-Arctic shipping routes navigable by midcentury. *Proceedings of the National Academy of Sciences Plus*, 110, pp.4871–4872.

Talikoti, M. (n.d.). *UNIPOLAR VS BIPOLAR LIKERT SCALE QUESTIONS.* Retrieved from https://www.questionpro.com/blog/unipolar-likert-scale/

The Arctic Portal. (2012). *Central Arctic Shipping Route.* [Image]. Retrieved 26 Jun 2012 from http://library.arcticportal.org/1690/

The Baltic and International Maritime Council [BIMCO]. (2019). *The Ice Navigation and Seamanship Handbook* (e-book). London: Author.

The Northern Sea Route Administration. (n.d.). *Search and rescue, Prevention of pollution by oil.* [Image]. Retrieved from http://www.nsra.ru/en/pso.html

The Northern Sea Route: Rivalling Suez? (2014). Retrieved May 2, 2014, from http://www.eiu.com/industry/article/591780243/the-northern-sea-route-rivalling-suez/2014-05-02

Transpolar Sea Route. (n.d.). In *Wikipedia*. Retrieved from http://en.wikipedia.org/wiki/Transpolar_Sea_Route

VERNY, J., and GRIGENTIN, C. (2009). Container shipping on the Northern Sea Route. *International Journal of Production Economics*, 122(1), pp. 107–117.

Wang, E., Alp, N., Shi, J., Wang, C., Zhang, X. & Chen, H. (2017). Multi-criteria building energy performance benchmarking through variable clustering based compromise TOPSIS with objective entropy weighting. *Energy, 125*, 197-210.

Wang, Z., Ge, S. S., Zhang, R., Qian, L. X., Yang, M. G. & Xu, G. (2017). Risk assessment of the Northeast Passage of Arctic based on Rough set theory and Hesitate Analytic Hierarchy Process. *MARINE SCIENCE BULLETIN*, 36(5), 512-520.

World Meteorological Organization [WMO]. (2019). WMO Statement on the State of the Global Climate in 2018, Geneva: Author.

Yao, Y. D. (2015). Security Assessment of Arctic Northeast Route Based on Fuzzy Comprehensive Evaluation. Master Thesis. Dalian Maritime University, China.

Zhang, c. (2020). *China's 'Arctic Silk Road' projects.* Retrieved January 9, from https://chinadialogueocean.net/12569-chinas-arctic-silk-road-projects/

Zerohedge (2017). China's Mysterious Arctic Silk Road. Retrieved November 15, from https://oilprice.com/Geopolitics/International/Chinas-Mysterious-Arctic-Silk-Road.html