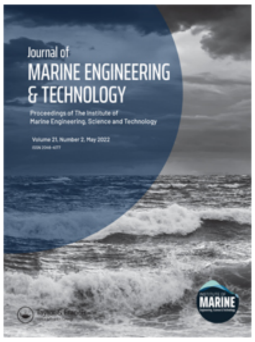

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A risk-based approach for determining the future potential of commercial shipping in the Arctic

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ABSTRACT
As global warming is causing a significant reduction in the extent and the thickness of Arctic sea ice, a narrative for future large-scale commercial shipping in the Arctic has started to evolve. However, while most efforts have aimed to assess the financial benefits along with potential savings in greenhouse gas emissions, few studies have explored risk patterns and safety issues associated with Arctic shipping and its current commercial alternatives in a geospatial manner. This study aims at addressing this gap in the literature, by assessing the risk factors associated with Arctic shipping, in particular, risks along the Northern Sea Route (NSR) connecting European and Asian ports. Its main component includes a global least-cost analysis, aiming to assess global and Arctic risk factors associated with commercial shipping, to derive the least risk paths from 10 major ports in Europe to 10 in Asia. To project the results into the future, and thus assess the future potential of the NSR as a viable and less risky alternative, a dataset on predicted sea ice thickness within 2010–2099, restricted the analysis based on the penetration capabilities of three selected vessel types. Ultimately, the study concludes that maritime transportation, bound for East-Asia, commencing from most northern European ports, could benefit from the NSR, not just in terms of distance savings, cost reduction and less CO2 production, but also as a safer alternative. Lastly, two recommendations drawn from our results aim to assist decision-makers in facilitating future Arctic transportation by addressing accessibility and safety issues.

Highlights

- We explore risk patterns and safety issues associated with Arctic shipping and its current commercial alternatives in a geospatial manner.
- We assess the future potential of the northern sea route (NSR) as a viable and less risky alternative for European-Asian shipping.
- We provide a discussion on pros and cons of utilising the NSR in terms of distance savings resulting in cost reduction as well as less CO_2 production, and as a safer alternative.

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1. Introduction

In the recent decades, the Arctic has experienced a rapid reduction in the extent and thickness of sea ice, and as the Arctic region continues to warm even faster than the global mean, year-round reductions of sea ice are projected to continue (IPCC 2014). Yet, despite the extraordinary transformations and risks of detrimental change to critical ecosystems and wildlife, the challenges epitomised by climate change has ignited optimism for a future with commercial shipping in the Arctic and subject to opinion, this optimism presents prospect or peril. The previously inaccessible shipping lanes in the Arctic have the potential to serve as maritime shortcuts between world economic centres in Europe and Asia. The Northern Sea Route (NSR), linking Europe with Asia, through the Arctic, has the potential to reduce the distance between Europe and Asia by as much as 40% (Ørts Hansen et al. 2016), cutting the transit time by 10–15 days (Rodrigue et al. 2016) as well as reduced costs and environmental pollution in terms of greenhouse gas emissions. In fact, summer sea ice has already been reduced to a thickness and extent which is navigable for reinforced containerships and tankers, enabling them to traverse thin patches of sea ice. In 2017, the

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reinforced Russian tanker 'Christophe de Margerie' travelled the NSR in record speed, and without the need for an icebreaker escort, for the first time, carrying a cargo of liquefied natural gas (LNG) from Hammerfest in Norway to Boryeong in South Korea in just 19 days (Barkham 2017), while in 2018 the first commercial containership, Mærsk's ice ship 'Venta Mærsk', successfully passed through the NSR in 37 days in a one-off trial passage from Vladivostok to Bremerhaven (Humpert 2019).

Thus, the logic behind the rationale of using the NSR for commercial shipping to reduce distance and travel time, which will ultimately lessen total fuel consumption, thereby cutting greenhouse gas emissions, bunker fuel costs as well as vessel operating costs (Rahman et al. 2014). Consequently, the NSR may not only spark economic sentiment but could also contribute to achieve the vision and objectives of the climate change strategy for shipping, which aims to cut global greenhouse emissions from the shipping industry by 50% by 2050, compared to 2008 emission levels (Shukman 2018).

However, despite the potential of reaping financial benefits and cutting CO_2 emissions, arctic shipping is associated with several risks, posing a significant threat to the ships involved as well as the sensitive and fragile environment. In recognition of this, the long-awaited International Code for Ships Operating in Polar Waters i.e. the Polar Code was adopted by IMO in 2014 (International Maritime Organization (IMO) 2015), entering into force on January 1st, 2017 (Allianz 2017). The Polar Code addresses issues such as the design, operation and safety procedures of vessels operating in Arctic and Antarctic waters, as well as environmental protection, in order to mitigate some of the associated risk factors, including a lack of hydrographic studies, the ice factor and the ability of salvagers to respond to an incident (Allianz 2017).

Due to the uncertain predicament of the Arctic, and the potential benefits and risks associated with Arctic shipping, the issue has received notable attention in the literature in recent years, e.g. in (Arctic Council 2009; Ho 2010; Lasserre 2014; Lee and Kim 2015; Ørts Hansen et al. 2016; Melia et al. 2017). However, most have aimed at assessing the economic potential associated with arctic shipping (Buixadé Farré et al. 2014; Lasserre 2014; Ørts Hansen et al. 2016), the institutional framework, policies and governance issues (Arctic Council 2009; Stokke 2013; Vanderzwaag et al. 2018) or the environmental impact (Lamson 1987; Larsen et al. 2016; Lindstad et al. 2016). Few have assessed, compared and predicted the risk scenarios, associated with the NSR and its alternatives, such as the southern sea route (SSR) through the Suez Canal.

The main objective of this study is to address this gap in the literature, with the aim of assessing the key risk factors associated with Northern Route and Southern Route shipping and project these risk scenarios into the future, using data from modelled Arctic sea ice predictions. The primary analysis was guided by a global level least cost path component, using risk factors as the integrated weighting structure and predicted sea ice thickness as a restriction. The aim is to assess the future evolution of the shipping industry between the European and Asian economic centres, emphasising risk as a core component. Furthermore, a multicriteria analysis of risk factors associated with arctic shipping specifically will supplement the global level least cost analysis, aiming to identify areas of increased/heightened risk. This analysis will be framed by the risk factors, however, as environmental considerations are one of the primary concerns associated with Arctic shipping, due to the sensitive environment, this component will accentuate fragile ecosystems and protected areas as a core component.

2. Literature review

2.1. Related work

Transportation in the Arctic poses serious risks caused by the unique characteristics of the region, such as ice, climatic changes and remoteness. The uncertainty in the performance of vessel operating systems and humans requires robust risk analysis and management tools in order to predict possible accidents and provide decision-support to prevent them and ensure safety at sea (Khan et al. 2018). For Kum and Sahin, safety is a real problem in the Arctic with accidents resulting in injuries and deaths increasing year by year since 1994 (Kum and Sahin 2015), proving the essentiality of a root cause analysis along with advancements in risk management and provision. Khan et al. proposed in 2018 an Object-Oriented Bayesian Network model for the dynamic prediction of oil tanker-ice collision probability in the NSR considering the state of navigational and operational systems, weather and ice conditions and human, while a year earlier Afenyo et al. had worked on the case of ship-iceberg collision, by also following the Bayesian Networks methodology (Afenyo et al. 2017). Similarly, a risk model based on operational and environmental factors was developed by Baksh et al. showing the East Siberian Sea as the riskiest area for collision, foundering and grounding for an oil-tanker in the NSR (Baksh et al. 2018). Considering a decision-making approach, the Fizzy Analytic Hierarchy Process was applied to rank the key criteria that influence the decisions of shipping operators when using the shipping routes in the Arctic, concluding that economy and safety are the most important among the influential factors (Tseng and Cullinane 2018).

2.2. Background on risk factors in global and Arctic shipping

As the shipping industry has become the mainstay of the global economy, maritime risk management issues continue to change, revealing new types of risks and hazards for the industry, and thus the identification of risk factors and their continuous mitigation should be emphasised. According to Allianz (2017) risk factors are defined as 'any external factors causing or contributing to an incident while at sea', including among others collision, allision and foundering that are not caused by human error or mechanical failure. This distinction is important to make, as it is estimated that 75% of all maritime accidents are attributed to human error (Allianz 2017), and thus beyond the scope of this study.

Shifting and potentially harsh weather conditions and climatic variables have always been a primary concern to the shipping industry, and incidents caused by weather extremes constitute the most frequent and severe risk factors in the shipping industry, with Capt. Andrew Kinsey noting that '*the severity of weather events, for whatever reason, is more pronounced and frequency is increasing*' (McDonald 2018). Even with the latest technological achievements in meteorological forecasting, the shipping industry is considerably damaged by natural catastrophes, such as hurricanes, storms or groundings due to strong winds, with recent examples the Superstorm Sandy in 2012 and damage of $84m and Hurricane Katrina in 2005 with $33m marine hull losses (Lloyd's 2017)

In particular, *wind speed* and *wave heights* are two primary external factors affecting ship movement and depending on the intensity level, both can pose a severe danger to a ship (Chang et al. 2014; Butt et al. 2015; Stornes 2015). Winds can be elusive, and contradictory to common perception, ship weight and size do not confine the way wind affects a ship. Similarly, significant *wave heights* create unpredictable motion resulting in the reduction of propeller thrust and drag increase from steering corrections. Constant corrections to the course and ship speed affect ship's performance in rough weather conditions.

Besides the hazards and risks determined by weather patterns and climatic variables, geographical hazards play a significant role in the safe navigation of ships. Examples of this type of risk include narrow channels with *shallow water*, as well as coral reefs (Bennett O'Brien 2015). Based on Stornes (2015), narrow coastal waters i.e. *shallow water* are considered as one of the primary risk factors, particularly in combination with extreme winds and high waves.

Although maritime infrastructure, including port network and search and rescue facilities, do not contribute to added risks for a ship while at sea, the relative distance to the nearest facilities may impact the extent and consequence of an accident. Therefore, the *distance to ports* is a safety concern to the shipping industry, particularly in areas, such as the Arctic, where maritime infrastructure is sparse and disconnected. The ability for authorities to reach a ship, provide search and rescue operations, salvage a wreck and clean up after an oil spill is essential, in order to limit the impact from a potential catastrophe at sea.

Next to the 'global level' risk factors, several risk factors also pose a severe threat to shipping, however, these are mainly limited to a local and regional extent. These include the risk of *icebergs*, *piracy* and geopolitical instability, such as the Yemen conflict and territorial disputes in the South China Sea. *Icebergs*, extreme conditions and a lack of detailed hydrographic studies in the Arctic (hereafter referred to as *icebergs*) pose a severe threat to ships traversing arctic and Antarctic regions. Icebergs pose an imminent danger to a ship, particularly as most of the iceberg is subsurface, making them difficult to detect and size. The difficulty in detecting icebergs is only impeded as many sizeable icebergs are frozen into thin layers of first-year sea ice. Besides, the icebergs themselves, extreme conditions caused by low temperatures threaten the survivability of ships essential computer systems, making emergency preparedness procedures and special tools for ice removal an essential component for arctic shipping (Allianz 2017). The risk of piracy has been a highly debated topic in recent years, particularly in the Gulf of Aden and south-east Asia where piracy continues to pose a threat to the shipping industry. However, international efforts to address the issue, as well as the ability of major shipping companies to respond to the threat by hiring private security companies to stay and protect the ship while traversing these regions, has had some effect in recent years. Even so, attempts to contain the issue has not addressed it completely, and a return of activity in Somalia has shown that the risk should not be underestimated, particularly in West Africa and the Far East (Allianz 2017).

The remainder of the paper is structured as follows. Section 3 presents materials and methods applied in the study. Section 4 illustrates the achieved results while having them discussed in Section 5. Finally, the study draws some conclusions and future research directions in Section 6.

3. Materials and methods

3.1. Data and study area

As this study aims to identify the least risk sea routes between Europe and Asia, the analysis was conducted at a near-global level based on the main risk factors indicated in the previous section, and thus delineated by the ocean surfaces lying outside of the geographical extent of Europe and Asia. In addition to the 7 core data components with respect to risk factors, data on projected sea ice thickness was collected, using the subcomponent simulating long-term monthly mean changes (2005–2099) of global sea ice thickness, from the Hadley Global Environment Model 2 – Carbon Cycle (HadGEM2-CC). This data was acquired from the Lawrence Livermore National Laboratory peer node of the Earth System Grid Federation (available at https://esgf-node.llnl.gov/search/esgf-llnl/), in a netCDF-4 format conforming to the NetCDF Climate and Forecast (CF) Metadata Conventions (http://cfconventions.org/). As part of the Coupled Intercomparison Project (CMIP), developed in the auspices of the Intergovernmental Panel on Climate Change (IPCC), the model output conform to the Representative Concentration Pathways (RCPs), which assumes varying baselines of greenhouse gas emissions and atmospheric concentrations, air pollutant emissions, and land use (IPCC 2014). The model acquired for this study, uses the RCP4.5 scenario as a baseline. The RCP4.5 is an intermediate mitigation emission scenario that stabilises direct radiative forcing at 4.5 W/m2 (~650 ppm CO2 equivalent) by 2099 (IPCC 2014). The data components and acquisition process of the 7 risk factors are described further below:

- Global ocean *wind speeds* consist of monthly averaged wind variables calculated over the global ocean from May 2007 to January 2017. The data was acquired from the Copernicus Marine Environment Monitoring Service (CMEMS) under the identifier WIND_GLO_WIND_L4_REP_OBSERVATIONS_012_003 in NetCDF format (http://marine.copernicus.eu).
- Global average significant *wave heights* were acquired from CMEMS, under the identifier GLOBAL_ANALYSIS_FORECAST_WAV_001_027, in NetCDF format. Consisting from daily measurements and forecast predictions, the average values were extracted from this dataset, using a representative sample of 7 daily averages (1st, 5th, 10th, 15th, 20th, 25th, 30th) of each month.
- *Shallow water* areas derive from a global bathymetry dataset, downloaded from openDEM (http://www.opendem.info/), originally derived from the General Bathymetric Chart of the Oceans GEBCO_2014 Grid, version 20141103 www.gebco.net, (Weatherall et al. 2015) in vector format. Considered shallow water, depth values of 25 m or less was extracted from the complete dataset.
- As a measure of climatic extremes, a dataset on *cyclone intensity* was downloaded from the PREVIEW Global Risk Data Platform (http://preview.grid.unep.ch) as a raster surface, which is created and hosted by UNEP/GRID-Geneva and Supported by the United Nations International Strategy for Disaster Reduction (UNISDR). The dataset entitled tropical cyclones wind speed buffers footprint 1970–2009 includes an estimate of tropical cyclones windspeed buffers footprint of maximum Saffir-Simpson category.
- Maritime infrastructure was measured based on the relative distance to the nearest port facilities (distance to ports). The World Port Index (Pub 150) from the National Geospatial-Intelligence Agency (National Geospatial Intelligence Agency) provides information on the location, physical characteristics, and the facilities and services offered by major ports and terminals worldwide. From each vector point in this dataset, buffer zones were created using Euclidean distances analysis. From these distances, 5 categories consisting from incremental steps of 200 km, where less than 200 km (equal 1) is considered the safest areas and further than 800 km is considered the most dangerous (equal 5), were used as a measure of maritime infrastructure.
- Data on piracy-related incidents at sea, during the period from 2006 to 2018, was acquired from the International Maritime Organization (http://www.imo.org) (International Maritime Organization (IMO) 2018), as a geo-referenced point dataset. This point feature dataset was used to calculate kernel densities, in order to extract a surface layer with approximate densities in all grid cells.
- A dataset was developed to represent the added danger from icebergs and harsh weather conditions in the Arctic as vectors. This dataset is based on a thorough literature review on climatic extremes in the Arctic, as well as data on iceberg sightings and approximate iceberg densities from simulation models.

Lastly, as a key constituent in a least-cost analysis, 10 major ports in Europe and Asia were selected as source and destination points. These ports were selected based on their respective size, as reported to the World Shipping Council (WSC), as well as considerations of spatial distribution. Ultimately, a point feature layer was created as a representation of the final selection of 10 source and 10 destination points, using the reported coordinates for each port from https://www.searoutes.com. The chosen

Table 1. Source and destination ports used in the least-cost analysis.

European ports		Asian ports		Distance (NM)	
Name	Country	Name	Country	Suez Canal	NSR
Rotterdam	Netherlands	Shanghai	China	10525	8217
Antwerp	Belgium	Singapore	Singapore	8293	–
Copenhagen	Denmark	Shenzhen (Hong Kong, Guangzhou)	China	10382	8956
Bremen	Germany	Busan	South Korea	11031	7611
Valencia	Spain	Qingdao	China	9146	9896
Algeciras	Spain	Tianjin	China	9693	9679
Felixstowe	U.K.	Kaohsiung	Taiwan, China	9840	8779
Piraeus	Greece	Keihin Port	Japan	8496	–
Istanbul	Turkey	Laem Chabang	Thailand	6584	–
Gioia Tauro	Italy	Manila	Philippines	7283	–

ports and the indicative distances between them when going through the Suez Canal and the NSR are presented in Table 1.

3.2. Methods

In this study, least cost analysis was applied using the primary risks associated with global, and arctic shipping, as the core cost components, thus forming the basis for a risk-based cost surface. The objective was to identify the least cost routes, in terms of risks, between 10 major ports in Europe and 10 spatially distributed major ports in East and Southeast Asia. The core risk factors were identified from an extensive literature review on risks associated with global maritime shipping, and consists of *wind speed*, *wave height*, *shallow water* areas, *cyclones*, *piracy*, maritime infrastructure (*distance to ports*), as well as the generally harsh climatic conditions in addition to *icebergs*, specifically in the Arctic. Recognising that all 7 risk factors do not necessarily apply at a regional and local level, the two major region-specific risk factors, *icebergs* and *piracy*, was selected to avoid bias.

3.2.1. Cost distance analysis

Least cost path analysis (LCPA) is a distance analysis within geographic information science (GIS), which enables users to determine the most cost-effective route between two or multiple sources and destination points, based on a cost surface, computed by combining several criteria representing different issues (Chang 2016). In the present study, the LCPA was conducted in the Cost Path tool in ArcMap from all source points (European ports) to all destination points (Asian ports) based on the produced risk maps.

Particularly, aside from specifying the source and destination points, the cost path tool requires the use of two additional raster surfaces: the least cost distance raster and the back-link raster, which were created using the Cost Distance and Cost Back-Link tools. The execution of these tools requires the setting of a source point and the cost raster. The European ports were divided to individual point shapefiles and an iterative model, created with ArcMap's Model builder, was used to iterate the cost surfaces, displaying the variations of risk factors combined with the decadal predictions of sea ice extent. Each pair of produced cost distance and cost back link surfaces were then called in a Python script, for the computation of each path for each year, month and vessel type examined for each of the selected ports.

3.2.2. Analytical Hierarchy Process

As a precursor to a least-cost analysis, the relationship between risk or friction cost criterion must be established through a weighting system. One means to support users in establishing a weighting structure is by using the Analytical Hierarchy Process (AHP). AHP is a commonly used method for deriving ratio scales from discrete or paired comparisons (Bagheri and Azmin 2010). Using this method, multiple criteria are compared with each other, to establish a weighting structure based on the relationship between all criteria. These comparisons stem from the literature review and are presented in Table 2. Using Saaty's methodology, the 7 risk factors were evaluated and compared to each other on a scale of 1–9 with differential semantic scoring (Saaty 1987). The scale of differential scoring presumes that the row criterion is of equal or greater importance than the column criterion. The reciprocal values (1/3, 1/5, 1/7, or 1/9) are

Table 2. Pairwise ranking matrix of risk factors.

	Wind	Waves	Shallow Waters	Distance to Ports	Cyclones	Piracy	Icebergs
Wind		1	3	5	8	8	9
Waves	1		3	5	8	8	9
Shallow Waters	1/3	1/3		3	5	5	6
Distance to Ports	1/5	1/5	1/3		4	4	5
Cyclones	1/8	1/8	1/5	1/4		1	3
Piracy	1/8	1/8	1/5	1/4	1		3
Icebergs	1/9	1/9	1/6	1/5	1/3	1/3	

used where the row criterion is less important than the column criterion. AHP has been broadly used throughout literature ((Effat and Hassan 2013); (Berrittella et al. 2009); (Bagheri and Azmin 2010); (Suresh et al. 2007); (Castellanos Abella 2008)).

4. Results

The first task was to generate least risk paths from 10 European to 10 Asian ports based on a risk map, calculated from the 7 risk factors and the changes of sea ice thickness throughout the study period (decades from 2010 to 2099) for two different seasons (March and September). The sea ice wintertime maximum, in March and September, were selected as representable months for the winter and summer periods for the computation of the risk maps, while data on sea ice thickness were used to confine results to those representing 3 different types of ships, with different capacities. The vessel types were distinguished based on their ice-penetrating qualities, determining the thickness of the sea ice that they can effectively penetrate. The three representational vessel types used in this study are; a container ship with a penetration ability of 0.2 m, a slightly reinforced vessel, conforming to Polar class 6-7, (1 m) and a reinforced vessel of Polar Class 3–4 (1.5 m).

4.1. Calculation of risk maps

Based on a literature review on maritime incidents, 7 risk factors were selected and evaluated by establishing a pair-wise weighting system. A winter and a summertime weighted overlay (risk map) were created, using AHP as a method for retrieving a percentwise weighting structure between all risk factors; *wind speed*, *wave heights*, *cyclones*, *shallow water*, *piracy*, *icebergs,* and *distance to ports*. The risk factors were ranked based on a review on the likelihood and potential outcome of an incident caused by the individual risk factors. This ranking was used to inform the final weighting structure of all risk factors using the AHP approach. The outcome of the pairwise ranking exercise conducted through AHP is presented in Table 3, along with the actual and risk values in the original and reclassified datasets for each of the risk factors. The reclassification is required due to the differentiations of the numbering systems with the different ranges combined in a single analysis.

The seasonal 5-scale risk maps produced through Weighted Overlay tool are based on the above-mentioned weighting structure and displayed in Figure 1 below. The wintertime (March) risk map has a greater variation in risks, as well as higher risk values, primarily due to the higher winds and waves during the Arctic fall and winter. The summertime (September) values are much more moderate, and the changes are subtle in the northern hemisphere.

4.2. Least cost analysis: least risk paths through the northern sea route

The two risk surfaces were processed in combination with the sea ice thickness data, to create null values from ice thicknesses exceeding the capacity of each selected vessel type, and the output raster layers were used as cost surfaces, to determine the least cost paths. Observations on the produced least cost paths are presented here based on firstly the seasonal variation among vessel types, followed by specific observations of the trajectory of paths along the northern sea.

Firstly, regarding the results in September, more than 50% of routes are indicated to be shorter and less risky when passing through the Arctic, ranging from 56% to 65% depending on the vessel type. More specifically, the average proportional least risk routes through the NSR, is at 65%, regarding vessel types with a penetration rate of 1.0 and 1.5 m. A standard container ship has slightly lower penetration rates at 56%. On the other hand, the results in March indicate a considerable seasonal variation when compared to the summertime results. No standard containership will be able to traverse the NSR during March until 2099, while March shipping for slightly reinforced vessels (1.0 m) is possible, and least risky, only in the years of 2040 and 2060. On the other hand, a reinforced vessel type (1.5 m), will be much more effective in traversing the Arctic sea with a penetration rate of 48%.

The specific trajectory of the least risk paths along the northern sea route was comparing to a collection of least distance paths (assuming an ice-free Arctic sea), created the least distance cost environment. The most significant features were examined, accounting firstly for the differences over time among the vessel types in summer, and subsequently between summer and winter time navigation. The least cost routes will be compared to those of a least distance path analysis, thus allowing for comparison of risks and arctic sea ice, to the shortest northern sea route path, in terms of distance.

The maps presented in Figure 2 and Figure 3, display the shortest distance path and a sample of least risk paths for selected years. In the top part of the map in Figure 2, the predicted least risk paths in September for a standard containership (SIT $<$ 0.2 m) and a slightly reinforced vessel (SIT $<$ 1.0 m) are shown, and in the lower part of the map, the reference, least distance paths are included. This allows for a detailed comparison of a measure of absolute distance, risk factors, and

Table 3. Calculated weights from AHP.

Risk factor	Weight	Description	Actual Values	Field Value	Scale Values	Risk
Wind speed	32%	Wind and waves are considered the highest ranked risk factors, of equal importance. This is primarily determined by the likelihood of an incident, particularly foundering and container droppings, being triggered by or contributed too, by strong winds and waves.	8-9 m/s	1	5	Low
			9-10 m/s	2	4	Moderate
			10-11 m/s	3	3	High
			11-12 m/s	4	2	Very High
			> 12 m/s	5	1	Extremely High
			0–8 m/s	No Data	5	Low
Wave height	32%	2-3 m	1	5	Low	
			3-4 m	2	4	Moderate
			4-5 m	3	3	High
			5-6 m	4	2	Very High
			> 6 m	5	1	Extremely High
			0–2 m	No Data	5	Low
Shallow water	15%	The second most common type of maritime incidents are groundings, and besides those accidents triggered by human error, the majority are caused by undetected submerged features and shallow water areas. The impact from these grounding incidents can have a catastrophic impact, e.g. the Exxon Valdez oil spill, and thus *shallow water* is considered the 2nd highest ranked risk factor	Depth of less than 25 m	1	1	Extremely High
			Depth of more than 25 m	2	5	Low
Distance to ports	10%	*Distance to ports* has a profound impact on the potential scale of an emergency at sea, and particularly in the Arctic. Accordingly, and despite not contributing directly as a risk factor, the indirect contribution of maritime infrastructure as a mechanism for enhancing safety at sea, makes the distance to ports the fourth highest ranked criteria.	< 200 km	1	5	Low
			200–400 km	2	4	Moderate
			400–600 km	3	3	High
			600–800 km	4	2	Very High
			> 800 km	5	1	Extremely High
Cyclones	4%	Linked to wind and waves, extreme weather events caused by *cyclones* can have potentially catastrophic impacts on container ships, contributing to everything from container loss to foundering.	Category I	1	5	Low
			Category II	2	4	Moderate
			Category III	3	3	High
			Category IV	4	2	Very High
			Category V	5	1	Extremely High
			0	No Data	5	Low
Piracy	4%	Still considered a threat, the likelihood of being attacked by pirates is limited, however, the outcome could be potentially catastrophic. For a shipping company, the potential of having a ship grounded and inactive, potentially for years, as well as having personal lives at risk, is disastrous, particularly if the outcome results in a loss of lives or multimillion-dollar ransoms.	NA	1	5	Low
			NA	2	4	Moderate
			NA	3	3	High
			NA	4	2	Very High
			NA	5	1	Extremely High
			NA	No Data	5	Low
Icebergs	3%	*Icebergs* are considered the lowest ranked risk factor in this study, primarily because of the relatively few documented cases of iceberg collisions. However, additional traffic in Arctic waters, as well as melting sea ice calving further *icebergs*, will likely cause further incidents in the future, should the NSR be used for commercial shipping. Furthermore, the *icebergs* risk factor includes considerations about the extreme conditions in the Arctic, which exacerbates the likelihood of an accident caused by damages to essential equipment, material, and systems.	Extreme Conditions	*1*	*2*	Very High
			Extreme Conditions + High density of Icebergs	*2*	*1*	Extremely High
			NA	*No Data*	*5*	*Low*

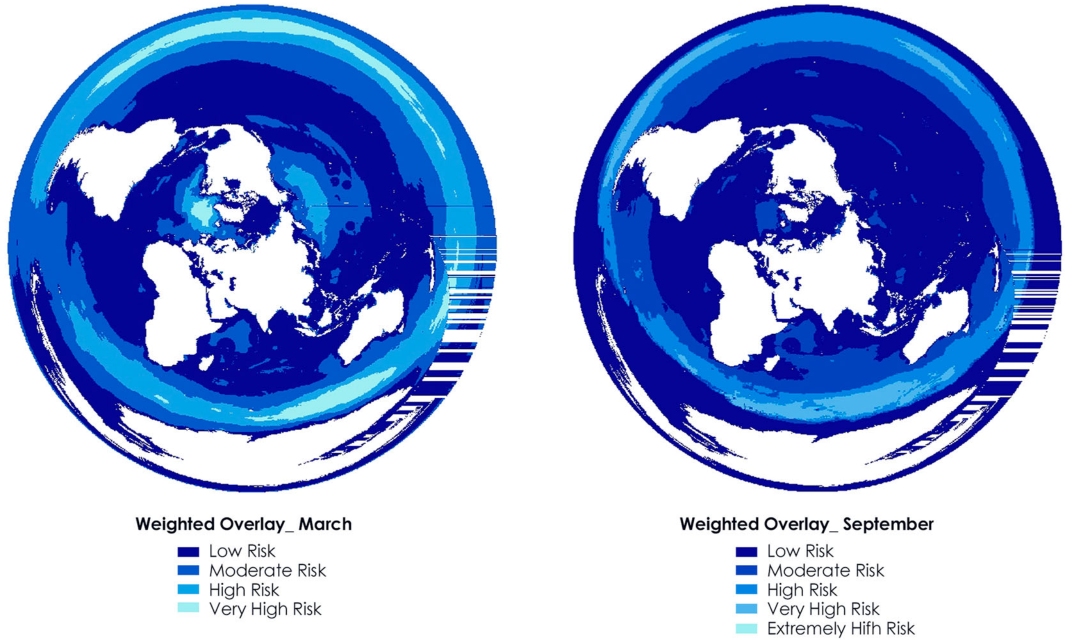

Figure 1. Seasonal risk maps (March left and September right).

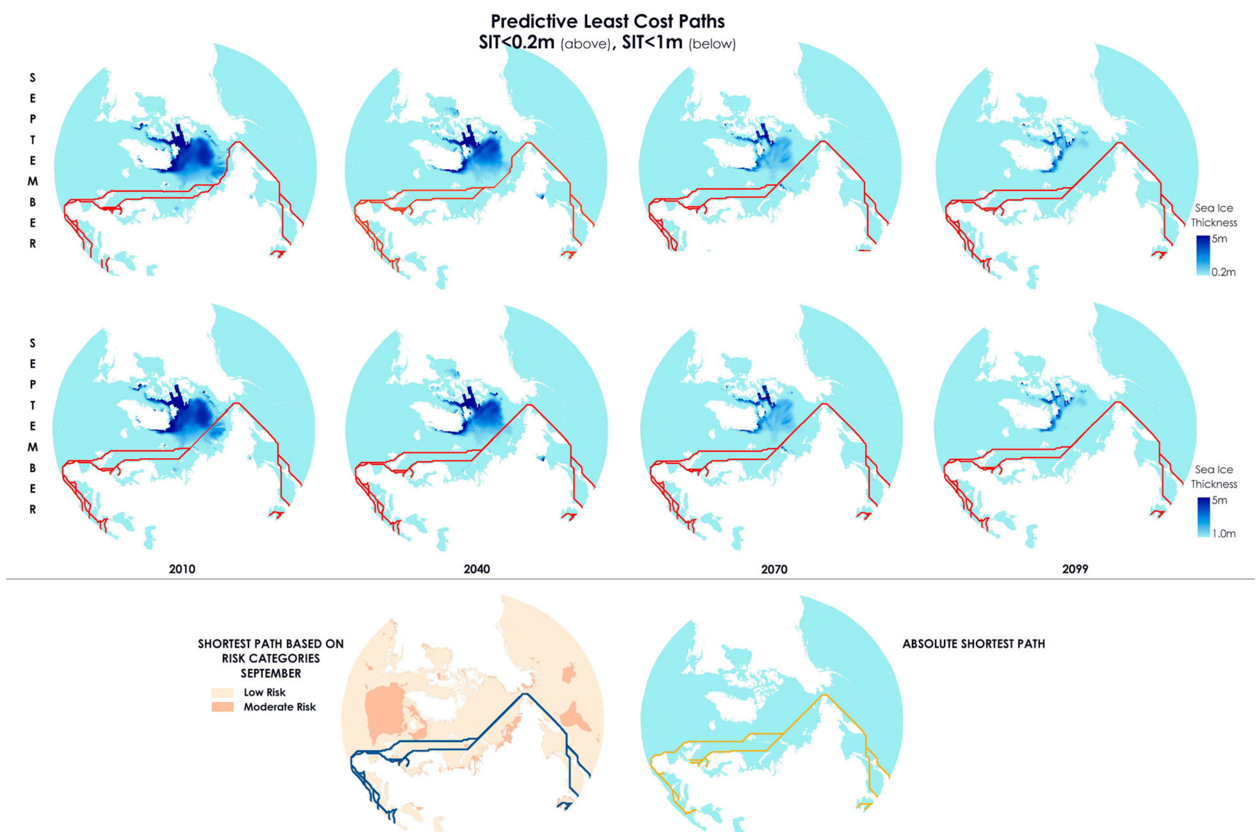

Figure 2. Predicted least risk paths for September for a standard containership (0.2 m) and a slightly reinforced vessel (1 m).

sea ice thickness. As can be seen from the map, a standard containership will be able to traverse the Arctic sea in September, throughout the study period, however, initially the routing will stick very close to the Russian coastline, whereas a changing pattern is observed from 2040, where the sea ice has melted to an extent which enables ships to traverse areas closer to the north pole. From 2070 and onwards, the least risk paths are almost

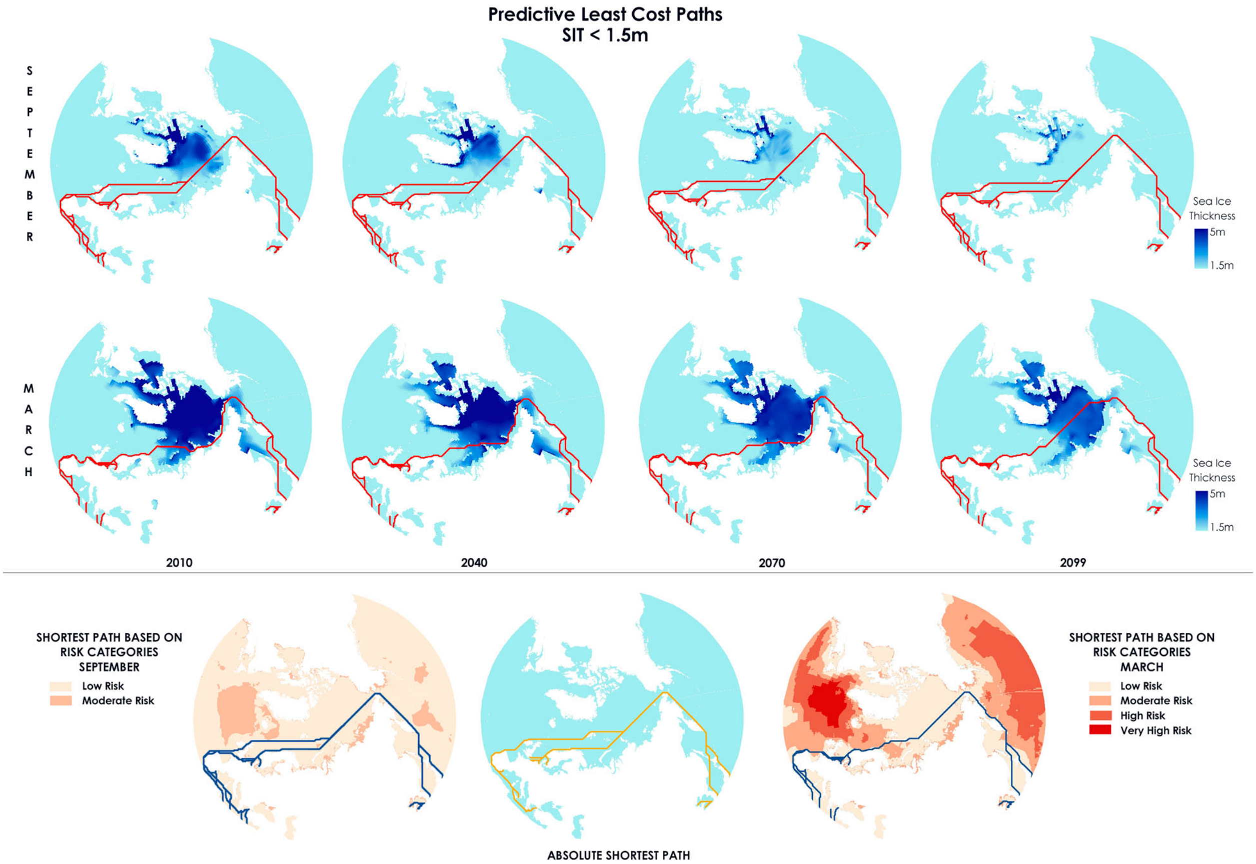

Figure 3. Predicted least risk paths for September and March for a reinforced vessel (1.5 m).

identical to those of the reference least distance paths, indicating a strong relationship between distance (time spent at the ocean) and risks. Slightly reinforced vessels are already capable of traversing the least distance paths in 2010, continuing to be able to do so throughout the study period.

The map presented in Figure 3 includes the variation of routes for a reinforced vessel with a 1.5 m penetration rate for both summer and winter time. The wintertime results have not been included for the vessel types 0.2 m and 1 m due to the limitation caused be sea ice thickness. Thus, as previously mentioned, no standard containership will be able to traverse the NSR throughout the study period during wintertime, and a vessel type of 1 m will only be able to travel the route in 2040 and 2060. Accordingly, a heavily reinforced vessel is needed to traverse the Arctic sea during wintertime throughout the period. However, firstly, as can be seen from the map a reinforced vessel with a penetration rate of 1.5 m will already now be able to traverse a summertime route, closely resembling that of a least distance path. During winter, the reinforced vessel will be able to traverse a route, similar to that of the summertime route for the standard containership and slightly reinforced vessel types, clamming closely to the Russian coastline. This pattern will continue throughout the study period, and only change in the latter part of the century, allowing for navigation through the centre of the Arctic sea, thus decreasing the total distance travelled.

Looking more specifically into how least risk paths will change over time, relative to distance travelled, the graph presented in Figure 4 shows the evolution of least risk routes in terms of km, from Copenhagen to the Japanese port of Kelhin, for each ship type. The graph also includes a baseline shortest path, which is 12,750 km long.

As shown in Figure 4, reinforced vessels are capable of navigating a route closely resembling the kilometre range of the baseline path, in September. For a standard containership, however, a dramatic decrease in kilometres travelled is seen in the first part of the study period, reaching a minimum distance around 2070, cutting approximately 500 km from the 2010 measurement. For a reinforced vessel with a 1.5 m penetration rate, the changes during winter are even more dramatic, falling from a path clamming to the Russian coastline, measuring almost 14,000 km to around 13,000 km at the end of the study period. This indicates the potential to significantly cut transition times, as well as decrease fuel costs and cut emissions associated with marine transportation. Furthermore, as these least risk routes are preferred to that of the alternative Suez Canal route, Arctic shipping

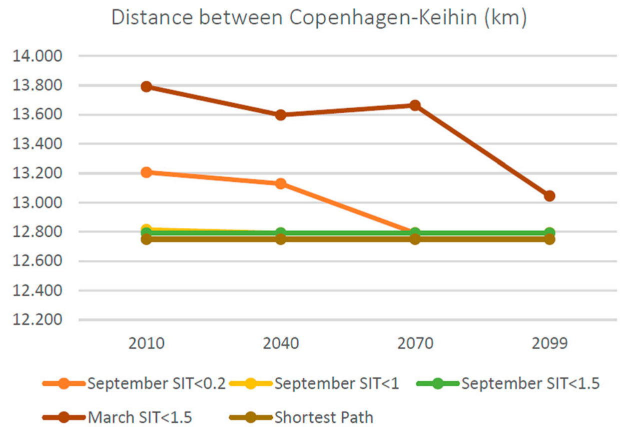

Figure 4. Changes in distance over time in least risk paths between the ports of Copenhagen and Kelhin.

may also provide a safer alternative, especially when considering that the shortest route through the Suez Canal is more than 2 times longer, at approximately 25,200 km. However, even though these results indicate that the NSR provides a less risky alternative, the sensitivity of the environment, as well as the remoteness of the Arctic sea to maritime infrastructure presents additional challenges and concerns.

4.3. Risk assessment of the Arctic shipping

To support decision makers and risk management authorities in shaping directions towards a more sustainable and less hazardous future of Arctic shipping, a multicriteria analysis was also conducted in order to identify areas of potentially high risk. The analysis was conducted from an environmental perspective, which is one of the primary concerns related to future Arctic shipping. The sensitive and fragile environment, combined with harsh conditions and a scarce maritime infrastructure enhances the risk and exacerbates the impact of a potential disaster.

The same datasets, which were used in the least cost analysis, were used in the multicriteria analysis, except for the *cyclones* and *piracy*, both of which do not pose a serious risk to shipping in Arctic waters. However, the weights were adjusted, specifically to emphasise the environmental perspective. The AHP approach was used to rank and weight the five different criteria used (*wind speed*, *wave height*, *icebergs*, *distance to ports* and *shallow water*). The final weights used are presented in Table 4.

Wind and waves still pose the greatest risk overall, however, in the Arctic ocean, maritime infrastructure is particularly scarce. The concerns for an environmental disaster is exacerbated by the fact that authorities have limited scope and opportunity to react quickly to

Table 4. AHP calculated weights for multicriteria analysis.

Risk factor	Weight
Wind speed	28%
Waves height	28%
Distance to ports	28%
Icebergs	9%
Shallow water	7%

an incident, as the limited capacity and resources are intensified by the scarcity of potential ports to be used as vantage points for salvage operations. Therefore, *distance to ports* is ranked equally as important as waves and wind, followed by *icebergs* and *shallow water*. By determining the weights, a weighted overlay analysis could be conducted in GIS, and from the output, three distinct risk classes were identified in the Arctic. However, to take into account, not only the risk of an incident but also the potential impact on fragile ecosystems, the reclassified high-risk areas were overlaid and intersected with a dataset of marine protected areas in the Arctic (UNEP-WCMC and IUCN [2018]). From this intersection, three distinct classes were developed;

(1) High-risk areas within 100 km from a marine protected area (Extreme risk)
(2) High-risk areas within 500 km from a marine protected area (Very high risk)
(3) High-risk areas further than 500 km away from a marine protected area (High risk)

The result of the multicriteria analysis is shown in Figure 5, which shows that the majority of the waters in the central Arctic sea, between Russia and the North Pole, is considered areas of increased risk. This is largely due to a combination of the harsh weather conditions, the risk of icebergs and the long distances to the nearest port/search and rescue facilities.

5. Discussions

Transarctic transportation has the potential to significantly reduce the travel distance and time for commercial shipping between Europe and Asia, ultimately contributing to significant savings in fuel costs and emissions. This is particularly true for transportation purposes between ports in Northern Europe and north-east Asia, where the cost savings potential is the largest, compared to the alternative southern route through the Suez Canal. As Figure 4 indicates, the distance between Copenhagen and the Japanese port of Keihin will dramatically change during the study period using the NSR. By 2099, the least risk paths will largely resemble the shortest possible path

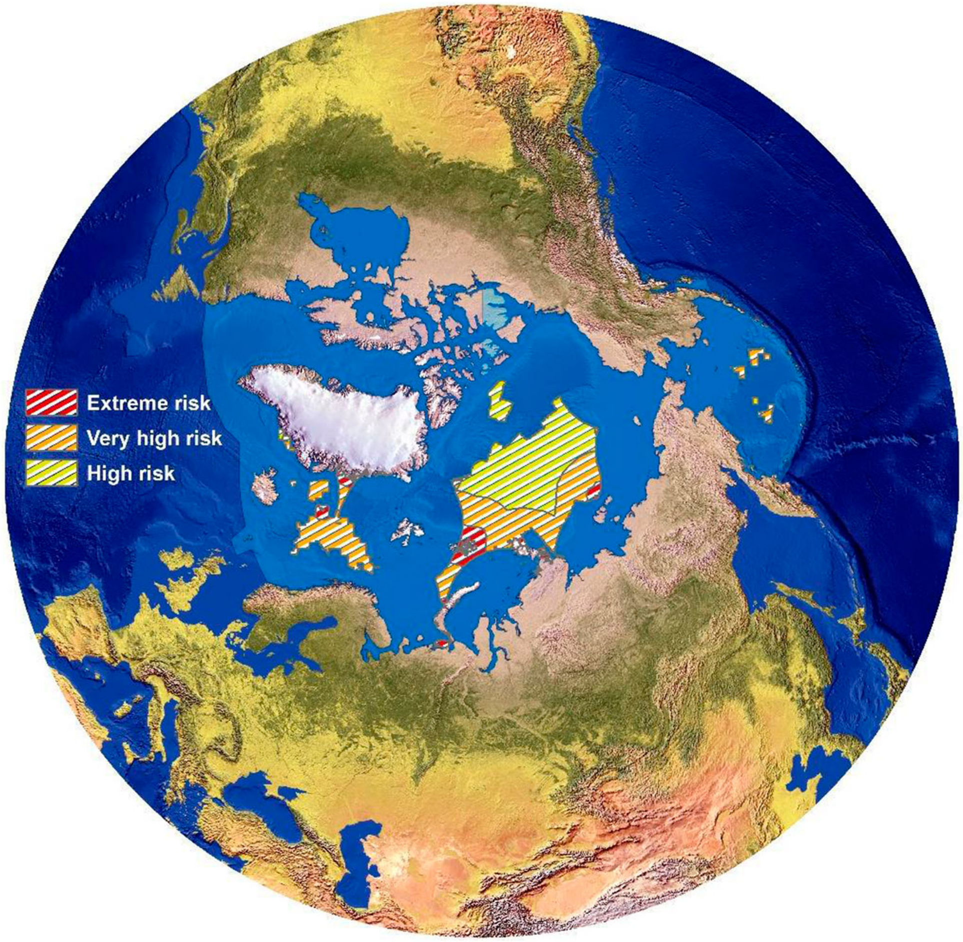

Figure 5. Arctic shipping risk map (Environmental focus).

through the Arctic, if no sea ice is present and this will increase the opportunity for commercial arctic shipping. However, the fact that these least risk paths also parallel the paths used in a least distance analysis, also points towards the fact that risk is very much a variable of time, and time (distance travelled) is one of the greatest risk factors in the shipping industry.

However, how feasible is commercial shipping through the NSR and what type of containership would allow for continuous arctic transportation throughout the twenty-first century? Currently, the navigation of the NSR imposes significant requirements and demands on vessel type, and the need for additional strengthening, reinforcement, and equipment. Thus, even though economic incentives may be high, so are the costs for acquiring the minimum technical components needed to navigate the arctic ocean. These investments in reinforced hulls and additional equipment may impede the economic benefits of year-round trans-arctic shipping.

However, navigating the NSR during the minimum summer sea ice extent, between June and October, is foreseeable for a standard containership within the near future. The average percentage of least cost paths traversing the Arctic, throughout the study period, for each ship type and from each European port is shown in Figure 6 below. As can be seen, it is estimated to be no difference between the number of arctic least cost paths for a vessel with a 1.0 and 1.5 m penetration rate, whereas the difference between a vessel with a 0.2 m penetration rate and the other two vessel types is limited.

Thus, according to the model used in the study, commercial shipping during the summer sea ice minimum should already be feasible in the foreseeable future, without the need for significant reinforcements. However, even so, the inherent dangers of Arctic shipping remain, and vessels will still need to adhere to the Polar Code, and this may imply additional costs associated with Arctic shipping even in the summer sea ice minimum.

During the winter maximum sea ice thickness i.e. March, however, the passage of the NSR is predicted to be only feasible using significantly reinforced vessels. Standard containerships or slightly reinforced vessels with a penetration rate of up to 1.0 m are largely predicted to be unable to navigate the arctic ocean in the winter sea ice maximum throughout the study period. However, the inability to penetrate the sea ice during winter

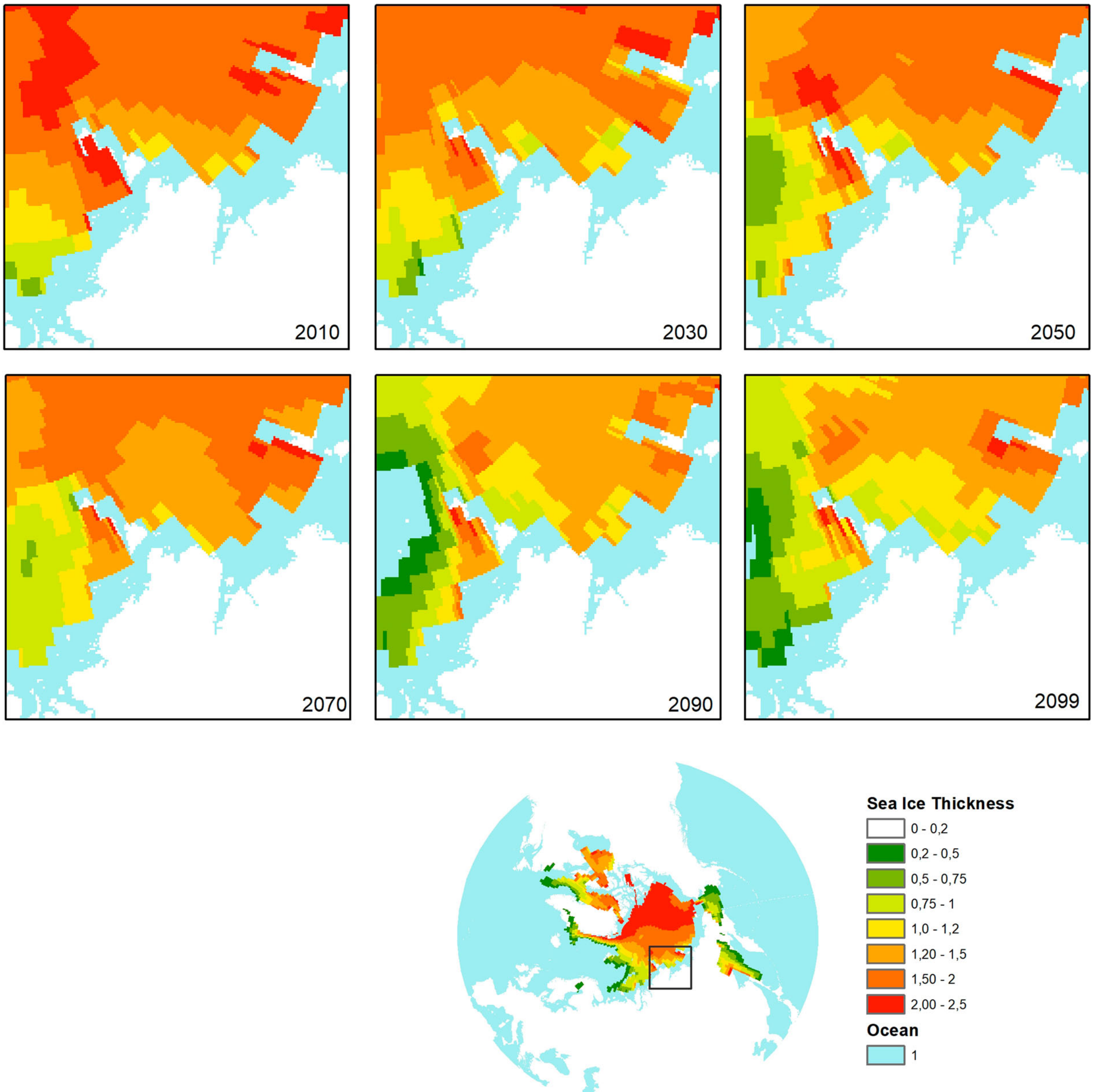

Figure 6. Predicted sea ice thickness near Bolshevik island from 2010 to 2099.

throughout the study period is largely determined by the thickness and extent of the sea ice in a small stretch of ocean in the western part of the Laptev Sea. As shown in Figure 6, trans-arctic passage is mainly determined by the sea ice thickness in this small area, to the east of Bolshevik island. According to the Hadgem2-cc model, the sea ice thickness will remain above 1.0 m throughout the study period in this small stretch of ocean and thus will remain a barrier for arctic trans passage during the winter.

5.1. Environmental considerations

Using a risk-based model, and the predicted thickness of the Arctic ice sheet, from 2010 to 2099, this study has concluded that the future of Arctic shipping does not only offer the potential for economic benefits and emission savings but could also present a safer and more reliable route between the economic centres of Europe and Asia. However, the environmental risks are exacerbated by the limited maritime infrastructure, which limits the opportunities for search and rescue, as well as salvage operations, to mitigate the extent and impact of a severe accident in the Arctic ocean. Remembering the Exxon Valdez oil spill in Alaska in 1989, similar scenarios have been strongly debated and remain one of the primary causes of concerns about Arctic shipping. However international efforts, such as those imposed through the Polar Code has the potential to underpin the existing policies

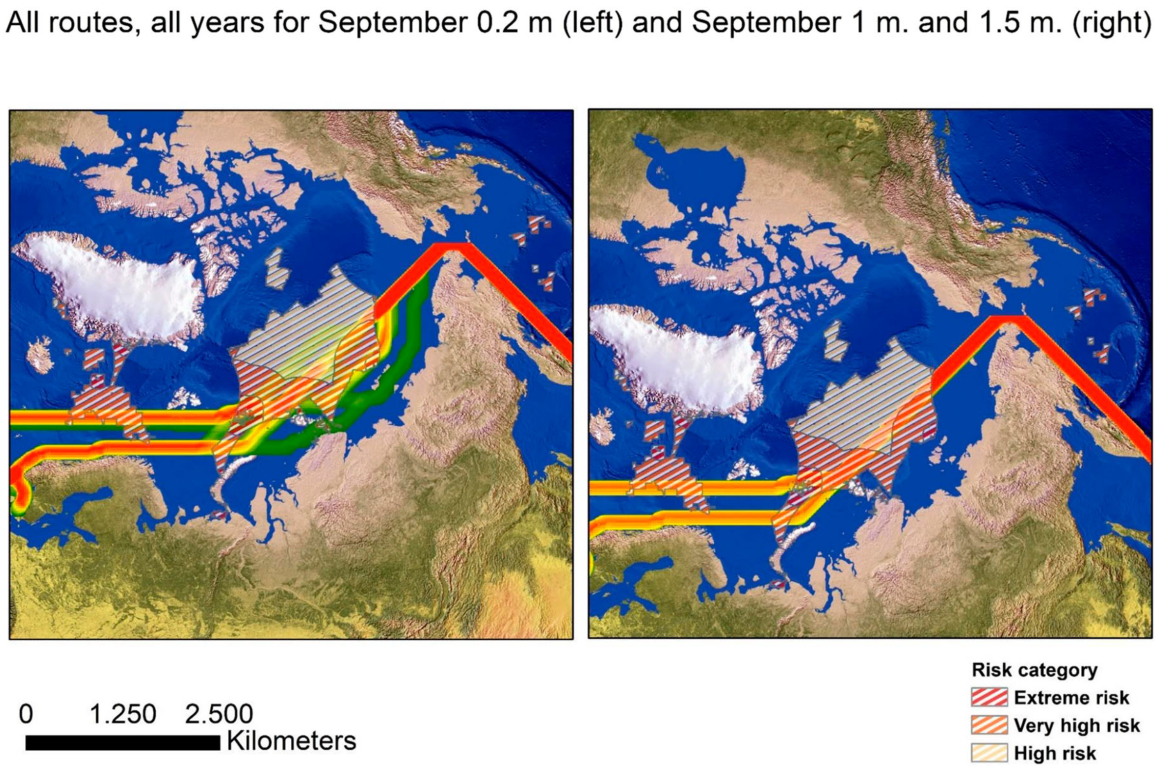

Figure 7. Heatmap indicating the variation and concentration in all least risk routes until 2099 overlaid with the Arctic risk map.

for environmental protection in the Arctic and mitigate the potential of a disastrous oil spill in the fragile Arctic waters.

The arctic shipping risk map, developed as an outcome of this study, also highlights the areas of greatest concern, in terms of the likelihood of an incident caused by the primary risk factors and the vicinity of these areas to environmentally sensitive areas in the Arctic (Marine Protected Areas). In this risk map, the distance to existing maritime infrastructure hubs (ports) is one of the primary risk factors associated with Arctic shipping, and the areas of greatest concern are also furthest away from existing ports in the Arctic. Looking at the global level study, and the least risk paths, the results of the analysis shows that most of the least risky paths throughout the study period will tend to concentrate in the areas of concern, identified in the risk map. Figure 7 illustrates the concentration and variation of the September least cost paths, for all vessel types. As this is the time of summer minimum ice extent, the 1.0 and 1.5 m vessels achieved almost the same penetration rate and thus the routes are nearly identical, thus presented in one map. The paths of the standard containership, with a penetration ability of 0.2 m, concentrates along the Russian coastline in the first couple of decades of the analysis (2010–2030), whereafter it shifts to the north and spreads in an irregular pattern, concentrated in the middle of the main risk zone identified in the risk map. For the 1 and 1.5 m vessels, the paths throughout the century are almost identical and concentrated in the middle of the high-risk zones. Several conclusions can be drawn from this pattern. Keeping in mind, of course, that the global level study focuses on risks for the ship itself, and the risk map focuses on the environment, these results indicate that the predominant factor determining risks at sea is associated with time, as discussed in the previous section. Thus, the actual distance covered, and the time spent at sea is a primary risk factor. Our results indicate that to minimise risks, a ship is likely to sail through higher risk areas, to avoid spending additional time at sea, as it is the time spent at sea that poses the greater risk. Accordingly, the development of Arctic summertime least risk routes identified in Figure 7, is close to the expected development of Arctic shipping lanes in the twenty-first century, which are likely to resemble the least distance paths.

Thus, recognising that shorter distances travelled will not only decrease risk but also increase economic benefits and emission savings, the focus should be shifted towards the development of a plan of action for increasing safety in Arctic shipping in the future emphasising the fragile environment, ecosystems, and biodiversity.

Furthermore, recognising that sparse maritime infrastructure in the Arctic pose one of the greatest risk factors, particularly in addressing environmental issues, the

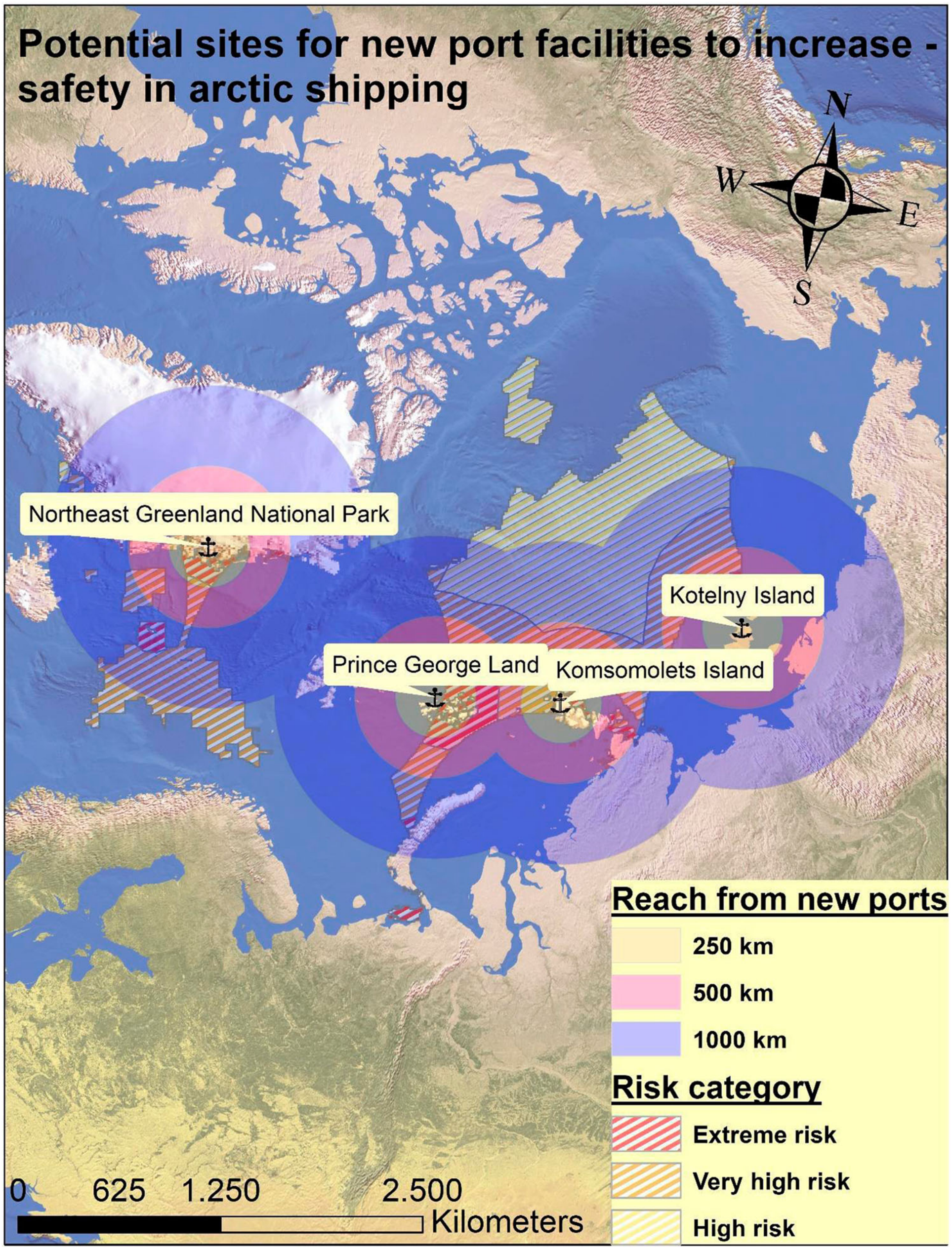

Figure 8. Potential sites for future arctic ports to increase safety in Arctic shipping.

further development of additional port facilities and search and rescue centres could be used to mitigate safety- and environmental issues. In Figure 8, four potential locations for such additional maritime infrastructure is suggested, three on Russian islands located in the south of the arctic ocean and one in the northeast of Greenland. This map was developed based on the Arctic shipping risk map with an environmental focus, resulting in the creation of an additional weighted surface, where the location closer to the higher risk areas was prioritised and preferred. The surface was clipped to the extent of the Arctic land areas and ultimately the two highest categories (4 + 5) from the weighted layer were extracted. From these high potential values, four points were suggested, and a multiple ring buffer zone was created from each of these four new potential sites for port development, to illustrate the reach in km. The resulting layer indicates potential sites, from where authorities would be able to launch rescue and salvage operations, within the majority of the areas identified as high risk, from an environmental perspective.

5.2. Sensitivity analysis

This study presents an innovative approach for predicting risks associated with commercial shipping during the period between 2010 and 2099 and more specifically the comparable risks between the NSR and the SSR. All safeguards and considerations have been used to ensure an objective and rationalised approach, however the authors also recognise that the conclusions are, to some extent, subjective, and based on best judgement. The aim of this study is to reignite efforts to assess and quantify the risks associated with future commercial shipping in the Arctic, and the methodology presented here could be further advanced, and applied, in future attempts of assessing risks. The risk factors used in this study (wind, waves, shallow water, cyclones, piracy, and icebergs) are all chosen from a selection of critical risk factors in the shipping industry, identified through an extensive literature review. However, these 7 risk factors are by no means exhaustive, and they are largely delimited by risks which can be modelled and quantified in a geospatial environment. Thus, while acknowledging that a wide range of other risk factors (i.e. lack of experienced crews, lack of proven training standards, quality of ships, market mechanisms driving (risky) optimizations, etc.) could pose a more critical threat to ships operating in the arctic, these have not been included due to the inability for global modelling and quantification of such variables.

Recognising that the results may have been inherently different, should an alternative selection of risk factors have been used, future research should aim to further assess, holistically, how risk factors in commercial shipping are integrated, how they correlate and how they determine risk scenarios.

Furthermore, the weighting structure used to determine the individual weights of the risk factors to derive the cost surface used in the least cost path analysis is fundamental for the prediction of the eventual paths and crucial in determining whether the northern route or the southern route provides the least risky alternative.

Even though the weighting structure is based on an extensive literature review, determining an exact weighting structure between individual risk factors is subject to opinion and discussion. Any small changes in the relative weights between these risk factors could, therefore, lead to substantial change in the final ranking. Though outside the scope of this study, the weighting structure could be further quantified and interpreted, to further optimise the relative weights between the risk factors.

Also, a global level study has been used throughout the least cost analysis component of this section, meaning that all risk factors have been considered and weighted at a global level, even though piracy and cyclones are not considered as risks in the Arctic and icebergs are not considered a risk on the SSR. Alternatively, the risk factors could have been considered regionally, and subsequently merged, however, this would likely result in an unequal weighting distribution between the risk factors that do have global level proportions, and thus the cost surface would less comparable at the global level and would likely favour one region. Accordingly, the final selection of the risk factors used in this study is a result of a decision-making process underlined by an unbiased effort to distribute risks equally, at the global level. Thus, as icebergs and the extreme conditions in the Arctic add an additional risk component in the Arctic, piracy and cyclones was chosen as a risk factor in the global south, not because they are primary risk factors in themselves, but to maintain a weighted balance between risk factors in both regions.

Another component of uncertainty is the relative variation of risk factors in time. In this study, a review of risk factors has identified the primary risk factors affecting the shipping industry presently, however, the outcome of this analysis results in a static risk surface, representing current risk factors. However, as a key component of this study is to predict changes, using the sea ice thickness, this static risk map is applied in a dynamic environment, assuming that the risk factors will largely represent future risks. This, of course, is an assumption, and the least cost paths are very sensitive to changes to those risk factors, as discussed previously. Ultimately, this could potentially be accounted for if model data was used for predicted future data on climatic variables, such as wind, waves, cyclones and potentially icebergs, however changes to variations in piracy, maritime infrastructure and to some extent bathymetry is largely dependent on geopolitical considerations and decisions, and thus relatively difficult to predict into the future. Furthermore, it is assumed that these risk factors will remain the principal risk factors in the future, even though variations in risks are likely, not only considering geopolitical changes and changes in climatic variables, but also technological advancement, which may lead to future mitigation of the impact from existing risk factors. Thus, despite aiming to predict risks of Arctic shipping in the future, it remains impossible to predict changes to risk factors.

5.3. Utility of results

Despite having been developed in an academic sphere for academic purposes, the results and conclusions from this study could be used broadly, by corporations, NGO's, national or regional governments as well as international organisations. As mentioned in the introduction, the container shipping industry is generally regarded as one of the main components of global trade, and as a driver of economies of scales and global production system. Member countries, as well as companies, have invested hundreds of billions of dollars in maritime infrastructure

(World Shipping Council 2018). However, whereas shipping companies have developed sophisticated methods to determine the economic feasibility of the Arctic vs Suez Canal shipping routes, the potential and projected risks of Arctic shipping remain relatively uncertain. This study could provide additional guidance for companies seeking to reap the benefits of Arctic shipping, by providing targeted information on key risk factors associated with global shipping, as well as their impact on the shipping industry. Additionally, the Arctic risk maps could be used as a stepping stone for planning purposes and in determining future routes for Arctic shipping, which would not only underpin financial interests but also, potentially increase safety. This information could also be used by insurance companies involved in commercial shipping, as it could provide additional directions for determining insurance policies and premiums, and thus the main factor in determining the future of Arctic shipping.

Lastly, the integration of projected future sea ice thickness into the core of this study could be used as an innovative means of supporting company decisions to invest in equipment and reinforced vessels, which could be used to support cooperate activities in the Arctic. This study has provided directions on vessel types and equivalent sea ice penetration rate, as well as how these vessels will largely perform in the future, for the purposes of Arctic shipping. The projected navigability of the NSR could also be used by governments and regional governments to target strategies to support commercial shipping activities. This study has suggested four new locations for maritime infrastructure in the Arctic, which could be used to support regional development strategies and increase safety in shipping across the region. Furthermore, this study has concluded that a small area nearby Russia's Bolshevik island, is predicted to be the primary Arctic choke point for shipping purposes in the future, and this information could be used by local or regional governments to invest in targeted icebreaker escort services around this area, to support the safe navigation of commercial ships.

Governments or intergovernmental organisations (such as the International Maritime Organization) may use the results from this study to further develop Arctic shipping strategies, emphasising regulations to increase environmental safety as well as generally to increase efficiency in Arctic shipping. The Arctic shipping risk map may provide guidance on preferred NSR routing and the heat maps produced may be used as an indication of future sea transportation density along the main corridor, which could be used as a precursor for a targeted environmental and/or social impact assessment. This could be further used to support and shape developmental and environmental policies.

Lastly, the results from this study may also support non-governmental organisations (NGO's) in determining future impetus and strategic priorities for their programmes of work, and environmental and conser vation-oriented organisations may use the heatmaps and Arctic risk map to predict the future impact on sensitive marine environments and endangered species. This may be further used to shape strategic priorities as well as targeted campaigns to assist governments in developing environmentally sensitive policies and regulations. This information could also be used to support decision-making processes within the realm of Multilateral Environmental Agreements (MEA's), and thus underline and frame future directions of international environmental policies and regulations.

6. Conclusions and key recommendations

This study concludes that the northern sea route, in the future, may present both an economically viable and less risky alternative, to the conventional Suez Canal route, connecting Europe with Asia. Yet, despite the prospect of maritime transportation along the northern sea route, the results also indicate that year-round Arctic transportation may only be facilitated through significantly reinforced vessels, whereas summer transportation may be possible for standard containership within the foreseeable future. However, additional safety measures should be considered, not only considering the recently adopted polar code but primarily focusing on addressing the environmental risks, which are the main inhibitor for structural change and political support for largescale maritime transportation in the Arctic.

From this study, one specific recommendation aims to support decision-makers in addressing one of the primary aspects of environmental concerns, related to maritime infrastructure, and the inability of authorities to react to a potentially catastrophic event, due to the lack of existing vantage points for salvage operations. Hereby, two main recommendations are listed below.

Recommendation 1: A plan of action should include the development of additional ports, at strategic locations around the Arctic, which may mitigate the potential impact of disastrous events in the Arctic sea. In this study, we have identified four strategic locations (Figure 8) from where authorities and rescue personnel would be within reach of most of the high-risk areas associated with the primary risk factors and environmentally sensitive areas in the Arctic.

Recommendation 2: This study indicates that although commercial shipping would be possible within the foreseeable future, companies should invest in new vessels, or reinforcing existing vessels, conforming to at least Polar class 3-4, if aiming to maintain year-round commercial operation. However, as the main inhibitor of year-round navigation is determined by a small corridor, with relatively thick sea ice, around Bolshevik island, further investments in an icebreaker fleet in this area could potentially facilitate year-round navigation along the northern sea route.

6.1. Future directions

The potential opening of commercial shipping alternatives through the NSR has sparked considerable political interest in recent years. This interest has been accompanied by a multitude of scientific research studies, primarily addressing issues of financial potential, governance issues, and environmental concerns. This study aimed to uncover the risks associated with global shipping patterns through the NSR and its viable alternatives.

However, while aiming to address several concerns relating to the issue of safety and risks associated with shipping, risk analysis of arctic shipping patterns remains relatively unexplored and thus future research should address this gap in the literature, along with the inevitable coming age of commercial shipping in the Arctic. Further studies on Arctic maritime infrastructure could provide further evidence to support decision-makers and regional governments in establishing port facilities at strategic locations around the Arctic sea. While this has been briefly touched upon in this study, further research is needed in order to derive optimum locations, covering the entire Arctic ocean, and based on variables not addressed in this study, such as feasibility studies, environmental impact analysis, governance issues, etc.

Further research should also aim to address shipping related risks at the local level, aiming to include a more localised selection of risk factors which would be more applicable at local and regional level. Aside from this study, and studies looking specifically at the NSR routing patterns, further research on real-time wind direction and current patterns may support maritime planners in optimising routes taking in to account the benefits of climatic and weather variables that may assist ships in reaching their destinations quicker. Finally, strategic locations for intermediate stops along the route, not only taking into consideration safety issues but mainly considering options for loading and off-loading potential could provide further evidence to support a changing maritime network infrastructure system.

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