
Demystifying the Economic Viability of the Northern Sea Route

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ABSTRACT

This paper challenges the optimistic outlook on a near-term economically viable Northern Sea Route (NSR) by delving into the prospective impacts of utilizing the NSR over the traditional Suez Canal for shipping. The paper uses Chinese exports—of paint, computers, and motor vehicles—from Shanghai, China to Rotterdam, Netherlands as a case study to support this argument. The study examines transportation costs under varying sea ice conditions and incorporates icebreaker fees through a sensitivity analysis. Based on the analysis, the paper posits that the NSR will only be commercially viable for select goods when sea ice extent¹ reaches 25 percent or less. While projections suggest an ice-free Arctic by late mid-century, significant investment is needed for the NSR to compete with the Suez Canal. These investments are most justifiable for Russia, which could capitalize on icebreaker services and port fees as the route becomes more accessible. China may benefit from waiting on Russia's infrastructure development, while icebreaker companies would need to strike competitive rates and shipping liners should adopt a wait-and-see approach.

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INTRODUCTION

The Arctic is at the forefront of climate change, experiencing warming at a rate twice that of the global average.² The region is rapidly heading towards consistent seasonal ice-free conditions, with a 12.6 percent reduction in sea ice over the past forty years.³ Notably, since 2007, the Northwest Passage (NWP) and the Northern Sea Route (NSR) have been ice-free in late summer.⁴ Studies have highlighted that a decrease in sea ice cover can result in substantial distance savings, particularly between East Asia and Western Europe. This would mean up to 30 to 50 percent reduction in travel and goods' transport time across the NWP and NSR, compared to the Suez Canal.⁵ Accordingly, shipping companies, governments (especially China), and profit-driven ventures view the NSR as a potential global shipping route to cut transportation costs.

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within the NSR can impede transit times and impose vessel limitations, thus elevating shipping costs and negating the advantages of economies of scale. Second, the lack of stops along the NSR results in fewer opportunities for unloading and reloading cargo, limiting potential profits when compared to the Suez Canal. The challenges the NSR presents raise uncertainties about its superiority over the Suez Canal or its potential to improve China's export competitiveness.

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This paper employs two key approaches to comprehend the potential effects of the NSR on Chinese exports and dispel illusions surrounding the economic feasibility of the Northern Sea Route in the near realm. First, it assesses the transportation costs of select Chinese exports using the Suez Canal and compares them with costs using the NSR under varying sea ice conditions. Second, the paper conducts a sensitivity analysis test, comparing the resulting transportation costs for each Chinese export under different NSR icebreaker scenarios (fees), which depend on the prevailing sea ice conditions. This test reveals how transportation costs for each examined export are susceptible to icebreaker fees in comparison to the current shipping route through the Suez Canal.

This paper focuses on selected Chinese exports: Paint (Organoinorganic compound),⁶ computers,⁷ and motor vehicles.⁸ The transpor-

tation of these goods is simulated from Shanghai to Rotterdam, with a deliberate effort to maintain consistency across numerous variables to ensure an accurate comparison of routes and goods while also accounting for varying sea ice conditions.

Three scenarios are considered: Scenario A represents an ice-free NSR, Scenario B involves a sea ice extent of 25 percent, and Scenario C entails a sea ice extent of 50 percent.⁹

Summary of Findings

In an ice-free scenario, the NSR emerges as the most cost-effective option, featuring the lowest unit transportation costs and delivery prices across paint, computers, and motor vehicles. Under 25 percent sea ice extent conditions, the NSR maintains its competitive edge, offering the lowest unit transportation costs and delivery prices for motor vehicle exports, and equivalent costs for paint exports, compared to the Suez Canal. However, for computer exports, the Suez Canal proves to be the optimal choice when compared to the NSR with 25 percent and 50 percent sea ice conditions, offering lower unit transportation costs and delivery prices.

A generalization across the analyzed goods suggests that the NSR becomes economically viable when sea ice extent is around 25 percent and even then, only certain goods.

These findings delineate the threshold at which melted sea ice in the Arctic renders the NSR a cost-efficient and competitive route compared to the Suez Canal, along with identifying the specific types of goods that would be advantageous for exportation via the NSR. A generalization across the analyzed goods suggests that the NSR becomes economically viable when sea ice extent is around 25 percent and even then, only certain goods—in the present analysis, motor vehicles and potentially paint—exhibit competitive unit costs and delivery prices to the Suez Canal.

This paper is organized into three sections to comprehensively address the intricate aspects of transportation costs, delivery prices, and the overall impact on China’s export competitiveness. Its organization and methodology are inspired by Shelton Metcalf’s master’s thesis at The Fletcher School, which explored U.S. export competitiveness under the Panama Canal expansion in 2013.¹⁰

BACKGROUND

Shipping Routes

In the current shipping landscape, exports from Shanghai to Rotterdam primarily use the Suez Canal. However, the ongoing impact of ice melt in the Arctic Ocean introduces two alternative shipping paths: the NWP and the NSR. The NWP traverses American and Canadian waters, while the NSR extends through Russian waters into northern Europe.¹¹ This paper focuses exclusively on the NSR due to its increasing viability and relevance.

The Suez Canal, a critical maritime pathway, links the Mediterranean Sea to the Red Sea. This canal holds immense significance, accounting for 12 percent of global trade, hosting approximately 30 percent of global container traffic, and facilitating the transport of over USD 1 trillion worth of goods yearly.¹²

Between the ports of Shanghai and Rotterdam, a vessel's journey via the Suez Canal is ~10,799 nautical miles¹³ whereas through the NSR, it would be covered in ~7,559 nautical miles.¹⁴ In 2021, the Suez Canal accounted for 1.27 billion metric tons of cargo, while the NSR accounted for a mere 34.9 million metric tons.^{15,16} This illustrates the potential for expanded trade along the NSR.

The Selection of Paint, Computers, and Motor Vehicles

The paper focuses on the evaluation of three distinct Chinese goods—paint, computers, and motor vehicles—because of their distinct vessel usage that results in diverse transportation costs, and due to their individual manufacturing processes and pricing structures. This deliberate choice facilitates a foundational understanding of how the NSR may impact Chinese international trade.

The selection rationale for paint stems from its classification as an organo-inorganic compound, ranking as the fifth most exported good classification from China to the European Union (EU).¹⁷ Organo-inorganic compounds play fundamental roles in the production of drugs, dyes, and plastics, with paint falling under the category of dye exports.

Computers fall within the telecommunications equipment category, the most imported goods by the EU from China.¹⁸

Motor vehicles have been chosen because China is the largest exporter of cars.¹⁹ In the EU, they rank fifteenth among imports from China, while cars are the EU's primary export to China.²⁰

The Role of Sea Ice Conditions

Sea ice extent reduces vessel speed, extends transit times, and affects vessel sizes due to constraints on water depth, known as draft measurements. In icy conditions, icebreakers are necessary, typically reducing vessel size, as high sea ice extents require specialized icebreakers that are smaller in size. Therefore, cargo capacity is reduced and extra costs are incurred.²¹ Freight and insurance rates fluctuate depending on variables such as voyage duration, risks, personnel requirements, and technology.

ANALYSIS AND FINDINGS

To precisely assess and compare transportation costs, the model utilized in this section aims to control for external factors and remove unnecessary fluctuations. The analysis can thereby focus on key distinctions between each route and scenario. The transportation cost model assumes direct delivery from Shanghai to Rotterdam. Vessels are presumed to travel at their fastest average speeds,²² with specific types of exports, using designated vessels.²³

This study assumes constant sea ice conditions throughout the year,²⁴ which allows the study to find a specific sea ice condition threshold that results in profitable shipping, outlining specific scenarios: an ice-free Northern Sea Route in Scenario A, 25 percent sea ice extent in Scenario B, and 50 percent sea ice extent in Scenario C. The study considers 25 percent and 50 percent sea ice conditions as they reflect the current climate while ice-free conditions reflect a potential future.

Transit Times

For NSR Scenarios B and C, adjusted speeds are applied due to sea ice coverage.

Table 1: Transit Time (in days) for Paint, Computer, and Motor Vehicle Exports²⁵

Product Name	Suez Canal²⁶	NSR (Scenario A)	NSR (Scenario B)	NSR (Scenario C)
<i>Paint Exports (Chemical Tanker)</i>	27.13	18.53	21.00	24.23
<i>Computer Exports (Container Vessel)</i>	19.41	13.12	15.75	19.68
<i>Motor Vehicle Exports (RoRo Vessel)</i>	21.12	14.32	16.58	19.68

Analysis of shipping times from Shanghai to Rotterdam reveals that for all product categories—paint, computers, and motor vehicles—the NSR offers faster shipping times. This is particularly advantageous for paint and motor vehicle exports, where the NSR consistently outperforms the Suez Canal in almost all scenarios. For computer shipments, the Suez Canal remains marginally quicker than the 50 percent sea ice-covered NSR.

Vessel Sizes and Cargo Capacity

For ease of analysis, the paper assumes exporters will use the largest vessel available for each chosen route²⁷ and product, though, in practice, profit maximization may not always favor the largest vessel.

Under NSR Scenario A, where there are no vessel limitations, exporters may employ the largest possible vessel, which matches the capacity allowed in the Suez Canal. However, under NSR Scenarios B and C, the paper assumes a reduction in vessel size due to sea ice coverage. Specifically, in Scenario B, the vessel is assumed to be 25 percent smaller than in Scenario A, corresponding to the 25 percent sea ice extent. Similarly, in Scenario C, the vessel is assumed to be 50 percent smaller than in Scenario A, corresponding to the 50 percent sea ice extent.²⁸

Table 2: Cargo Capacities (in respective units) for Paint, Computer, and Motor Vehicle Exports²⁹

Export Product	Suez Canal	NSR (Scenario A)	NSR (Scenario B)	NSR (Scenario C)
<i>Gallons of Paint</i> ³⁰	14,520,000	14,520,000	10,890,000	7,260,000
<i>TEU/Vessel</i> ³¹	724,000	24,000	18,000	12,000
<i>Vehicles/Vessel</i> ³²	8,000.00	8,000.00	6,000.00	4,000.00

A comparative analysis of cargo capacities reveals that the Suez Canal exhibits parity with, or surpasses, the Northern Sea Route (NSR) for all three products under consideration. Given the improbability of Scenario A materializing in the foreseeable future, the Suez Canal demonstrably outperforms the NSR in terms of cargo carrying capacity and the potential for profit maximization through economies of scale.

Unit Cost of Transportation and Analysis

To obtain the unit cost of transportation, the sum of transportation costs including vessel charter fees/ocean freight rates/auto transport rates, canal transit fees, insurance rates (including risk premiums), and

import tariff rates, were converted into common units for paint (gallons), computers (per computer), and motor vehicles (per vehicle) by dividing the whole of transportation costs by the unit carrying capacity of the vessel as seen in the tables above.

Table 3: Unit Cost of Transportation for Paint, Computer, and Motor Vehicle Exports³³

Product Metric	Suez Canal	NSR (Scenario A)	NSR (Scenario B)	NSR (Scenario C)
USD/Gallon	\$1.99	\$1.75	\$1.85	\$2.16
USD/Computer	\$0.87	\$0.85	\$1.06	\$1.27
USD/Vehicle	\$5,510.92	\$4,822.50	\$5,131.33	\$5,498.50

The results indicate that the most cost-effective route is NSR Scenario A. NSR Scenario B is next in cost-effectiveness for paint and motor vehicles. The Suez Canal is the least cost-effective route for motor vehicle exports but the second most cost-effective route for computers. Thus, the NSR has so far proven to have great economic benefits.

Having established the unit costs of transportation for all three goods, the paper will proceed to determine the final delivery prices for each commodity for both routes under all scenarios.

Delivery Prices

Delivery price, encompassing all costs from production to import tariffs, is a crucial determinant of an exporter's competitiveness in a foreign market.³⁴ The relationship between the delivery price and the market price is pivotal, with lower delivery prices indicating greater competitiveness. Exporters aspire to minimize delivery prices to enhance their market position.

To determine the delivery price, the origin price of each product—the cost of production—was added to the goods' unit cost.

Table 4: Delivery Price for Paint, Computers, and Motor Vehicle Exports³⁵

Product Metric	Suez Canal	NSR (Scenario A)	NSR (Scenario B)	NSR (Scenario C)
USD/Gallon	\$3.99	\$3.75	\$3.85	\$4.16
USD/Computer	\$1,492.87	\$1,492.85	\$1,493.06	\$1,493.27
USD/Vehicle	\$16,402.92	\$15,714.50	\$16,023.33	\$16,390.50

The results illustrate that transportation costs do not have a large effect on computer exports, i.e. the competitiveness between the NSR and Suez Canal is marginal. Whereas transportation costs have a considerable impact on paint exports and, to a lesser extent, motor vehicles. Therefore, the NSR is the preferable route for paint and motor vehicles especially when the sea ice extent is 25 percent or less.

Sensitivity Analysis

An important additional cost element needs to be accounted for—icebreaker services. Specifically, this analysis scrutinizes the cost implications of using icebreakers, in scenarios with varying sea ice extents (B and C), with rates assessed in USD per ton of cargo.

Sensitivity Test Results

Following the sensitivity test, paint exports cost an additional USD 0.14 per gallon in Scenario B and an additional USD 0.24 per gallon in NSR Scenario C; computer exports cost an additional USD 0.05 per unit in Scenario B and an additional USD 0.09 per unit in NSR Scenario C, and; motor vehicle exports cost an additional USD 41.86 per unit in Scenario B and an additional USD 72.80 per unit in NSR Scenario C.³⁶

Table 5: Delivery Price After Sensitivity Analysis for Paint, Computers, and Motor Vehicle Exports³⁷

Product Metric	Suez Canal	NSR (Scenario A)	NSR (Scenario B)	NSR (Scenario C)
<i>USD/Gallon</i>	\$3.99	\$3.75	\$3.99	\$4.39
<i>USD/Computer</i>	\$1,492.87	\$1,492.85	\$1,493.06	\$1,493.27
<i>USD/Vehicle</i>	\$16,402.92	\$15,714.50	\$16,065.19	\$16,463.30

Adding the icebreaker costs into the overall transportation expenses, results in noteworthy changes: paint exports under NSR Scenario B match that of the Suez Canal route, and motor vehicle exports under NSR Scenario C now surpass the Suez Canal in having the highest unit cost per vehicle. With the addition of icebreaker costs, the analysis shows the NSR becoming less competitive for paint exports under NSR Scenario B as well as for motor vehicle exports under NSR Scenario C.

Analysis Summary and Findings

In reality, due to varying sea ice conditions throughout the year, the NSR is only viable when there are ice-free conditions. At 25 percent sea ice extent, motor vehicle exports are the only competitive product to export via the NSR. Furthermore, taking into consideration fluctuations in sea ice extent,³⁸ motor vehicle exports via the NSR would have a competitive edge for approximately one week in the year 2023. These findings challenge the notion of an economically viable NSR in the foreseeable future. Generalizing the goods used in this study across China’s exports, the NSR won’t become an economically feasible route until sea ice extent is 25 percent or less, for a resounding part of the year, and even then, it is only justified for some exports—those in the same category as motor vehicles—until ice-free conditions become apparent at which point the NSR is competitive for all goods.

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POLICY IMPLICATIONS AND INDUSTRY GUIDANCE

This paper has unveiled the potential of the Northern Sea Route as an alternative to the Suez Canal. The findings reveal that the former will be a viable choice only for specific products, under specific ice conditions. These findings hold varying implications for different stakeholders.

First, the Arctic shipping route serves as a reality check against the nearly romanticized notion of its immediate economic viability. Contrary to popular belief, economic gains are not readily attainable. Analysis indicates that the NSR becomes cost-effective only when the sea ice extent reaches 25 percent, and even then, it remains feasible only for select goods. A complete shift from the Suez Canal to the NSR for shipping goods from Shanghai to Rotterdam can only occur when ice-free conditions prevail. Projections suggest the NSR could be ice-free during summers between 2035³⁹ to late 2040s⁴⁰ and fully ice-free by 2050⁴¹ to 2065.⁴² Nevertheless, immediate economic benefits are not anticipated.

Shipping schedules are planned weeks to months in advance, offering the possibility of aligning shipments with periods of low sea ice extent. However, Arctic weather unpredictability and the absence of opportunities for cargo drop-off and reload along the route significantly diminish potential profit margins. Hence, it remains a reasonable assessment that the NSR will not emerge as a global shipping route until it is predominantly ice-free for a substantial portion of the year.

Chinese exporters and government officials can utilize these findings to strategically allocate resources toward vessels capable of navigating icy waters and icebreakers. Monitoring sea-ice conditions enables them to discern optimal timing for investing in such vessels, training personnel, and developing large-scale icebreakers.⁴³ However, as previously discussed, this constitutes a long-term investment strategy with delayed returns. Moreover, it entails substantial financial outlay, particularly considering that only select goods are economically viable for shipping via the NSR

..... in icy conditions. The construction of a large-scale icebreaker spans a decade and carries a staggering cost of approximately USD 1 billion, with additional expenses incurred for maintenance and extending operational life.⁴⁴ Given these factors, it may be prudent to contemplate this process in the near future; investments of this magnitude would be impractical, especially considering that only goods with high transportation costs relative to final delivery prices warrant shipment in or below 25 percent sea ice conditions.

..... routes by 2050, a ten-year icebreaker development project could be obsolete by the time it is complete. Chinese exporters, government officials, and potential NSR users like South Korea and Japan⁴⁵ might be better advised to defer such extensive investments until the Arctic conditions are ice-free. At the moment they can invest in personnel training, vessel improvements to withstand the harsh environment, and navigational technology in Arctic conditions. When eventually deemed economical, investments could be made in the infrastructure along the NSR coastline, such as ports and maintenance facilities. Concurrently,

they can wait until countries such as Russia develop the NSR with ports and icebreaker services to avoid substantial financial commitments for marginal gains.

Russia faces an additional challenge: determining the optimal timing for investing in Arctic routes, ports, and icebreaker services based on sea ice conditions. Similar to China, Russia can benefit from this analysis to ascertain the economic feasibility of Arctic investments.⁴⁶ Given Russia’s potential role as a key port of call for vessels requiring refueling or maintenance along the NSR, they are in a favorable position to initiate investments earlier. Once the NSR becomes ice-free, shipping from East Asia to Northern Europe through this route promises significant economic advantages. At present, port construction costs along the Russian coast for the NSR are estimated at USD 1.7 billion.⁴⁷ While the expenses for port infrastructure and icebreakers may appear substantial, considering the Suez Canal facilitated transport of over USD 1 trillion worth of goods in 2021, such investments may seem justified. These facilities won’t become obsolete when the Arctic becomes ice-free; instead, they will reap higher benefits due to the future increased traffic.

Furthermore, Russia would enjoy a return on its investment throughout the entire transition period, not just in ice-free conditions; per the analysis above, for goods similar to motor vehicles, the NSR is viable even with ice coverage. Given that the NSR proves economically viable under certain ice conditions, it is prudent for Russia to prioritize investment in large-scale

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icebreakers ahead of other nations. This would not only alleviate the logistical challenges for shipping liners but also incentivize other countries to utilize the NSR, thereby enabling Russia to capitalize on icebreakers and port fees, enhancing its economic prospects.

Finally, icebreaker manufacturers and service providers have a vested interest in comprehending the rates that strike a delicate balance, ensuring the competitiveness of the NSR against the well-established Suez Canal. As demonstrated in the analysis, current icebreaker fees have rendered certain goods less competitive when transiting the NSR compared to the Suez Canal. By keeping fees at an optimal level—ideally low enough to maintain the NSR’s competitiveness—these companies could expedite the adoption of the route, leading to a larger pool of clients and increased demand for

their services. Additionally, shipping companies would be wise to adopt a wait-and-see approach regarding the NSR's development. Once investments are made and infrastructure is established, they can then consider retrofitting existing vessels to navigate icy conditions, thereby saving costs and ensuring efficient utilization of resources.

A CAUTIONARY NOTE

While the article focuses on potential economic gains from an ice-free Arctic, we must acknowledge the significant environmental drawbacks. An ice-free NSR, though lucrative, would be detrimental to global biodiversity and have catastrophic consequences for humanity, wildlife, and the planet as a whole. Considering the minimal economic gains against the extensive cascading costs of the biodiversity loss and environmental toll, actively anticipating an ice-free NSR is imprudent. *f*

ENDNOTES

- 1 Sea ice extent refers to the area of ice, of at least 15 percent ice concentration, that covers the Arctic Ocean at a given time.
- 2 Gianluca Meneghello, "How much has the Arctic ice declined, and how does that compare to past periods in the Earth's history?," Ask MIT Climate, Climate Portal, April 10, 2023, <https://climate.mit.edu/ask-mit/how-much-has-arctic-ice-declined-and-how-does-compare-past-periods-earths-history>.
- 3 Ibid.
- 4 Malte Humpert, "The Future of the Northern Sea Route - A "Golden Waterway" or a Niche Trade Route," The Arctic Institute, September 15, 2011, <https://www.thearcticinstitute.org/future-northern-sea-route-golden-waterway-niche/>.
- 5 Jenessa Duncombe, "Arctic Shipping Routes Are Feeling the Heat," Eos, July 6, 2022, <https://eos.org/articles/arctic-shipping-routes-are-feeling-the-heat>.
- 6 Transportation costs for paint is based on the average world price for a gallon of paint.
- 7 Transportation costs for computers based on Macbook Pro 16 inches. Traditionally, Apple assembles most Macbooks in China, particularly in the cities of Chengdu and Shanghai. Cheng Ting-Fang, "Apple to start making MacBooks in Vietnam by mid-2023," *Nikkei Asia*, December 20, 2022, <https://asia.nikkei.com/Spotlight/Supply-Chain/Apple-to-start-making-MacBooks-in-Vietnam-by-mid-2023>.
- 8 Transportation costs for motor vehicles are based on the MG Motor M4 electric vehicle. The British MG company was acquired by Shanghai Automotive Industry Corporation and has emerged as one of the best selling car brands in Europe specifically the M4 EV. Keith Bradsher, "China Is Flooding the World With Car Exports," *The New York Times*, September 6, 2023, <https://www.nytimes.com/2023/09/06/business/china-car-exports.html>.
- 9 The analysis will not consider scenarios above 50 percent sea ice extent as the study shows that usage of the NSR compared to the Suez Canal is impractical at 50 percent sea ice extent itself. Therefore, any value higher than 50 percent will produce the same result.

- 10 Shelton D Metcalf, "To what extent will the Panama Canal expansion lower transportation costs and enhance the competitiveness of exports from the United States?," The Fletcher School, Tufts University, April 18, 2013.
- 11 "Northern Sea Route and the Northwest Passage compared with currently used shipping routes," GRID-Arendal, accessed March 4, 2024, <https://www.grida.no/resources/7150>.
- 12 New Zealand Embassy in Cairo, "The Importance of the Suez Canal to Global Trade - 18 April 2021," New Zealand Ministry of Foreign Affairs and Trade, 2021, <https://www.mfat.govt.nz/en/trade/mfat-market-reports/the-importance-of-the-suez-canal-to-global-trade-18-april-2021/>.
- 13 "Routing," FluentCargo, accessed November 14, 2023, <https://www.fluentcargo.com/search?o=Shanghai%2C+China&d=Rotterdam%2C+Netherlands>.
- 14 Liangkun Xu, "Performance Analysis: Using the Northern Sea Route as an Alternative to Traditional Routes," *Journal of Marine Science and Technology* 30, no. 6 (2022): 359.
- 15 Malte Humpert, "Cargo Volume on Northern Sea Route Reaches 35m Tons, Record Number of Transits," *High North News*, September 13, 2022, <https://www.highnorthnews.com/en/cargo-volume-northern-sea-route-reaches-35m-tons-record-number-transits>.
- 16 There is already established transport of goods across the NSR. In 2013, the Chinese vessel *Yong Sheng* marked the first commercial transit from Dalian to Rotterdam via the NSR, and in 2017, the NSR witnessed the inaugural voyage of a Liquefied Natural Gas tanker from Norway to South Korea. Matt McGrath, "First tanker crosses northern sea route without ice breaker," *BBC*, August 24, 2017, <https://www.bbc.com/news/science-environment-41037071>.
- 17 "China-EU - international trade in goods statistics," European Commission, February 2024, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=China-EU_-_international_trade_in_goods_statistics#EU_and_China_in_world_trade_in_goods.
- 18 Ibid.
- 19 Peter Hoskins, "China overtakes Japan as world's top car exporter," *BBC*, <https://www.bbc.com/news/business-65643064>.
- 20 European Commission, "China-EU - international trade in goods statistics".
- 21 In 2003, an Arctic coalition directive prompted a considerable increase in icebreaker fees on the NSR, averaging around USD 23 per ton. Subsequently, in 2009, the fee for container cargo rose to USD 40 per ton. These fee levels appear exceptionally high, suggesting that negotiation may be a feasible consideration. For this reason, I have considered conditions under 25 percent sea ice extent as having a lower icebreaker rate of USD 23 per ton of cargo and a 50 percent sea ice extent as having a higher icebreaker rate of USD 40 per ton of cargo. Karl Magnus Eger, "Arctic Shipping Routes - Costs and Fees," Arctic Knowledge Hub, accessed March 8, 2024, <http://www.arctis-search.com/Arctic+Shipping+Routes++Costs+and+Fees>.
- 22 Chemical tankers' average speed is 13 to 17 knots; container vessels' average speed is 16 to 24 knots, and; roll-on roll-off (RoRo) vessels' average speed is 16 to 22 knots. Mayur Agarwal, "What is the Speed of a Ship at Sea?," Marine Insight, April 26, 2019, <https://www.marineinsight.com/guidelines/speed-of-a-ship-at-sea/>.
- 23 Paint exports use chemical tankers, computer exports use container vessels, and motor vehicles use RoRo vessels.
- 24 This is an unrealistic assumption as sea ice naturally has seasonal variations. For example in 2023, the Arctic's average sea ice extent for September was 31.2 percent whereas in March of 2023, sea ice extent was over 100 percent. The variation is removed for the purpose of calculation during the analysis stage and readded in the

- section “Policy Implications and Industry Guidance”. “How big is the Arctic ocean? And eight other Arctic facts,” World Wildlife Fund, accessed February 6, 2024, <https://www.worldwildlife.org/stories/how-big-is-the-arctic-ocean-and-eight-other-arctic-facts>; “Arctic Sea Ice Minimum Extent,” Vital Signs, Global Climate Change, NASA, accessed March 8, 2024, <https://climate.nasa.gov/vital-signs/arctic-sea-ice/>; and “Arctic sea ice reaches maximum extent for 2023,” National Snow and Ice Data Center, 2023, <https://nsidc.org/news-analyses/news-stories/arctic-sea-ice-reaches-maximum-extent-2023>.
- 25 Values in the table are derived from Sumner Levenson, “What Happens When All the Ice Melts? A Northern Sea Route Analysis of China’s Transportation Costs and Export Competitiveness,” The Fletcher School, Tufts University (2024 forthcoming).
- 26 On average it takes 12-16 hours to transit the canal itself. “How long does it take a vessel to transit the canal,” FAQ, Suez Canal Authority, accessed March 8, 2024, <https://www.suezcanal.gov.eg/English/Pages/FAQ.aspx>.
- 27 Despite draft and width limitations, the world’s largest chemical tanker, container vessel, and RoRo vessel have successfully passed through the Suez Canal. The largest chemical tanker in the world is the *Bow Orion* (used for paint exports). The world’s largest container vessel, *EVER ACME* (used for computer exports), transited the Suez Canal in February, 2023, holding over 24,000 TEUs (a TEU is a twenty-foot equivalent unit, a standard shipping container). The largest RoRo vessel is the *MV Tønsberg* (used for motor vehicle exports). “MV Tønsberg Roll-On / Roll-Off Vessel,” Ship Technology, April 11 2022, <https://www.ship-technology.com/projects/mv-tonsborg-roro-vessel/>; “World’s latest container ship *EVER ACME* transits Suez Canal on 1st sea voyage,” *Hellenic Shipping News Worldwide*, 2023, <https://www.hellenic-shippingnews.com/worlds-latest-container-ship-ever-acme-transits-suez-canal-on-1st-sea-voyage/>; “Bow Orion,” Odfjell, 2019, <https://www.odfjell.com/tankers/fleet/bow-orion/>.
- 28 The assumption of equal deductions in vessel sizes based on sea ice extent was made keeping in mind the scarce published research on vessel size equivalents to ice breakers. Therefore, with the knowledge that in icier conditions, specialized ice breakers are required which are typically smaller in size, the above deduction in sizes are assumed by estimation.
- 29 Values in the table are derived from Sumner Levenson, “What Happens When All the Ice Melts?”.
- 30 264 U.S. gallons fit in a cubic meter. Paint is typically sold globally in U.S. gallons.
- 31 Computer is based on Macbook Pro 16” dimensions: Height: 0.66 inch (1.68 cm), Width: 14.01 inches (35.57 cm), Depth: 9.77 inches (24.81 cm). A TEU’s dimensions are 20 feet long, 8 feet wide, and 8.6 feet tall. Accordingly, there would be 24501 computers in a TEU.
- 32 Dan Maloney, “RORO Vessels: Driving Cars Across The Ocean,” Hackaday, September 23, 2021, <https://hackaday.com/2021/09/23/ro-ro-vessels-driving-cars-across-the-ocean/>.
- 33 Values in the table are derived from Sumner Levenson, “What Happens When All the Ice Melts?”.
- 34 Delivery price includes all costs from production and shipping of the product. In this analysis, import tariffs are included as well, as they feature in the last mile delivery of said product.
- 35 Values in the table are derived from Sumner Levenson, “What Happens When All the Ice Melts?”.
- 36 Values derived from Sumner Levenson, “What Happens When All the Ice Melts?”.

- 37 Values in the table are derived from Sumner Levenson, “What Happens When All the Ice Melts?”
- 38 Previously excluded, as highlighted in endnote 23.
- 39 Lindsey Jacobson, “Arctic summers could be ice-free by 2035, reshaping global shipping routes,” *CNBC*, February 16, 2022, <https://www.cnn.com/2022/02/16/arctic-summer-could-be-ice-free-by-2035-enabling-faster-shipping.html>.
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- 46 Russia has made the development of the Northern Sea Route a state priority in the coming decades. However, sources vary as to how much Russia intends to invest, has invested, or has developed. As the war in Ukraine continues, it is likely that Russia has delayed the infrastructure development plans further.
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