Okhotsk Sea and Polar Oceans Research 5 (2021) 15-22

https://doi.org/10.57287/ospor.5.15

Review

Economic feasibility of Arctic shipping from multiple perspectives: a systematic review

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(Received September 24, 2020; Revised manuscript accepted January 3, 2021)

Abstract

The emerging interest in Arctic shipping driven by global warming results in a growing number of related academic publications. Considering the need for a systematic review that incorporates multiple perspectives of Arctic shipping on evaluating its economic feasibility, this study summarizes 60 selected publications made after 1999 that focus on eleven different aspects of the Arctic shipping including cost comparison of Arctic and conventional routes, environment concerns for navigating via Arctic routes, operational aspects, route choice modelling, feasibility of NSR (Northern Sea Route)/SCR (Suez Canal Route) combined service, criteria for choosing Arctic routes, navigation speeds, required freight rate, effects of Arctic shipping on other economics, engineering aspects of Arctic shipping, and Russian Arctic policy. Further, this review discusses their focused geographical markets, commodities, methodological aspects, factors for model developments, navigable periods, vessel sizes and types, sailing speeds, routing geometry, fuel types, and the feasibility of Arctic shipping. This review also highlights the limitations in previous studies especially due to the simplified assumptions made with transport cost models on fuel consumption, navigation speed, and vessels' engine specifications, among others if analyzing the economic feasibility of Arctic shipping.

Keywords: Arctic shipping, multiple perspectives, systematic review, economic feasibility

1. Introduction

The retreat of Arctic sea ice driven by global warming led to an emergent interest on Arctic shipping among researchers especially during the last decade (Theocharis and others, 2018) due to the potential cost and time saving of shipping via Arctic routes than the conventional routes (Pierre and Olivier, 2015; Stephenson and others, 2013; Xu and others, 2011). Apart from original research articles, several review articles (Lasserre, 2014; Meng and others, 2017; Theocharis and others, 2018) appeared although their scope was limited mainly to the comparative studies between the Arctic vs conventional routes and the commercial aspects of Arctic shipping. Owing to the high potential of Arctic shipping in the future, there is a need for a systematic review that focuses on the economic feasibility of Arctic shipping considering multiple perspectives that are summarized in a single article. Thus, this review aims to provide a better understanding of the economic feasibility of Arctic shipping by summarizing previous studies that focused on eleven different aspects.

As the remainder of this paper, Section Two explains the review method, and the results and discussion are given in Section Three. Finally, Section Four concludes the paper.

2. Review Method and Selection of Studies

Since this paper presents a systematic review of Arctic shipping, 60 research publications were selected for the review. To maintain quality, the majority of publications were selected from refereed international journals. First, we made a collection of studies using keywords such as Arctic shipping, Northeast Passage (NEP), Northwest Passage (NWP), and Northern Sea Route. Thereafter, we grouped the selected studies into eleven categories based on their main focus as explained in Section 3.1. Several publishers and databases including Scopus, Elsevier, Emerald Insight, and Taylor & Francis, among others were considered. The selected 60 papers were published in 33 international journals, two refereed international conferences, and one research organization as given in Table 1. Regarding their publication years (Fig. 1), the papers published on or after 1999 were selected and the majority were selected from the years 2017-2020 to provide a more updated review than the previous review articles.

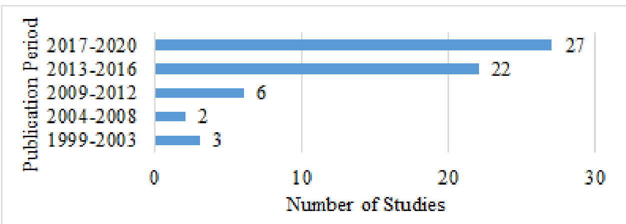

Fig. 1 Publication period of selected articles

Table 1. Sources of selected articles

Journal/Conference/Organization	No of Studies
Maritime Policy and Management	7
Journal of Transport Geography	5
Transportation Research Part A	5
Asian Journal of Shipping and Logistics	3
International Journal of Naval Architecture and Ocean Engineering	3
Climatic Change	2
International Journal of e-Navigation and Maritime Economy	2
International Northern Sea Route Programme (INSROP)	2
Maritime Economics and Logistics	2
The Polar Journal	2
Transport Policy	2
Arctic Review on Law and Politics	1
Canadian Journal of Remote Sensing	1
Geographical Review	1
Geophysical Research Letters	1
International Journal of Geographical Information Science	1
International Journal of Scientific & Technology Research	1
International Association of Maritime Economics Conference	1
Journal of Cleaner Production	1
Journal of Risk and Reliability	1
Journal of Ship Research	1
Maritime Business Review	1
Marine Policy	1
Ocean Engineering	1
Ocean Development and International Law	1
Polar Research	1
Polar Record	1
Port and Ocean Engineering under Arctic Conditions Conference	1
Research in Transportation Economics	1
Research in Transportation Business & Management	1
Safety Science	1
Scientific Reports	1
Ship Technology Research	1
The Cryosphere	1
Transportation Research Part D	1
Transportation Research Part E	1

3. Results and Discussion

This section discusses the results of the systematic review considering several subsections as follows.

3.1 Classification of Studies

Since this paper discusses the economic feasibility of Arctic shipping from multiple perspectives, selected 60 studies can be grouped into eleven categories as given in Table 2. Although a few studies focused on multiple aspects simultaneously, the categorization was done based on their main focus such that each study belongs to only one category. Accordingly, eight studies were selected on the cost comparison between Arctic routes and conventional routes. Among them, a majority focused on the comparison between NSR and SCR and a few on NWP, Panama Canal route, Cape route, and the Trans-Siberian railway. The environment and climate concerns for navigating through the Arctic sea were discussed by seven studies. They also focused on emission level, and impacts of global warming and climate change on the retreat of Arctic sea ice, among other issues.

Furthermore, eight studies focused on the operational aspects of Arctic shipping such as additional cost due to ice-water navigation, fuel types, and choice of ice-class, among others. The route choice between the Arctic and other routes were analyzed by five studies and some incorporated choice models to estimate the market share. Moreover, four studies focused on the feasibility of NSR/SCR combined service, which assumed the use of NSR during its navigable period and the SCR for the rest of the year. They focused on the network design for the combined service, scenario analysis with different navigable periods of NSR, vessel sizes, transit fees, and bunker price, among others. Further, the criteria for choosing Arctic shipping were discussed by two studies and they highlighted the significance of economic (e.g. time and distance saving), safety, and technical factors. Further, navigation speeds on Arctic routes were analyzed by three studies, and two studies calculated

Table 2. Categorization of previous studies

Category	Selected Studies
Cost comparison of Arctic routes and conventional routes	Cariou and others (2019), Ding and others (2020), Lasserre (2014), Otsuka and others (2013), Pruyn (2016), Shibasaki and others (2018), Theocharis and others (2018), Zhang and others (2016)
The environment and climate concerns for navigating through the Arctic sea	Chang and others (2015), Faury and Cariou (2016), Lindstad and others (2016), Meng and others (2017), Stephenson and others (2013), Yumashev and others (2017), Zhang and others (2018)
Operational aspects of Arctic shipping	Afenyo and others (2017), Erikstad and Ehlers (2012), Eguíluz and others (2016), Konygin and others (2015), Solakivi and others (2019), Tseng and Pilcher (2017), Wang and others (2018), Wang and others (2019)
Route choice models for the Arctic and conventional routes	Lasserre and Pelletier (2011), Lee and Song (2014), Wang and others (2018), Wang and others (2020), Zeng and others (2020)
Feasibility of NSR/SCR combined service	Furuichi and Otsuka (2014), Liu and Kronbak (2010), Xu and others (2018), Zhao and others (2016)
Criteria for choosing arctic shipping over other routes	Moon and others (2015), Tseng and Cullinane (2018)
Navigation speed on Arctic routes	Cariou and Faury (2015), Löptien and Axell (2014), Xu and others (2011)
Required freight rate on Arctic routes	Theocharis and others (2019), Somanathan and others (2009)
Effects of Arctic shipping on other economics	Ha and Seo (2014), Hong (2012), Rahman and others (2014), Sur and Kim (2020)
Engineering aspects of Arctic shipping	Aksenov and others (2017), Goerlandt and others (2017), Howell and Yackel (2004), Hu and Zhou (2015), Kamesaki and others (1999), Montewka and others (2019), Nam and others (2013), Overland and Wang (2007), Patey and Riska (1999), Spencer and Jones (2001), Wang and others (2020)
Russian Policy on Arctic Shipping	Bognar-Lahr (2020), Bognar (2016), Gritsenko and Kiiski (2015), Moe and Brigham (2017), Sevastyanov and Kravchuk (2020), Solski and others (2020)

the required freight rate for Arctic shipping services to cover all associated costs. Moreover, four studies analyzed the effects of Arctic shipping on other economics such as China and Korea, and they considered international cargo flows via Arctic routes for the analysis.

Due to the navigation via ice water, the economic feasibility of Arctic shipping is affected by its related engineering aspects. Although numerous studies are available on engineering aspects, only 11 studies were selected to highlight their focused issues. Accordingly, several studies analyzed the deforming of sea ice cover to examine the Arctic routes' navigability, sailing time with ice conditions, implications of ice-numerals on safe navigation, and the risks for vessels caused by ice drift and convoy collisions. Sea ice resistance and vessel's propulsion power were modeled incorporating vessel's specifications and hull-ice friction coefficient. Moreover, navigation speed reduction at environmental conditions such as ice concentration, ridge, and current direction was modeled. A few studies focused on route planning considering ice conditions, resistance, and net thrust provided by the ship and the effect of multiyear ice and various ice cover states on energy consumption.

Finally, the feasibility of Arctic shipping is greatly influenced by the Russian Arctic policy as summarized from six selected studies. They discussed the policy to develop NSR's transport-logistics aspects, the changes in Russian ice-breaking tariff, and Russian policy on building NSR's infrastructure by cooperating with other countries. They highlighted the conflict of interests with Russia in promoting independent navigation vs their income from icebreaker escorting, Russian policy to move their natural resources to global markets, and the competition between Russian state and private service providers on NSR activities. Several studies discussed the Russian policy on liberalizing the use of NSR by foreign actors vs increasing NSR's traffic by ships of Russian investors. Lastly, studies discussed the positions of Russia and Canada when negotiating the Polar code, and Russian jurisdictional claims on controlling the navigation of vessels via NSR.

Therefore, studies were selected covering multiple perspectives that influence the economic feasibility of Arctic shipping, which makes a significant contribution to the existing literature. The next few sub-sections discuss several important aspects of Arctic shipping which were summarized from all 60 studies.

3.2 Focused Geographical Markets, Shipping Routes, and Types of Commodities

Since the Arctic routes have different influences on individual markets, previous studies focused on various geographical markets as summarized in Fig. 2. Accordingly, that the majority of studies (14) included Japan or China as the origin/destination for shipping via Arctic routes could be due to their strategic locations in East Asia. Besides, Netherland (Rotterdam), German (Hamburg), and Russian ports were mainly included for the analysis. However, compared to Asian and European commercial ports, most Russian ports have a slightly different role as exporting ports of natural resources and some of them pursue becoming a hub of cargo transshipment. A few studies discussed the impacts of Arctic shipping on different regions such as Asia and Europe in general as their focused markets.

Fig. 2 Major countries/regions focused by studies

If considering the Arctic shipping routes focused by previous studies (Fig. 3), a majority of studies considered NSR/NEP (40) including the studies on Russian Arctic policy, and a few focused on NWP (6). However, 15 studies considered all Arctic routes in general. A comparatively less number of studies focused on the Trans-polar route could be due to the consistent presence of sea-ice and less developed ports and logistics infrastructure along this route.

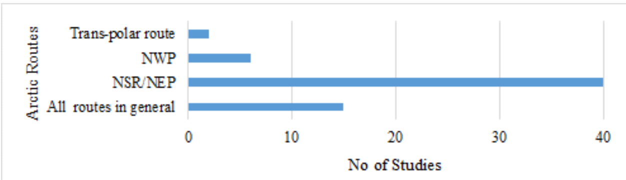

Fig. 3 Arctic shipping routes focused by studies

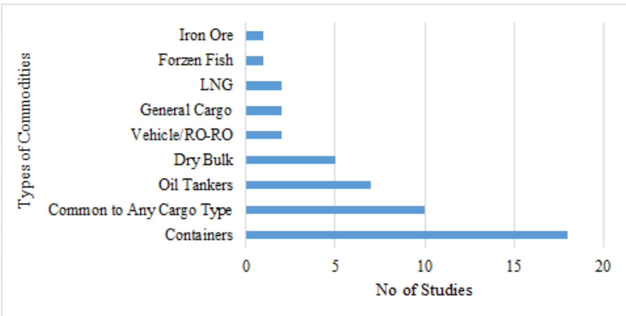

Fig. 4 Types of commodities focused by studies

As the types of commodities (Fig. 4), studies mainly focused on container cargo (18), implying the interests on Arctic routes from the liner shipping industry. The oil tankers and dry bulk cargo were focused by a few studies possibly with the discovery of natural resources along the Arctic coast. However, several studies (10) discussed Arctic shipping in general to any cargo types.

3.3 Methodological Aspects

For the data analysis methods (Fig. 5), the majority of studies (13) considered transport cost models to compare the costs via Arctic routes with alternatives and the optimization and simulation models especially considering engineering aspects. The macroeconomics models were used by several studies to analyze the impacts of Arctic shipping on trade patterns among countries. A few studies (4) used Multi-Criteria Decision-making (MCDM) techniques for analyzing perception-based data. The potential use of AIS (Automatic Identification System) for modeling Arctic shipping aspects was highlighted by five studies. Besides, 10 studies considered qualitative approaches mainly for analyzing expert opinions on the Arctic shipping potential and discussing the Russian Arctic policy.

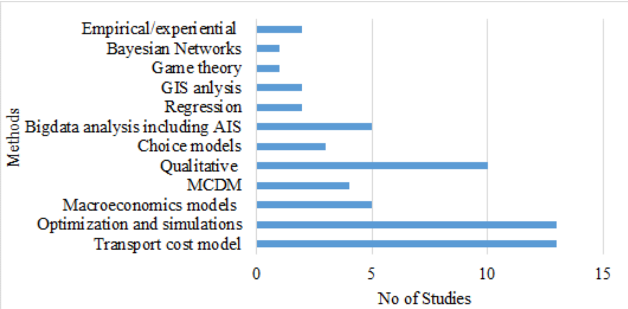

Fig. 5 Data analysis methods of previous studies

3.4 Factors Considered in Model Developments for Analyzing the Feasibility of Arctic Shipping

The feasibility of Arctic shipping was sensitive to the factors used in model development by previous studies as summarized in Table 3. Thus, the majority of studies (19) considered voyage costs including fuel cost, and a few studies considered different fuel consumption rates for arctic routes than conventional routes. Capital cost was significantly highlighted in many studies due to the higher ship-building cost (+10% by Otsuka and others (2013); +20%–30% by Zhao and others (2016)) when navigating through ice-water than the open water. Transit fees and ice-breaking fees of NSR, and canal toll of SCR were included in cost calculation with 16 studies and several studies (e.g. Liu and Kronbak; 2010; Zhao and others 2016) analyzed scenarios by changing NSR's transit fee. Besides, the insurance cost was significantly highlighted due to the risk associated with navigating through ice-water. Considering the impacts of Arctic shipping on the environment, the Carbon tax was incorporated in cost calculation by several studies (4). However, factors such as delays and waiting time, and exchange rates were incorporated by a limited number of studies.

In summarizing the factors considered in models for analyzing Arctic shipping feasibility (Table 3) and the various issues discussed from the studies that focused on engineering aspects of Arctic shipping, it is observed that most of those engineering aspects were not directly incorporated in economic feasibility analysis due to the simplified assumptions on average navigation speed for the entire route, fuel cost, and vessels' engine specifications, among others.

Table 3. Factors considered in model development

Factors Considered	No of Studies
Voyage cost, fuel cost, fuel consumption rates	19
Capital cost, depreciation cost	17
Transit fee, ice-breaking fee, canal toll	16
Insurance	12
Crew cost	12
Maintenance cost	11
Operating cost in general	10
Port charges	8
Ice condition, ice thickness	5
Carbon tax, emission	4
Load factor	3
Delays and waiting time	2
Port time	2
Exchange rates	1

3.5 Arctic Shipping Specific Considerations

3.5.1 Navigable Period

The navigable period has crucial impacts on the feasibility of Arctic shipping. Regarding the duration of the navigable period assumed by previous studies, the majority of studies highlighted the feasibility of summer navigation, although several studies (Furuichi and Otsuka, 2014; Ha and Seo, 2014; Liu and Kronbak, 2010; Shibasaki and others, 2018; Wang and others, 2018; Zhao and others, 2016) assumed multiple navigable periods as scenario analysis. Despite the ice condition, a few studies assumed all year navigation via Arctic routes. Besides, Xu and others, (2018) assumed a dynamic navigable window depending on the sea-ice extent.

3.5.2 Vessel Sizes and Types

Due to the differences in routes' geometry, the characteristics of vessels passing through Arctic routes can be different than those of conventional routes. Thus, Table 4 summarized the sizes and types of vessels used by previous studies if modeling traffic via Arctic routes. Considering the limitations with Arctic routes, the majority of studies assumed container vessels with less than 10,000 TEUs capacity, although a different range of capacities including larger vessels was assumed for scenario analysis by a few studies (3). In terms of bulk cargo vessels, Panamax vessels were used by the majority of studies including multiple vessel sizes for scenario analysis. Moreover, the majority of studies assumed ice-classed vessels mainly 1A-class despite that a few studies did not consider ice-classed vessels. Further, the scenario analysis with different ice-classed vessels was done by a few studies (7).

Table 4. Sizes and types of vessels on Arctic routes

Study	Size	Type
Cariou and Faury (2015)	40,000 DWT Handymax	1A (IAS)
Theocharis and others (2019)	Suezmax, Aframax, Panamax, Handymax	1A (Arc4) ice class
Ding and others (2020)	9 ship sizes between 5089 - 21237 TEUs	ice-class
Erikstad and Ehlers (2012)	N.A.	Non-ice-class to 1AS ice class
Faury and Cariou (2016)	Panamax oil tanker	1A
Furuichi and Otsuka (2014)	6,500 CEU car carrier, 4,000 TEUs	Ice class
Ha and Seo (2014)	650, 4300, 5000, 8000 TEUs	DAS
Konygin and others (2015)	70 000 t DWT tanker	Arc 6
Lasserre (2014)	4500 TEU	1AS
Lindstad and others (2016)	Dry bulk (Panamax and Capesize)	N.A.
Liu and Kronbak (2010) Wang and others (2018)	4300 TEU	Ice class 1B
Otsuka and others (2013)	75,000 dwt (bulk), 147,500 m3 (LNG), 12,383GT (reefer)	Ice-class IA
Pruyn (2016)	11 ship sizes between 17,800- 289,400 DWT	ice-class 0, 1, 2, with given specifications, regular vessel with ice breaker
Shibasaki and others (2018)	147,500 m3, 172,000 m3, LNG carrier	Arc 4, Arc 7
Somanathan and others (2009)	N.A.	CAC3
Solakivi and others (2019)	7 ship sizes between 500–700 TEU, 10,000–12,000 TEU	IA and IAS Ice Class (FSCIR)
Stephenson and others (2013)	N.A.	PC3, PC6, open-water vessels with high, medium, and no ice-breaking capability
Xu and others (2011)	10,000 TEU	non-ice class
Xu and others (2018)	8000, 10 000, 12 000, 14 000 and 16 000 TEUs	ice-class 1A (Finnish-Swedish) or ARC4 (Russian)
Yumashev and others (2017)	> or < 2500 TEU, > or < 50,000 DWT (bulk)	ice-strengthened vessels in the future
Zhang and others (2016)	Panamax, Aframax	Arc 4
Zhao and others (2016)	4800 TEU	ice-strengthened ship

3.5.3 Vessel Sailing Speeds

Several studies assumed lower speed for vessels on Arctic routes than those on conventional routes (Ding and others, 2020; Furuichi and Otsuka, 2014; Lasserre, 2014; Pruyn, 2016; Shibasaki and others, 2018; Wang and others, 2018; Zhang and others, 2016). A few studies assumed multiple speed levels based on the ice-numeral (Somanathan and others, 2009; Zhang and others, 2018) or ice-thickness (Cariou and others, 2019; Xu and others, 2018; Olivier and Pierre, 2016). However, the majority of studies assumed the speed at ice water in between 10-15 knots although Pruyn (2016) assumed 9 knots with ice-breaker assistance.

3.5.4 Fuel Types for Vessels

Table 5 summarizes the fuel types assumed by previous studies for vessels navigating via Arctic routes. Accordingly, the majority assumed IFO 380 and some studies analyzed scenarios with multiple fuel types such as LFO, MGO, and LNG considering environmental aspects. Further, several studies assumed changes in fuel prices as scenarios without specifying the fuel types to understand the sensitivity of fuel price.

Table 5. Fuel types for vessels

Fuel Types	No of Studies
Intermediate Fuel Oil (IFO 380/IFO 180)	10
Marine Gas Oil (MGO)	5
Heavy Fuel Oil (HFO)	4
Liquified Natural Gas (LNG)	3
Light Fuel Oil (LFO)	2
Do not specify the fuel type	8

3.5.5 Routing Geometry

To enhance the accuracy of cost estimation, previous studies divided the entire Arctic route into different legs and zones. Studies assumed seven zones (Ding and others, 2020; Olivier and Pierre, 2016; Pierre and Olivier, 2015; Zhang and others, 2016) along the NSR based on NSR transit fee and ice pilotage fee and three legs along the NSR (Xu and others, 2011; Yumashev and others, 2017; Zhao and others, 2016) considering the sea ice condition. Chang and others (2015) assumed four zones based on the navigability along the NSR and Cariou and others (2019) assumed 49 subzones along the NSR based on ice thickness data from 2006 to 2016. Considering the NWP, Somanathan and others (2009) assumed 9 legs based on spatial and temporal variation of ice conditions.

3.6 Feasibility of Arctic Shipping

In summarizing the findings of previous studies, the majority of studies highlighted the feasibility of Arctic routes in general or under some conditions as listed in Table 6. The feasibility of Arctic routes was mainly highlighted at high fuel prices (5), with a long navigable period (4), with certain vessel sizes (4), for specific origins/destinations (4), when sea-ice diminishes (4) and with low transit fees (3). Moreover, Arctic routes were feasible with certain fuel types and with emission tax based on two studies. Significance of having a high load factor and average vessel speed was also highlighted. Considering the distance-saving effect, the feasibility of short-haul navigation was discussed. Conversely, 13 studies highlighted that Arctic routes will not be feasible due to the number of reasons given in Table 6. Among them, the risk with weather conditions and a short navigable period (5), limited navigation speed (5), high cost of ice-class vessels (5), and ice-breaking and transit fees (5) were highlighted by the majority of studies.

Table 6. Feasibility of Arctic shipping

Feasibility of Arctic Shipping		**No of Studies**
Feasible in general		8
Feasible only at	High fuel prices	5
	Long navigable period	4
	Certain vessel sizes	4
	Specific origins/destinations	4
	Sea-ice diminishes	4
	Low transit fees	3
	Certain fuel types	2
	With emission tax	2
	Certain sailing speed	1
	High load factor/ cargo volume	1
	Independent sailing without ice-breaker	1
	High global emission	1
	Short-haul	1
Not feasible due to	Risk with difficult weather conditions and a short navigable period	5
	Limited navigation speed	5
	High cost of ice-class vessels	5
	Ice-breaking and transit fees	5
	Vessel size's restrictions on navigation paths	4
	High emission per unit cargo	3
	Low load factor/ cargo volume	2
	Under-developed infrastructure	2
	Supply chain risk and uncertainty	2
	Political and legal aspects	2
	Impacts of cold temperature on cargo	1
	Differences in navigational practices	1

The majority of studies quantitatively discussed the benefits of Arctic routes (e.g. 40% reduction of voyage distance with NSR than SCR according to Liu and Kronbak, 2010) and some as the reduction of sailing days and emission levels. A few studies evaluated the expert opinions on the feasibility of Arctic routes (e.g. Lasserre and Pelletier, 2011; Moon and others, 2015; Tseng and Pilcher, 2017). Several studies that concluded Arctic shipping as not feasible followed qualitative approaches, thus they could discuss negative aspects with various non-quantitative factors that were not incorporated in transport cost models. Moreover, the parameters, assumptions, input values, and target markets for cost calculations were different among studies, which could be a reason for deriving their different conclusions on the Arctic shipping feasibility. Besides, the difficulty in identifying all credible parameters to incorporate with model development might lead to diverse conclusions from previous studies. Thus, it is challenging to make a unified conclusion on the Arctic shipping feasibility from previous studies.

3.7 Limitations of Previous Studies and Future Research Directions

As the limitations of previous studies, the feasibility of Arctic routes was sensitive to the parameters used in their models. Some studies analyzed the feasibility for a single voyage, which did not consider the factors such as the number of possible round trips that can be made and a reduction in capital cost by reducing the number of vessels. Studies excluded important stakeholders such as shippers, port operators, and vessel owners. They barely considered the operational challengers with NSR/SCR combined service when changing routes twice a year, just-in-time operations in liner shipping, and the loss caused by excluding strong intermediate markets (e.g. Singapore, India) when using Arctic routes. The diseconomy of scale with small vessel sizes, opportunity cost with heavy vessels which limit the cargo-carrying capacity, and changes in load factors with Arctic routes were not highlighted by many studies. Studies on economic feasibility analysis barely incorporated detailed engineering aspects of sea-ice navigation such as multiyear ice and sea-ice resistance, among others discussed by related previous studies. Therefore, these limitations highlight the directions for further research.

4. Conclusion

This paper presents an updated review on Arctic shipping based on 60 selected articles published after 1999, that focus on cost comparison of Arctic vs. other routes, environmental and climate concerns, operational aspects of Arctic shipping, route choice, NSR/SCR combined service, criteria for choosing Arctic routes, sailing speed, required freight rate, effects on other economics, engineering aspects and Russian Arctic policy. Studies were summarized by highlighting their focused geographical markets, commodities, methodological aspects, factors for model developments, navigable periods, vessel sizes and types, sailing speeds, fuel types, routing geometry, the feasibility of Arctic shipping, and the limitations highlighted by them. Accordingly, Arctic routes were feasible mainly at high fuel prices, with a long navigable period, with certain vessel sizes, for specific origins/destinations, when sea-ice diminishes, and with low transit fees. However, the risk with weather conditions and a short navigable period, limited navigation speed, high cost of ice-class vessels, and ice-breaking and transit fees were highlighted as the main reasons for concluding the infeasibility of Arctic shipping. Studies mainly focused on container cargo, including Japan or China as origins/destinations, and considered summer navigation mostly with 1A-class vessels. Most studies used transport cost models for the feasibility analysis. However, apart from some operational aspects that were not incorporated by previous studies, it is also important to incorporate sea-ice resistance, ships' propulsion systems, and variations of ice-thickness, among others if analyzing economic feasibility because they were highlighted as the important engineering aspects of Arctic shipping by related previous studies. Moreover, to confirm the economic feasibility, the Russian Arctic policy should promote the NSR's attractiveness regardless of their monopolistic features because the NSR is one alternative that is compared with other routing options in the global shipping market. Hence, this review develops a better initial understanding of Arctic shipping from multiple perspectives simultaneously. As the limitations, this review did not discuss the regulatory and political agreements of Arctic states which also influence the economic feasibility of Arctic shipping, thus they can be incorporated in further studies.

References

Afenyo, M., F. Khan and 2 others (2017): Arctic shipping accident scenario analysis using Bayesian Network approach. *Ocean Eng.* 133, 224-230.

Aksenov, Y., E.E. Popova and 5 others (2017): On the future navigability of Arctic sea routes: high-resolution projections of the Arctic ocean and sea ice. *Mar. Policy*. 75, 300–317.

Bognar-Lahr, D (2020): In the Same Boat? A Comparative Analysis of the Approaches of Russia and Canada in the Negotiation of the IMO's Mandatory Polar Code. *Ocean Dev. Int. Law*. 51(2), 143-161.

Bognar, D (2016): Russian Proposals on the Polar Code: Contributing to Common Rules or Furthering State Interests? *Arct. rev. law polit*. 7 (2), 111-135.

Chang, K.Y., S.S. Hea and 3 others (2015): Route planning and cost analysis for travelling through the Arctic Northeast Passage using public 3D GIS. *Int. J. Geogr. Inf. Sci*.

Cariou, P., A. Cheaitou., O. Faury and S. Hamdan (2019): The feasibility of Arctic container shipping: the economic and environmental impacts of ice thickness. *Marit Econ Logist*.

Cariou, P. and O. Faury (2015): Relevance of the Northern Sea Route (NSR) for bulk shipping. *Transp. Res. Part A.* 78, 337–346.

Ding, W., Y. Wang., L. Dai and H. Hu (2020): Does a carbon tax affect the feasibility of Arctic shipping?. *Transp. Res. Part D.* 80: 102257.

Eguíluz, V., Fernández-Gracia, J. and 2 others (2016): A quantitative assessment of Arctic shipping in 2010–2014. *Sci Rep*. 6, 30682.

Erikstad, S.O. and S. Ehlers (2012): Decision Support Framework for Exploiting Northern Sea Route Transport Opportunities. *Ship Technol. Res*. 59 (2).

Faury, O. and P. Cariou (2016): The Northern Sea Route competitiveness for oil tankers. *Transp. Res. Part A.* 94, 461-469.

Furuichi, M. and N. Otsuka (2014): Economic feasibility of finished vehicle and container transport by NSR/SCR-combined shipping between East Asia and Northwest Europe. *International Association of Maritime Economics*, July 15-18, Norfolk, VA, USA.

Goerlandt, F., J. Montewka and 2 others (2017): An analysis of ship escort and convoy operations in ice conditions. *Saf. Sci*. 95, 198–209.

Gritsenko, D. and T. Kiiski (2015): A review of Russian ice-breaking tariff policy on the northern sea route 1991–2014. *Polar Rec.* 52 (263), 144-158.

Ha, Y.S. and J.S. Seo (2014): The Northern sea routes and Korea's trade with Europe: Implications for Korea's Shipping Industry. *Int. J. e-Navigation and Marit. Econ.* 1: 73-84.

Hong, N. (2012): The melting Arctic and its impact on China's maritime transport. *Res. Transp. Econ.* 35(1), 50-57.

Howell, S.E.L. and J.J. Yackel (2004): A vessel transit assessment of sea ice variability in the Western Arctic, 1969–2002: implications for ship navigation. *Can. J. Remote Sensing*, 30 (2), 205–215.

Hu, J. and L. Zhou (2015): Experimental and numerical study on ice resistance for icebreaking vessels. *Int. J. Nav. Archit. Ocean Eng*. 7, 626~639.

Kamesaki, K., S. Kishi and Y. Yamauchi (1999): Simulation of NSR shipping based on year round and seasonal operation scenarios. INSROP Working Paper No. 164.

Konygin, A., S. Nekhaev and 4 others (2015): Oil tanker transportation in the Russian arctic. *Int. J. Sci. Technol. Res.* 4, 03.

Lasserre, F (2014): Case studies of shipping along Arctic routes. Analysis and profitability perspectives for the container sector. *Transp. Res. Part A*. 66: 144–161.

Lasserre, F. and S. Pelletier (2011): Polar super seaways? Maritime transport in the Arctic: an analysis of shipowners' intentions. *J. Transp. Geogr.* 19, 1465-1473.

Lee, S.W. and J.M. Song (2014): Economic possibilities of shipping though Northern Sea route. *Asian J. Shipping Logist*. 30 (3), 415-430.

Lindstad, H., R.M. Bright and A.H. Strømman (2016): Economic savings linked to future Arctic shipping trade are at odds with climate change mitigation. *Transp. Pol.* 45: 24-30.

Liu, M and J. Kronbak (2010): The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe. *J. Transp. Geogr*. 18, 434–444.

Loptien, U. and L. Axell (2014): Ice and AIS: ship speed data and sea ice forecasts in the Baltic Sea. *The Cryosphere*. 8, 2409–2418.

Meng, Q., Y. Zhang and M. Xu (2017): Viability of transarctic shipping routes: a literature review from the navigational and commercial perspectives. *Marit. Pol. Manage.* 44(1), 16-41.

Moe, A. and L. Brigham (2017): Organization and Management Challenges of Russia's Icebreaker Fleet. *Geogr. Rev.* 107 (1), 48-68.

Montewka, J., F. Goerlandt and 3 others (2019): Toward a hybrid model of ship performance in ice suitable for route planning purpose. *J. Risk and Reliability*. 233 (1), 18–34.

Moon, D.S., D.J. Kim and E.K. Lee (2015): A Study on Competitiveness of Sea Transport by Comparing International Transport Routes between Korea and EU. *Asian J. Shipping Logist.* 31 (1), 001-020.

Nam, J.H., I. Park and 4 others (2013): Simulation of optimal arctic routes using a numerical sea ice model based on an ice-coupled ocean circulation method. *Int. J. Naval Archit. Ocean Eng*. 5, 210-226.

Otsuka, N., K. Izumiyama and M. Furuichi (2013): Study on Feasibility of the Northern Sea Route from Recent Voyages. *22nd International Conference on Port and Ocean Engineering under Arctic Conditions.* June 9-13, Espoo, Finland.

Overland, J.E. and M. Wang (2007): Future regional Arctic sea ice declines. *Geophys. Res. Lett*. 34, L17705.

Patey, M. and K. Riska (1999): Simulation of Ship Transit Through Ice, INSROP Working Paper No.155.

Pruyn, J.F.J (2016): Will the Northern Sea Route ever be a viable

alternative?. *Marit. Pol. Manage.* 43(6), 661-675.
Rahman, N.S.F.A., A.H. Saharuddin and R. Rasdia (2014): Effect of the Northern Sea Route Opening to the Shipping Activities at Malacca Straits. *Int. J. e-Navigation and Marit. Econ.* 1, 85-98.
Sevastyanov, S. and A. Kravchuk (2020): Russia's policy to develop trans-arctic shipping along the Northern sea route. *The Polar Journal.*
Shibasaki, R., T. Usami and 3 others (2018): How do the new shipping routes affect Asian liquefied natural gas markets and economy? Case of the Northern Sea Route and Panama Canal expansion. *Marit. Pol. Manage.*
Solakivi, T., T. Kiiski and L. Ojala (2019): On the cost of ice: estimating the premium of Ice Class container vessels. *Marit Econ Logist.* 21, 207–222.
Solski, J.J., T. Henriksen and A. Vylegzhanin (2020): Introduction: regulating shipping in Russian Arctic Waters: between international law, national interests and geopolitics. *The Polar Journal*.
Somanathan, S., P. Flynn and J. Szymanski (2009): The Northwest Passage: A simulation. *Transp. Res. Part A.* 43, 127–135.
Spencer, D. and S.J. Jones (2001): Model-Scale/Full-Scale Correlation in Open Water and Ice for Canadian Coast Guard "R-Class" Icebreakers. *J. Ship Res*. 45 (4), 249–261.
Stephenson, S.R., L.C. Smith and 2 others (2013): Projected 21st-century changes to Arctic marine access. *Clim. Change.* 118, 885–899.
Sur, J. M. and D.J. Kim (2020): Multi criteria evaluation of beneficial effect of commercializing Northern Sea Route on Europe and Asia countries. *Asian J. Shipping Logist.*
Theocharis, D., S. Pettit and 2 others (2018): Arctic shipping: A systematic literature review of comparative studies. *J. Transp. Geogr.* 69, 112-128.
Theocharis, D., V.S. Rodrigues., P. Stephen and J. Haider (2019): Feasibility of the Northern Sea Route: The role of distance, fuel prices, ice breaking fees and ship size for the product tanker market. *Transp. Res. Part E.* 129: 111–135.
Tseng, P. and N. Pilcher (2017): Assessing the shipping in the Northern Sea Route: a qualitative approach. *Marit. Bus. Rev.* 2 (4), 389-409.
Tseng, P. and K. Cullinane (2018): Key criteria influencing the choice of Arctic shipping: a fuzzy analytic hierarchy process model. *Marit. Pol. Manage.* 45(4), 422-438.
Wang, C., X. Hu and 3 others (2020): Numerical simulation of ice loads on a ship in broken ice fields using an elastic ice model. *Int. J. Naval Archit. Ocean Eng*. 12, 414-427.
Wang, Y., R. Zhang and 2 others (2018): Investigating the effect of Arctic sea routes on the global maritime container transport system via a generalized Nash equilibrium model. *Polar Research.* 37(1), 1547042.
Wang, H., Y. Zhang and Q. Meng (2018): How will the opening of the Northern Sea Route influence the Suez Canal Route? An empirical analysis with discrete choice models. *Transp. Res. Part A*, 107, 75-89.
Wang, Z., J.A. Silberman and J.J. Corbett (2020): Container vessels diversion pattern to trans-Arctic shipping routes and GHG emission abatement potential. *Marit. Pol. Manage.*
Wang, D., D. Li and 4 others (2019): Development situation and future demand for the ports along the Northern Sea Route, *Res. Transp. Bus. Manag.* 33.
Xu, H., Z. Yin and 3 others (2011): The potential seasonal alternative of Asia–Europe container service via Northern sea route under the Arctic sea ice retreat. *Marit. Pol. Manage.* 38:5, 541-560.
Xu, H., D. Yang and J. Weng (2018): Economic feasibility of an NSR/SCR-combined container service on the Asia-Europe lane: a new approach dynamically considering sea ice extent. *Marit. Pol. Manage.*. 45(4), 514-529.
Yumashev, D., K.V. Hussen and 2 others (2017): Towards a balanced view of Arctic shipping: estimating economic impacts of emissions from increased traffic on the Northern Sea Route. *Climatic Change.* 143, 143–155.
Zeng, Q., L. Tingyu and 3 others (2020): The Competitiveness of Arctic Shipping over Suez Canal and China-Europe Railway. *Transp. Pol.*
Zhang, Y., Q. Meng. and S.H. Ng (2016): Shipping efficiency comparison between Northern Sea Route and the conventional Asia-Europe shipping route via Suez Canal. *J. Transp. Geogr.* 57, 241–249.
Zhao, H., H. Hua and Y. Lin (2016): Study on China-EU container shipping network in the context of Northern Sea Route. *J. Transp. Geogr.* 53, 50–60.
Zhang, Z., D. Huisingh and M. Song (2018): Exploitation of trans-Arctic maritime transportation. *J. Clean. Prod.* 212, 960-973.

Summary in Japanese

和文要約

多様な観点に基づく北極海輸送の経済的実現性に関する体系的レビュー

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地球温暖化を契機とする北極海輸送への関心の高まりにより，最近では多くの関連研究が発表されている．本研究は，北極海輸送の経済的実現性を多様な観点から評価する体系的な研究レビューを行うことを目的に，1999年以降に出版された北極海輸送に関する60編の研究論文・報告書を整理し，その主目的に応じて11の分野に分類した．具体的には，北極海輸送と他ルートとのコスト比較，北極海航行時における環境への影響，運航に関する検討，輸送ルート選択モデル，既存ルートとの混合輸送の実現可能性，北極海輸送利用の基準，航行速度，通航料金の水準，北極海輸送利用による経済的影響，北極海輸送に関する工学的側面，そしてロシアの北極政策である．さらに，各研究の対象地域と品目，分析手法，分析において着目した要素，航行可能期間や船舶のサイズ・アイスクラス・速度に関する想定，分解能，燃料の種類，各研究において得られた北極海輸送が成立する条件についても整理した．また，特に北極海輸送の経済的実現性を検討するにあたり，多くの既存の輸送費用算定モデルにおいて燃料消費，航行速度，エンジン規格等のもたらす影響が十分に考慮されていないことなど，既存研究の限界についても明らかとした．

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