FEASIBILITY OF THE NORTHERN SEA ROUTE:

CASES FROM THE OIL PRODUCT TANKER MARKET

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A THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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Abstract

This Thesis examines the feasibility of the Northern Sea Route for oil product tankers. First, a systematic literature review is conducted to evaluate the extant literature regarding comparative studies between Arctic and traditional routes. Second, three modelling cases are developed to assess the feasibility of the Northern Sea Route compared to the traditional routes via the Suez Canal and the Cape of Good Hope for the oil product tanker market, based on historic voyages and major trade flows between Europe and Asia.

The Thesis draws from classical microeconomic cost theory and classical maritime economics theory to study the economics of the Northern Sea Route. A Required Freight Rate analysis is developed to assess the competitiveness of competing routes. The methodological approach has two objectives. First, the cost assessment is based on ship speed optimisation to minimise the required freight rate of a route alternative. Second, the cost assessment is based on real ship speeds to determine the required freight rate of a route alternative. On the one hand, the cost minimising speed can be optimised with respect to cost and market factors. On the other hand, the real speed tends to depart from the optimal point owing to organisational and technical constraints, ship, and voyage-specific factors, as well as weather factors, amongst others. The main factors considered in the analysis are distance, fuel prices, ship speed through ice, seasonal navigation, icebreaking fees, ice damage repairs, ship size, capital and operating costs, commodity prices and in-transit inventory costs, as well as fuel types and operational modes, concerning commercial factors and environmental regulations. Unique primary and up-to-date secondary data were obtained and used in the analysis.

The Thesis contributes to knowledge by explaining quantitatively the use of NSR since 2010, and by employing important cost, market, navigational, and technological factors to establish relationships between factors that affect route choice in the context of Arctic shipping. It contributes to methodology by employing speed and cost models which are informed by current and future technologies, as well as insightful approaches to transport modelling. It contributes to practice through the findings of the systematic literature review and the modelling research, and provides an understanding of the factors that promote or hinder the competitiveness of Arctic routes, why and how.

Publications

Theocharis, D., Pettit, S., Sanchez Rodrigues, V. and Haider, J. 2018. Arctic shipping: A systematic literature review of comparative studies. *Journal of Transport Geography* 69, pp. 112-128. doi: 10.1016/j.jtrangeo.2018.04.010

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Theocharis, D., Sanchez Rodrigues, V., Pettit, S. and Haider, J. 2021. Feasibility of the Northern Sea Route for seasonal transit navigation: The role of ship speed on ice and alternative fuel types for the oil product tanker market. *Transportation Research Part A: Policy and Practice* 151, pp. 259-283. doi: 10.1016/j.tra.2021.03.013

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Ο ΘΕΟΣ ΜΕ ΣΩΖΕΙ

GOD IS MY HELP

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List of Abbreviations

AFC	Average Fixed Cost
AIS	Automatic Identification System
ARA	Amsterdam-Rotterdam-Antwerp
ATC	Average Total Cost
AVC	Average Variable Cost
Cape	Cape of Good Hope
CEAS	Computerised Engine Application System
CHNL	Centre for High North Logistics
CO_2	Carbon Dioxide
CRF	Capital Recovery Factor
DAS	Double Acting Ship
DWT/dwt	Deadweight Tonnage
ECAs	Emission Control Areas
ETS	Emissions Trading Scheme
FC	Fixed Costs
GHG	Greenhouse Gases
GT	Gross Tonnage
GWP	Global Warming Potential
H&M	Hull and Machinery
HSFO	High Sulphur Fuel Oil
ICE	Intercontinental Exchange
IFO	Intermediate Fuel Oil
IMO	International Maritime Organisation
Kg-CO_2-eq/t	Kilograms of CO_2-Equivalent per tonne
kW	Kilowatt(s)
LCS	Least Cost Speed
LIBOR	London Interbank Offered Rate
LNG	Liquefied Natural Gas
LOA	Length Overall
LPG	Liquefied Petroleum Gas
LPP	Length between Perpendiculars
LR1	Long Range 1
LR2	Long Range 2
LR3	Long Range 3
LS	Lumpsum
M. US$	Million U.S. Dollars
m.t.	Metric Tonne(s)
m^3	Cubic Metre(s)
MC	Marginal Cost
MCDM	Multi-Criteria Decision-Making
MGO	Marine Gasoil
MILP	Mixed-Integer Linear Programming

MMBtu	Metric Million British Thermal Unit
MPS	Most Profitable Speed
MR	Medium Range
n.m.	Nautical Mile(s)
NBP	National Balancing Point
NEP	Northeast Passage
NSR	Northern Sea Route
NSRA	Northern Sea Route Administration
NWP	Northwest Passage
OD	Origin-Destination Pair(s)
P&I	Protection and Indemnity
PC3	Polar Class 3
PC4	Polar Class 4
PC5	Polar Class 5
PC6	Polar Class 6
R&M	Repairs and Maintenance
RFR	Required Freight Rate
SCNT	Suez Canal Net Tonnage
SCR	Suez Canal Route
SDR	Special Drawing Rights
SFOC	Specific Fuel Oil Consumption
SGC	Specific Gas Consumption
SLWL	Summer Loaded Waterline
SMCR	Specified Maximum Continuous Rating
SO_x	Sulphur Oxides
SPOC	Specific Pilot Oil Consumption
STS	Ship-To-Ship
TC	Total Costs
TCE	Timecharter Equivalent
TEU	Twenty-foot Equivalent Unit
TPC	Tonnes per Centimetre Immersion
TSR	Transpolar Sea Route
TTF	Title Transfer Facility
UKC	U.K./Continent
US$/t	U.S. Dollars per tonne
USD or US$	U.S. Dollar(s)
USD/RUB	U.S. Dollar – Russian Rouble
VC	Variable Costs
VLSFO	Very Low Sulphur Fuel Oil
WPA	Waterplane Area
WS	Worldscale

Glossary

Aframax: Tankers between 85,000-124,999 deadweight (dwt), used in short to medium-haul crude oil and dirty oil products trades. Trading routes include voyages between the North Sea or West Africa to Europe or the USA, from the Middle East Gulf to Asia, and voyages in the North Sea, the Caribbean, the Mediterranean, and the Indo-Pacific regions (Clarksons 2021).

Arbitrage: A market condition where the difference in the price of a commodity between two geographic regions creates opportunities to make a profit. The commodity is bought in a region where it has a low price and is sold in a region where it has a high price. The cost to transport the cargo is also factored in the price difference. Arbitrage opportunities should disappear in competitive and efficient markets (McKinsey 2021). This occurs when the supply and demand of a commodity are balanced through changes in price and quantity.

Auxiliary engines: Small engines used to provide electrical power in a ship.

Ballast: Sea water contained in tanks, or cargo spaces, when a ship is not loaded with cargo, to increase the draught in order to achieve a desired stability, draught and trim for efficient operation (Stopford 2009; Wärtsilä 2021).

Beam: extreme width of a ship, also called breadth (ICS 2014; Wärtsilä 2021).

Break-even level: The level of production where cost equals revenue. In voyage estimation for tanker chartering, the break-even level does not include operating and capital costs. Yet, these are deducted from the total cost estimation to calculate the overall profit. In general, short and long-term costs must be balanced with revenue (ICS 2014).

Capital costs: Costs that do not vary with output, and once a company obtains a ship, they become fixed costs. Ship finance sources range from full equity (shipowner's private funds) to bank financing (asset-backed mortgages i.e. loans), to capital markets (e.g. corporate bonds, public equity offerings, retained profits), and other sources, such as various forms of leasing, export agency financing, shipyard financing, and private placements amongst others (Alizadeh and Nomikos 2009; Stopford 2009; Giannakoulis 2016). Bank financing through loans remains the most important method of finance over the years. In the case of bank financing through loans, capital costs include capital repayments and interest, depending on the loan terms and the level of interest rates (Alizadeh and Nomikos 2009).

Capital recovery factor (CRF): Tthe ratio that determines the present value of a stream of annual payments. Present value is the current value of a future amount of money or a stream of cashflows, and is calculated based on a rate of return. The capital recovery factor is used to estimate the annual repayment of a loan (Evans and Marlow 1990).

Charterer (cargo owner): A party who hires a ship for a period of time (time charter) or reserves a ship for a single voyage (voyage charter) from a shipowner (Stopford 2009).

Clean oil products: Refined oil products transported by clean product tankers (coated tankers) with special coating to maintain their quality (McKinsey 2021). The main categories of clean oil products include gasoline, naphtha, gasoil/diesel, jet fuel/kerosene, reformate, and clean condensate.

Condensate: There are various definitions of this fuel. It is typically separated out of a natural gas or crude oil stream of production, and treated as crude oil. It contains naphtha and natural gas liquids material, and can be blended with crude oil or sold directly in the market. Some condensates contain a high volume of jet fuel and diesel material and little residue material (McKinsey 2021; EIA 2021). Clean condesate can be used as an intermediate cargo for either crude oil tankers or clean product tankers in order to switch from the dirty to the clean market, depending on market conditions. This option reduces cleaning expenses and enables trading in the dirty market (Platts 2021).

Deadweight (DWT or dwt): The weight a ship carries. It is the difference between the lightweight and loaded displacement, and includes: cargo, fresh water, fuel, lubricating oil, stores, water ballast, crew and effects, and baggage and passengers, and is measured in metric tonnes (m.t.)[1] (Barrass 2004; Stopford 2009; ICS 2014). The term ‘payload’ is used as an alternative in this Thesis.

Dirty oil products: Oil products transported by crude oil tankers, and principally refer to heavy fuel oils.

Displacement: The total weight of lightship and deadweight i.e. the total weight of water displaced by a ship at a certain draught (summer, winter, or other) (ICS 2014). Displacement equals deadweight plus lightweight. The latter does not vary throughout the life of a ship and remains relatively stable, whereas the former varies depending on how much a ship is loaded (Barrass 2004).

[1] One metric tonne equals 1,000 kilograms.

Draught: The vertical distance between the waterline and the point of the hull which is deepest in the water. Various definitions of draught exist depending on the type of cargo loaded on board a ship, the season and relevant regulations (MAN Diesel and Turbo 2013a).

Exchange rate: The rate at which two currencies are exchanged in the foreign currency markets.

Freight market: A market place where sea transport transactions occur between market participants.

Gasoil/Diesel: A category referring to either intermediate products (light atmospheric gasoil, heavy atmospheric gasoil, vacuum gasoil, coker gasoil, hydrocracked gasoil) or finished oil products (diesel, heating oil or industrial gasoil, marine gasoil/marine diesel) (McKinsey 2021).

Gross Tonnage (GT): It is estimated based on the volume of all enclosed spaces of a ship. It is used in the formation of manning regulations, safety rules, registration fees, and port dues.

Heavy Fuel Oil: A category referring to various refined products ranging from kerosene to residual fuel oil. It typically refers to residual fuel oils, or heavy fuel oils (McKinsey 2021).

Ice class ship: A ship equipped with an enhanced hull and other arrangements to be able to operate through ice water. The Finnish-Swedish Ice Class notation is adopted in the analysis of this Thesis (Trafi 2017a).

In-transit inventory: The inventory which refers to cargo in transit i.e. cargo sold and being transported but have not reached its destination.

Jet Fuel/Kerosene: This refined oil product is the fuel principally used for aircraft jet engine propulsion and other jet turbine applications. Kerosene is the blendstock used to make jet fuel, but is also sold directly as fuel oil. It has other uses in a range of industries, as well as in various production processes of other oil products, including diesel, heavy naphtha, gasoline, and heavy fuel oils (McKinsey 2021).

Laden: A condition where a ship is loaded with cargo.

Length overall (LOA): extreme length of a ship (ICS 2014).

Lightweight: The weight of a ship as built, including engines, boiler water, lubricating oil, and cooling water system (ICS 2014).

London Interbank Offered Rate (LIBOR): It is the primary interest rate against which loans are issued in the Eurocurrency markets (Alizadeh and Nomikos 2009).

LR1: Tankers between 55,000-84,999 dwt, used in medium to long-haul clean oil products trades. This tanker type includes coated non-IMO[2] graded tankers and IMO III tankers (Clarksons 2021).

LR2: Tankers between 85,000-124,999 dwt, used in medium to long-haul clean oil products trades. This tanker type includes coated non-IMO graded tankers and IMO III tankers (Clarksons 2021).

LR3: Same as Suezmax, but sometimes refers to a tanker type involved in clean oil products trades.

Lumpsum rate: A rate that applies when crude oil and refined oil products price movements create temporary irregular trade opportunities. They are similar to spot freight rates in that freight is paid to a shipowner by a charterer for delivering a cargo on a specific route. All costs are generally paid by the shipowner unless otherwise specified in the charter party. Costs are estimated based on the farthest ports from a range of ports between the origin and destination, including any transit fees (ICS 2014).

Medium Range (MR): Tankers between 25,000-54,999 dwt, used for oil products trades, including MR and Handysize tankers. They are used in short to medium-haul oil products trades on intra-Asian routes, and on trades from the Middle East Gulf and the Indian Sub-Continent to the Indo-Pacific region and Europe. This tanker type includes coated non-IMO graded tankers, IMO III tankers, IMO II tankers with average tank size greater than 3,000 cubic metres or equivalent, tankers of unknown IMO grade, and uncoated non-IMO graded tankers. The term does not include tankers with stainless steel tanks (Clarksons 2021).

Middle distillates: A term referring to refined oil products such as jet fuel, kerosene, gasoil and diesel (McKinsey 2021).

Naphtha: Light naphtha: refined oil product used as petrochemical feedstock, or directly as a gasoline blendstock . Heavy naphtha: Feedstock used in the reformer to make reformate for gasoline blending (McKinsey 2021).

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[2] IMO: International Maritime Organisation. A specialised agency of the United Nations responsible for regulating shipping.

Operating costs: Costs related with a ship's service. They do not vary significantly with the route used or voyage undertaking, and are generally considered as fixed costs. This cost category includes crew costs, costs for stores and consumables, repairs and maintenance costs, insurance costs, and administration or general costs.

Period market: The market where cargo transport transactions are traded for a certain period (months or years).

Required Freight Rate (RFR): The RFR is calculated by adding all costs of a voyage or series of voyages for a period of time (operating, voyage, and capital) and dividing them with the total cargo quantity transported to obtain the cost per tonne (metric) of cargo. The RFR establishes the break-even point of operations.

Shipowner: A party who owns a ship and undertakes the delivering of cargo under a voyage charter or a time charter contract.

Special Drawing Rights (SDR): The SDR is an international reserve currency, created by the International Monetary Fund, to supplement its member countries' official reserves (IMF 2021b).

Spot freight rate: Freight rate which is determined by the interaction of supply and demand in the spot market**.**

Spot market: The market where cargo transport transactions are traded for immediate delivery.

Spread: The rate at which loans are priced on top of the LIBOR rate, which varies depending on the prevailing market conditions, the profile of the shipowner, the nature of the collateral, and the competition in the ship financing market (Alizadeh and Nomikos 2009; Giannakoulis 2016; Petrofin 2017).

Suez Canal Net Tonnage (SCNT): A tonnage measurement of a ship, which is used for the calculation of the Suez Canal Tolls.

Suezmax: Tankers between 125,000-199,999 dwt, used in medium and long-haul crude oil and dirty oil products trades. Trading origins include West Africa, the Mediterranean and Black Sea regions, and the Middle East Gulf region (Clarksons 2021).

Time charter: A time charter contract stipulates that a charterer hires a tanker for a specified period of time (e.g. one month, three month, six month, one year, three year time charters) i.e. in the period market, and pays the shipowner on a US$ per day basis. The charterer pays for the voyage costs, port dues and canal tolls, and cargo-handling costs, whereas the shipowner pays for the operating costs, and recurring capital costs, if any. The trip charter contract is similar to the time charter contract but refers to a single voyage or the chartering of a ship for only a few days. The trip charter contract is more common in the dry bulk sector but has been used occasionally in some tanker trades (ICS 2014).

Timecharter equivalent rate (TCE): The TCE rate of a spot freight rate is calculated in the following way: Earnings are first calculated on a US$ per tonne basis using the Worldscale (WS) 100 and the WS rate of a certain voyage. The resultant freight rate is multiplied by the cargo quantity to obtain the gross freight. The net freight is obtained by deducting shipbrokers' commisions from the gross freight. The gross voyage expenses are then deducted from net freight, resulting in voyage surplus. The TCE is then obtained by dividing the voyage surplus by the number of days it takes to complete the voyage (ICS 2014). The TCE rate reflects net freight earnings, and is used by shipowners to compare alternative voyage offers in the spot market, as well as to compare earnings with period market contracts i.e. with time charter rates (Alizadeh and Nomikos 2009).

Tonnes per Centimetre Immersion (TPC): The change in draught by one centimetre, resulting from the addition or removal of a particular mass (Wärtsilä 2021).

Voyage charter: A voyage charter contract stipulates that a shipowner agrees to transport a specific cargo from a loading port to an unloading port for a fixed price i.e. spot rate in US$ per tonne in the spot market. The shipowner pays for all the expenses of the voyage, that is, operating costs, voyage costs, port dues and canal tolls, and cargo-handling costs, including recurring capital costs, if any. The tanker spot freight market uses the Worldscale Index (WS) to define the actual cost for a certain voyage in US$ per tonne.

Voyage costs: Costs that vary with output and occur once a ship is committed to undertake a voyage. This cost category includes fuel costs, port dues and canal tolls, and cargo-handling costs.

Worldscale Index (WS): The worldscale index is used in the tanker sector to calculate spot freight rates in US$ per tonne i.e. prices under a voyage charter contract. The WS predetermines a specific tanker size operating between a loading and an unloading port and returning back to the loading port, under a fixed speed, fuel consumption, and hire cost element, including port and fuel costs, and canal dues (Worldscale 2021). The calculated freight rate in US$ per tonne is defined as the WS 100, or the *flat rate*, which serves as the break-even rate for a specific voyage. If, for example the reported WS rate for a certain trade route is WS 50, then assuming a hypothetical flat rate of that route, WS 100, of 17.72 US$/t, the amount a shipowner will receive is 8.86 US$/t, that is, half the flat rate.

1. Introduction

This chapter introduces the topic of Arctic shipping and provides a background of important factors that determine the economics of the Northern Sea Route (NSR). Then, the motivation for undertaking this research is described. Historic events with respect to the use of the NSR between 2010 and 2020 are presented with reference to factors leading to the emergence of this ice-infested sea route as an alternative between Europe, the Baltic, the Russian Arctic, and Asia. The identified gaps of the literature are presented and both the Systematic Literature Review Questions and Research Questions of the PhD Thesis are outlined. A brief description of the methodological approach is provided and the structure of the Thesis is presented.

1.1 Background

Arctic shipping is an emerging topic within maritime transport research, demonstrating an increasing number of publications across various areas and themes during the last ten years. Lavissière et al. (2021) who conducted a systematic review on Arctic shipping research across various disciplines using a textometric approach, refer to Arctic transport as an emerging field on its own. Lasserre (2014) and Lasserre (2015) identified 26 comparative studies between Arctic and traditional routes from 1991 to 2013, whilst Meng et al. (2016) reviewed 25 studies regarding navigational and commercial perspectives. Ng et al. (2018) provided a literature review on climatic, physical, economic, environmental and social issues of Arctic shipping. Panahi et al. (2021) reviewed the Arctic-related port literature considering several themes, such as, economic, social, connectivity-related, operational, managerial, and environmental amongst others.

The NSR is the most studied Arctic sea route in the literature, given the prevailing sea ice conditions and recent infrastructure and project developments in the Russian Arctic, favouring mainly this Arctic route than the Northwest Passage (NWP) or the Transpolar Sea Route (TSR) (Eguíluz et al. 2016; Zhang, Meng, Ng 2016; NSRA 2016; Lasserre et al. 2020; Faury, Alix et al. 2020; CHNL 2021a; Gunnarsson 2021). The Northeast Passage (NEP) is a maritime passage comprising many routeing alternatives linking the Atlantic and the Pacific Ocean through the Russian Arctic coastline. The NSR, which is part of the NEP, is officially defined by Russia as the route stretching from Novaya Zemlya in the west to the Bering Strait in the east (Østreng and Eger 2013). The NSR can potentially offer distance and time savings depending on origin-destinations (OD) as well as prevailing market conditions and ship positioning. However, physical factors largely determine the commercial viability of voyages through the Arctic.

Variability in sea ice conditions (extent, thickness, and concentration), fog, darkness, harsh climate, and low temperatures (Stephenson et al. 2014; Faury and Cariou 2016; Aksenov et al. 2017; Faury, Cheaitou et al. 2020) make the NSR a very challenging environment to operate, where ice class ships, that is, ships with enhanced hulls and special equipment depending on the ice class notation, are required for operations.

The economic feasibility of the NSR for deep-sea shipping is primarily determined by sea ice conditions, where both inter and intra-annual variability of sea ice across all navigation zones can affect the extent of the navigation season and route economics alike (Smith and Stephenson 2013; Stephenson et al. 2014).

Speed through ice is an important factor that increases the uncertainty concerning transit times, and affects voyage and operating costs alike (Wergeland 1992; Mulherin 1996; Kitagawa 2001; Faury and Cariou 2016; Pruyn 2016). Ship speed through ice can be variable depending on local sea ice conditions, the navigation season, the ice class of a ship, and the zone or zones of navigation (Faury and Cariou 2016; Cariou and Faury 2020; Faury, Cheaitou et al. 2020; Cheaitou et al. 2020; Cariou et al. 2021), with high speeds increasing voyage frequencies and profitability, and very low speeds increasing costs, all else being equal (Wergeland 1992; Guy 2006; Lasserre 2014; Lasserre 2015).

The use of the NSR also entails certain premiums, including additional crew, insurance, and capital costs, as well as increased fuel consumption depending on the ice class of a ship and sea ice conditions (Erikstad and Ehlers 2012; von Bock und Polach et al. 2015; Solakivi et al. 2018; Solakivi et al. 2019; Faury, Cheaitou et al. 2020; Cheaitou et al. 2020). The risk of ice damage repairs can further increase costs and may render voyages unprofitable even if the NSR offers shorter distances (Tanker Company 2018; Tanker Company 2020).

Most importantly, icebreaking fees largely affect the competitiveness of the NSR (Liu and Kronbak 2010; Furuichi and Otsuka 2015; Cariou and Faury 2015; Gritsenko and Kiiski 2016; Moe and Brigham 2016; Zhao et al. 2016; Xu et al. 2018; Wang et al. 2020). On the one hand, official icebreaking fees are determined by the prevailing U.S. Dollar – Russian Rouble (USD/RUB) exchange rates, which reduce the potential of the NSR under high fuel prices (Shibasaki et al. 2018), due to the inverse relationship between oil prices and the value of Russian Rouble (Beckmann and Czudaj 2013; Yang et al. 2017; Chuffart and Hooper 2019). On the other hand, a combination of fixed discounted fees and high fuel prices significantly increases the competitiveness of the NSR (Liu and Kronbak 2010; Gritsenko and Kiiski 2016; Xu et al. 2018; Wang et al. 2020).

Revenue factors, such as average load factors, deadweight (dwt) utilisation and ship size are crucial in order to exploit economies of scale (Wergeland 1992; Schøyen and Bråthen 2011; Lasserre 2014; Lasserre 2015; Furuichi and Otsuka 2015; Zhang, Meng, Ng 2016; Xu et al. 2018). Yet, difficult ice conditions may prevent larger ships of using the route north of the New Siberian Islands in order to avoid the shallow Sannikov Strait.

1.2 Motivation

The recent focus on the NSR relates to the unprecedented reduction in the Arctic sea ice cover since 1979 (Stroeve et al. 2012; Parkinson and Comiso 2013; Stroeve and Notz 2018). Currently, there has been a growing body of literature within climate science projecting future accessibility on Arctic waters for either ice class or non-ice class ships to increase throughout the 21st century (Smith and Stephenson 2013; Melia et al. 2016; Serreze and Meier 2019; Wei et al. 2020). Whilst ice extent and thickness will remain the main obstacles for navigation between 2030 and 2050, other ice and climatic conditions (e.g. ice ridging and pressure, waves, circulation, winds) will mainly affect shipping beyond 2050 (Aksenov et al. 2017). These developments have led to the re-emergence of NSR as an alternative maritime route between Europe, the Russian Arctic, North America and Asia.

The NSR has gained popularity since the 2010s due to an increase in transit voyages between the Atlantic and the Pacific Ocean, and destination voyages that either originated or ended from/to Arctic ports (CHNL 2021a)[3]. There has been a gradual increase in summer/autumn destination and transit traffic between 2007 and 2013, followed by a steep drop between 2015 and 2018, and a significant increase in 2020 (ARCTIS 2021a, NSRA 2016; CHNL 2021a; Bloomberg 2021; Refinitiv Eikon 2021). An average of 51% of the exploratory NSR transit and destination voyages between 2011 and 2014 involved oil product cargo transport of various sizes, followed by a sharp decline to 12% between 2015 and 2020 (NSRA 2016; CHNL 2021a, Bloomberg 2021; Refinitiv Eikon 2021).

On the one hand, favourable sea ice conditions and distance savings explain part of the surge in exploratory voyages through the NSR during the last ten years. On the other hand, the nature

[3] Transit voyages refer to voyages conducted between the Atlantic and the Pacific Ocean through the Arctic. Destination voyages refer to voyages that originate or terminate within or outside the Arctic. Domestic or intra-Arctic voyages are voyages conducted within the Arctic and up to the Bering Strait. These definitions are generally in line with Østreng (2013, p. 10) except for the definition of domestic voyages.

of the transport system, geopolitics, certain cost and market factors, and commodity price developments, largely determine route choice. The marked difference in the number of destination and transit tanker voyages through the NSR between the periods 2011-2014 and 2015-2020 reflects the volatility in commodity and fuel markets, as well as other developments that impacted oil products flows and ultimately route choice from a global perspective.

Therefore, this Thesis is focused on the assessment of the NSR against the oil product tanker market, taking into account historic destination and transit traffic records, and developments in the global shipping and energy markets. This Thesis aims to explain the emergence of the NSR as an alternative for oil product tankers during 2011-2020. Moreover, it aims to explain the economic, navigational and environmental factors which affect its use compared to traditional sea routes between Europe and Asia.

Figure 1.1 shows the total number of destination and transit voyages, and those conducted by oil tankers in the summer/autumn navigation seasons of 2011-2020. Major events are highlighted throughout this period, which influenced the use of NSR for exploratory voyages, especially by oil product tankers. High commodity and fuel prices, a rising value of cargo on board and low oil products futures prices along with a competitive icebreaking tariff policy and Russia's ambitions to promote the NSR resulted in an increased number of exploratory tanker voyages, especially between 2011 and 2013 (Platts 2011; IEA 2012; IEA 2013; Gritsenko and Kiiski 2016; CHNL 2021a). The increase in destination and transit traffic during 2011-2013 was followed by a decline in 2014 (NSRA 2016; CHNL 2021a) owing to a number of factors, including low commodity prices, geopolitical factors, low crude oil and fuel oil prices, shifts in petroleum flows from the White and Barents Seas to the Baltic Sea, lower piracy insurance premiums for Suez Canal transits, and changes in icebreaking fees policy amongst others (Moe 2014; Reuters 2015; Platts 2016a; Bambulyak et al. 2015; Moe and Brigham 2016; Tanker Company 2018; Shapovalova et al. 2020). Moreover, the longer route via the Cape of Good Hope was used, especially during 2015-2017 and 2020, owing to the oil oversupply and very high commodity futures prices that favoured the delay of arrivals at the destination ports (IEA 2015; IEA 2017).

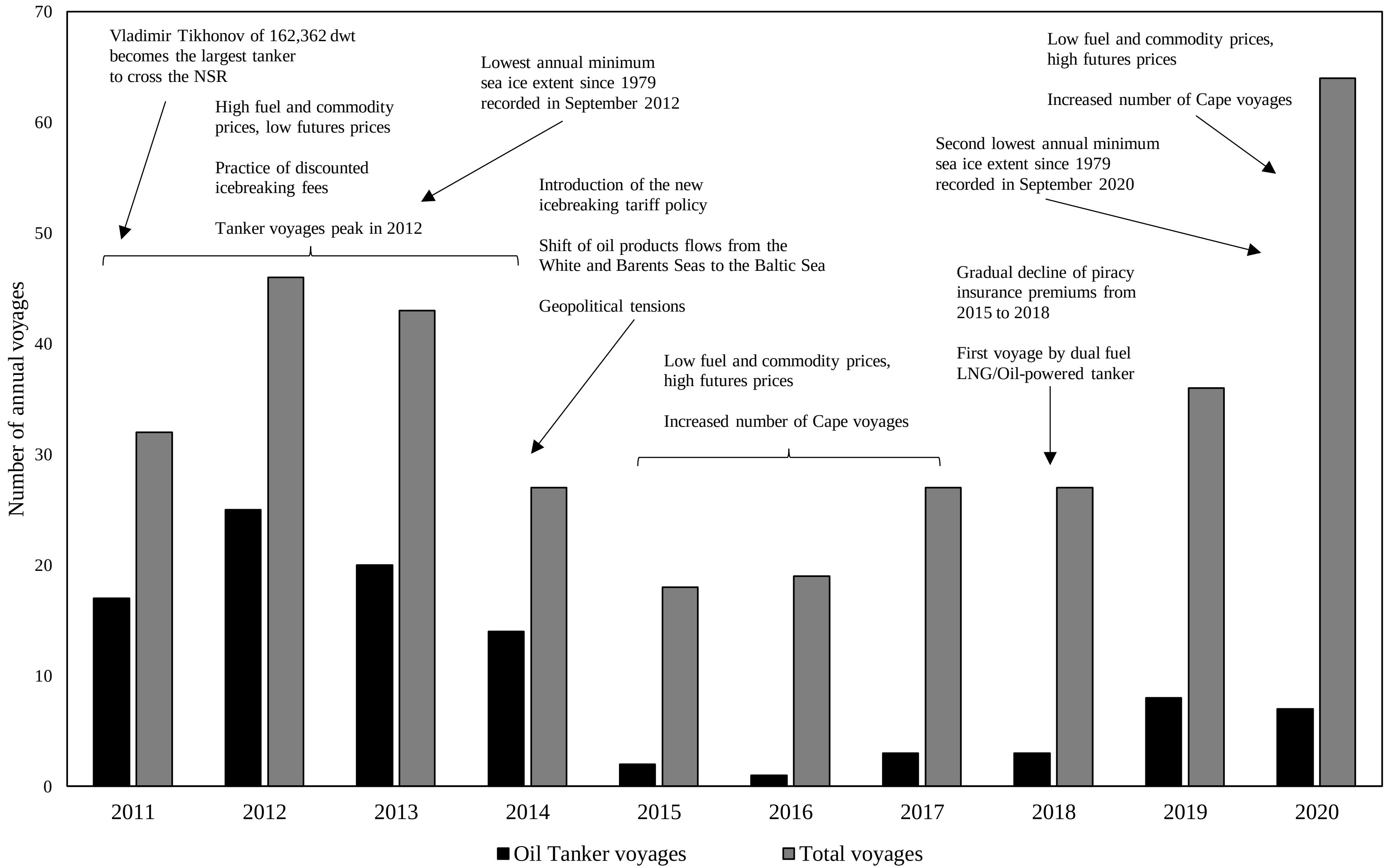


Figure 1.1. Number of voyages conducted on the NSR and major developments during 2011-2020.

1.3 Literature gaps and systematic literature review questions

A systematic literature review on Arctic shipping comparative studies is conducted in this Thesis. Although Lasserre (2014), Lasserre (2015), and Meng et al. (2016) surveyed the literature, there has not been systematic literature reviews evaluating the economic feasibility of Arctic routes to date. Moreover, no account has been taken of studies reporting on the environmental assessment of Arctic routes. Further, the aforementioned studies focus on research aspects and do not discuss the research methodological characteristics. The large number of discrepancies and differing assumptions regarding the parameters and results of the studies identified by Lasserre (2014) and Lasserre (2015) stress the need to evaluate the literature in a systematic way in order to identify factors that affect the viability of Arctic routes and add complexity to the route choice decision-making process. The aim of the systematic review is to evaluate the extant literature regarding comparative studies between Arctic and traditional routes from both economic (costs, profits) and environmental (emissions) perspectives between 1980 and 2021. The current state of Arctic shipping literature is evaluated in order to establish a new evidence base, identify research gaps, and suggest areas for future research and methodological approaches.

The following **Systematic Review Questions** are formulated in order to address the aim of the **systematic literature review** of the Thesis:

Main Systematic Review Question: According to the extant literature, what is the cost effectiveness, and what is the likely impact on emissions, of using Arctic compared to traditional routes, between 1980 and 2021?

Two further sub-questions are formulated for the purposes of the systematic review:

Systematic Review Question 1: Which research methods and data analysis techniques are employed to address the research questions in comparative studies on Arctic shipping literature?

Systematic Review Question 2: What are the emerging issues that need to be addressed?

1.4 Research gaps and research questions

The aim of the Thesis is to assess the economic feasibility of the NSR for oil product tankers by addressing the following gaps.

Whilst liner shipping economics dominate the Arctic shipping literature, there are a growing number of studies assessing tanker economics from various angles and factors, including economies of scale (Zhang, Meng, Ng 2016; Wang et al. 2020), seasonal (Song and Zhang 2013) or combined SCR/NSR annual navigation (SCR: Suez Canal route) (Von Bock und Polach et al. 2015; Faury, Cheaitou et al. 2020; Keltto and Woo 2020), the impact of sea ice on voyage economics (Von Bock und Polach et al. 2015; Faury and Cariou 2016; Faury, Cheaitou et al. 2020), as well as the impact of emissions taxes and environmental regulations (Keltoo and Woo 2020).

The extant literature investigates whether the NSR is a competitive alternative under specific conditions and certain periods of time. However, there have not been any studies that aimed to explain quantitatively why the NSR emerged as an alternative route for oil product tankers since the 2010s, and how cost and market factors, and emissions regulations affected its use between 2011 and 2020. Moreover, crucial economic factors which are coupled with inherent strategic and geopolitical issues encompassing the tanker trades and affect routeing patterns have not been addressed.

Currently, there is a very limited understanding as to how fuel price levels, icebreaking fees, and ship size affect the use of the NSR in the context of oil tanker shipping. Furthermore, distances based on both historic voyage patterns and major oil product flows have not been explored. The impact of commodity prices and in-transit inventory costs have not been addressed. Moreover, route choice in the wider context of oil products trades has not been considered.

Whilst the sea ice – ship speed dependency has been thoroughly investigated by employing historic sea ice thickness data to determine tanker speeds on the NSR (Faury and Cariou 2016; Faury, Cheaitou et al. 2020), there have not been studies that used data regarding ship speed on ice from actual tanker voyages conducted on the NSR, and therefore providing an alternative approach to the literature.

As regards the methodological perspectives, there have not been any studies on tanker shipping that employed ship speed optimisation in the modelling approach. Further, speed data reflecting real practices have not been considered, with tanker design speeds being the default assumption in all studies. Moreover, all papers rely on data from previous studies regarding operating and capital cost factors, and most of the secondary data used in the literature are not up-to-date.

Although the use of Liquefied Natural Gas (LNG) is considered in recent studies concerning liner shipping (Ding et al. 2020; Xu and Yang 2020), the literature on tankers has so far focused only on the use of Very Low Sulphur Fuel Oil (VLSFO) (Keltoo and Woo 2020; Wang et al. 2020). Moreover, there have not been studies that considered the future ban of heavy fuel oils in the Arctic (IMO 2020).

The following **Research Questions** are formulated in order to address the aim of the **modelling research** of the Thesis:

Research Question 1: Why did the NSR emerge as an alternative route for oil product tankers between Europe and Asia since the 2010s?

Research Question 2: How do cost and market factors affect the use of the NSR for oil product tankers?

Research Question 3: How does ship speed on ice affect the feasibility of the NSR for oil product tankers?

Research Question 4: How do different approaches to ship speed choice and cost modelling affect the feasibility of the NSR for oil product tankers?

Research Question 5: How do emissions regulations and alternative operational modes and fuel types affect the feasibility of the NSR compared to the traditional routes for oil product tankers?

1.5 Methodological approach

First, a systematic literature review is conducted in this Thesis. A systematic literature review is a review of the literature in which the best available evidence is identified, selected and critically appraised, and synthesised based on a specific review question to provide instructive and evidence-based answers (Booth 2012; Dickson et al. 2017). A systematic review is considered the best way to synthesise the findings of a number of studies which investigate the same research question(s) (Dickson et al. 2017). Moreover, a systematic review approach introduces the researchers to different research designs and methods, allows them to gain insights into the strengths and limitations of a body of literature, and enables them to develop critical skills in locating, appraising and synthesising findings from a number of studies (Dickson et al. 2017).

Second, a Required Freight Rate (RFR) analysis for competing maritime routes is developed in this Thesis. The RFR analysis determines the minimum cost per tonne of a route alternative from the shipowner's perspective. The minimum cost per tonne is the long-run equilibrium point between supply and demand, where revenue equals cost (Alderton 1981). Classical maritime economic theory holds that the (theoretical) optimum speed which minimises the cost per tonne is not affected by short-term freight rate volatility, port time or delays, and therefore is more appropriate for long-term planning than one which aims to maximise profit (Alderton 1981; Evans and Marlow 1990). A cost-based route comparison aims to establish the break-even point for a route and includes fixed and variable cost factors, such as operating and capital costs for different ship types and technologies, fuel costs, transit fees, and other voyage-related costs.

The methodological approach has two objectives. First, the cost assessment is based on ship speed optimisation to minimise the RFR of a route alternative. Second, the cost assessment is based on real ship speeds to determine the RFR of a route alternative. On the one hand, the (theoretical) cost minimising speed can be optimised with respect to cost and market factors. On the other hand, the real speed tends to depart from the optimal point owing to organisational and technical constraints, ship, and voyage-specific variables, as well as weather factors amongst others (Psaraftis and Kontovas 2014; Lindstad and Eskeland 2015; Adland et al. 2017; Adland and Jia 2018). Moreover, speed through ice on the NSR may not be optimised with respect to cost and market factors as on open water. The reason is that speed through ice primarily depends on sea ice conditions and may not equal the optimal speed. Thus, it has to be approximated based on either physical factors, such as ice thickness, or on real speeds recorded on the NSR. The assumptions for ship speed through ice on NSR in this Thesis are informed by Automatic Identification System (AIS) data of historic oil product tanker voyages conducted on the NSR.

1.6 Structure of the Thesis

The PhD Thesis is organised in seven chapters, which are summarised as follows:

Chapter 1 introduces the topic of Arctic shipping and the background of factors determining the economics of the NSR. The motivation for undertaking this research is presented with reference to historic events regarding the use of the NSR during 2011-2020, the identified gaps are described, and the Research Questions and Systematic Review Questions are outlined. A brief description of the methodological approach is provided and the structure of the Thesis is presented.

Chapter 2 provides a systematic literature review of comparative studies between Arctic and traditional sea routes and ship canals, and other land and air routes globally to address the Systematic Review Questions. The scope of the review is specifically defined to consider studies that compared the Arctic sea routes with any other transport routes at a micro-economic level. The time frame of the review covers the period between 1980 and 2021 (as of April).

Chapter 3 presents the methodology used to address the Research Questions of the modelling research of the Thesis. The Research Philosophy is outlined, followed by the description of the Research Design, Research Strategy, Nature of the Research, and Data Analysis Techniques. The Quality of the Research Design is described and ways of addressing Reliability, Validity and Ethics of the Research Design of this Thesis are presented. The fundamental relationships between costs and output are presented drawing from the classical microeconomic theory of costs. Cost and profit functions, and optimal levels of output are described analytically, drawing from classical maritime economics theory. Finally, the modelling approach is outlined and the modelling cases are presented.

Chapter 4 assesses the feasibility of the NSR against the SCR. The factors considered are distance, fuel prices, average ship speed through ice on NSR, icebreaking fees, ice damage repairs, ship size, varying capital and operating costs, and fuel types. The analysis explains the emergence of the NSR as an alternative route for oil product tankers between Europe, the Russian Arctic and Northeast Asia since 2010. First, costs are assessed during 2011-2014 and 2015-2017, reflecting developments of major cost and market factors which affected route choice. Second, costs are assessed for the years 2018, 2019, and 2020, respectively. The analysis is undertaken at the tactical/operational level for single oil product tanker voyages during the summer/autumn season.

Chapter 5 assesses the feasibility of the NSR against the SCR and Cape of Good Hope routes. The factors considered in the analysis are distance, fuel prices, average ship speed through ice on NSR, icebreaking fees, ice damage repairs, commodity prices and in-transit inventory costs, and fuel types and operational modes. The analysis in this chapter complements Chapter 4, by considering in-transit inventory costs, and addressing market structure and route choice in the wider context of oil product tanker flows drawing from AIS data of voyages conducted between the Far East and Europe in 2011-2020. The analysis is undertaken at the tactical/operational level for single oil product tanker voyages during the summer/autumn season.

Chapter 6 assesses the feasibility of the NSR against the SCR for seasonal navigation operations. The factors considered are distance, fuel prices, ship speed through ice on NSR, seasonal navigation, icebreaking fees, commodity prices and in-transit inventory costs, and fuel types and operational modes. The analysis in this chapter complements Chapter 4 and Chapter 5, by developing seasonal navigation scenarios and considering real hourly AIS speed data of historic tanker voyages conducted on the NSR to determine the varying speed through ice. The analysis is undertaken at the strategic level (choice of oil products/commodities and routes as an expert-based scenario).

Chapter 7 summarises the findings obtained from Chapters 2, 4, 5, and 6, and provides answers for the Systematic Review Questions of the systematic literature review and the Research Questions of the modelling research of the Thesis. Finally, the contributions of this PhD Thesis to knowledge, methodology, and practice are presented, and future research directions are provided.

The diagram below shows graphically the structure of the PhD Thesis.

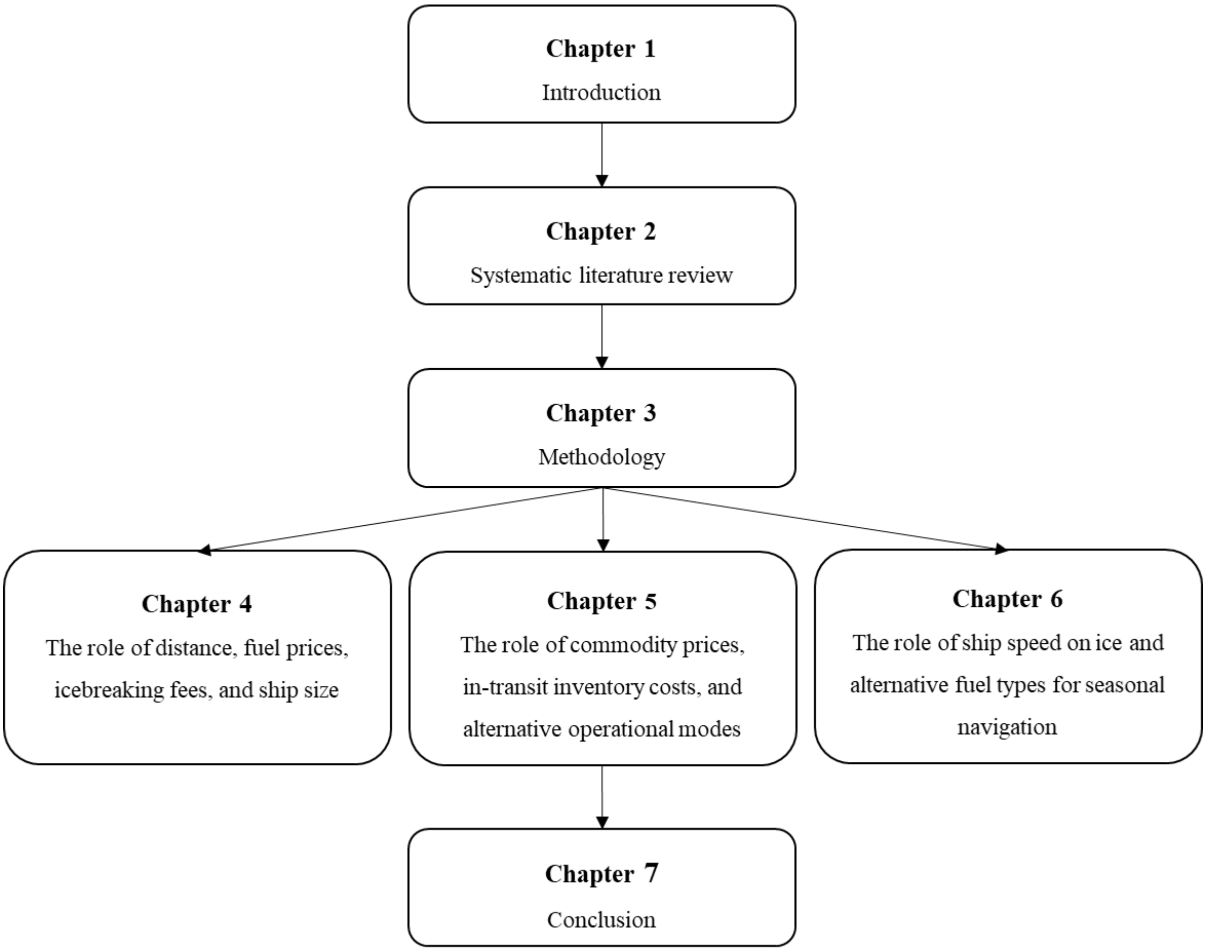


Figure 1.2. Structure of this PhD Thesis.

2. Systematic literature review

This chapter provides a systematic literature review of comparative studies between Arctic and traditional maritime routes and ship canals, and other land and air routes globally. The scope of the review is specifically defined to consider studies that compared the Arctic sea routes with any other transport routes at the micro-economic level of analysis. The time frame of the review covers the period between 1980 and 2021 (as of April). The basis of the analysis is the firm or the ship or ships, in case of a fleet in a shipping network. The methodological approach is first defined along with the steps that were followed towards the identification for the need of a review of the topic, initial searches in databases, selection of keywords, extraction of relevant studies, and the use of inclusion and exclusion criteria. A synthesis of the included studies and data extracted is presented. Following the analysis of the results, a reflection upon the current state of the art is attempted, and future research directions are identified based on both methodological and research themes. Finally, research gaps are identified with respect to the specific problem investigated in this Thesis. The research questions are then presented to address the gaps and the aim of the modelling research of the Thesis.

2.1 Methodological approach to systematic review

The systematic review of an extant body of literature can be traced back to the eighteenth century, where research synthesis emerged as a way to analyse medical studies in order to draw certain conclusions (Chalmers et al. 2002). Although research syntheses of a certain body of knowledge historically have been conducted in medicine, healthcare, and nursing research, the systematic literature review has now been established across many disciplines as a distinctive *research strategy*[4] (Dickson et al. 2017). Moreover, the emergence of evidence-based policy necessitated the need to conduct literature reviews scientifically in order to inform practice and policy (Petticrew and Roberts 2006). Thus, evidence for what works requires a systematic enquiry of the extant body of knowledge (Davies et al. 2000).

A systematic literature review is a review of the literature in which the best available evidence is identified, selected and critically appraised, and synthesised based on a specific *review question* to provide instructive and *evidence-based* answers (Booth 2012; Dickson et al. 2017). A systematic review is considered the best way to synthesise the findings of a number of studies which investigate the same research question(s) (Dickson et al. 2017). Moreover, a systematic

[4] Dickson et al. (2017) use the term 'research methodology'. Here, the term 'research strategy' is used, following Saunders et al. (2019). Definitions of these and other terms are provided in Section '3.4 Research Strategy', Chapter 3.

review approach introduces the researchers to different research designs and methods, allows them to gain insights into the strengths and limitations of a body of literature, and enables them to develop critical skills in locating, appraising and synthesising findings from a number of studies (Dickson et al. 2017).

According to Jesson et al. (2011), a systematic review is defined by its rigorous and transparent method, its structured approach and replicability, as well as by the use of specific analysis approaches of the reviewed studies, such as *narrative synthesis* and *meta-analysis* amongst others. On the other hand, the traditional review does not necessarily involve a defined method, it is more exploratory in nature and can follow a variety of styles, whilst it does not conform to any specific analysis procedures (Jesson et al. 2011). Table 2.1 presents the key differences between traditional and systematic approaches to literature review.

Table 2.1. Differences between narrative (traditional) and systematic reviews.

	Narrative reviews	**Systematic reviews**
Defining a question	May or may not be clearly defined	Clearly defined and well-focused Always required
Writing a protocol	Not usually required	Recommended/essential
Methodology	Does not follow explicit or rigorous methodology	Follows explicit and rigorous methodology
Searching	No pre-defined search criteria Not necessarily comprehensive Generally relies only on published literature Search strategies may be based on expert experience	Exhaustive and with an appropriate balance of sensitivity and specificity Carried out across a number of bibliographic databases, hand searching of reference lists from relevant papers and high-yield journals and documents/reports Grey (unpublished) literature sometimes searched Comprehensive and explicit searching methods used and reported
Definition of inclusion and exclusion criteria	Not essential No selection of studies based on study design	Essential Study design can be selected (e.g. only include qualitative data, Random Control Trials or both)

Source: Dickson et al (2017).

Table 2.1. Differences between narrative (traditional) and systematic reviews (continued).

	Narrative reviews	**Systematic reviews**
Screening titles and abstracts; selecting full-text papers	Generally carried out by one researcher by reading through relevant papers and based on their own experience	Explicit and systematic screening and selection, using predefined method Usually cross-checked by another researcher
Quality assessment	Not necessarily	Yes
Data Extraction	Yes	Yes
Analysis and synthesis	No clear method of synthesis	Can involve meta-analysis, narrative or qualitative synthesis
Application	Any field	Any field
Timescale	May be carried out relatively quickly	Can be time consuming due to rigour required
Replication	Not easily replicable	Explicit methods and therefore replicable

Source: Dickson et al (2017).

Tranfield et al. (2003) propose a review design for systematic literature reviews in the field of management and business studies. According to them, the use of principles applied in medical systematic reviews can make systematic reviews in business and management rigorous and can provide a reliable base for practitioners and policy makers in order to inform policy and practice. Moreover, they argue that these principles should be adapted to the business research needs owing to differences in ontological, epistemological and quality considerations between medicine and business research (Tranfield et al. 2003).

2.2 Systematic review process

According to Petticrew and Roberts (2006), the very first step of conducting a systematic review is to decide whether one is needed as a precursor to new research. Several reasons could warrant the undertaking of a systematic review instead of embarking directly on a new primary study. These could include uncertainty about what the evidence shows or uncertainty stemming from a debate in the literature regarding the relationship of certain variables. Thus, a systematic review could aid the researcher to clarify questions and provide a systematic and thorough overview of the evidence and recommendations for future research (Petticrew and Roberts 2006).

Table 2.2 shows the key steps in the systematic review process according to Pilkington and Hounsome (2017). The selection of a research topic within a scientific field or discipline is the first step towards the identification of a review question or questions. The focus of the review should be explicit, as it is of particular importance to formulate good answerable questions from the outset (Light and Pillemer 1984). According to Cherry and Dickson (2017), a systematic review question can be *descriptive*, *normative*, *observational* or *relational*, *causal* or *theoretical*. Table 2.3 provides the typology and definition of each of these review question types.

Table 2.2. Key steps in the systematic review process.

Step	**Description**
Identifying your review question, scoping searches and protocol	Identification of background literature and definition/refinement of the research question Writing a protocol enables planning how to answer a research question
Literature searching	Searching for publications to be included in the review using bibliographic databases
Screening titles and abstracts (Stage 1)	Selection of relevant studies
Obtaining papers	Obtaining full-text copies of all potentially relevant papers that fulfilled the Stage 1 inclusion criteria
Selecting full-text papers (Stage 2)	Application of rigorous inclusion/exclusion criteria
Quality assessment	Each individual study needs to be assessed for methodological quality
Data extraction	Presenting the data obtained from the included studies
Analysis/synthesis	Data may be synthesised using various approaches (e.g. meta-analysis, meta-ethnography)
Writing up and editing	Writing up of methods and results, and presentation of discussion of the findings

Source: Adopted from Pilkington and Hounsome (2017).

Table 2.3. Systematic literature review question types.

Typology of review questions	Description
Descriptive	Presenting a concept
Normative	Exploring preferences about what should happen
Observational or Relational	Investigating a relationship between two or more variables
Causal	Investigating the effect of one or more independent variables on one or more outcome variables
Theoretical	Exploring factors that cause a condition, event or process

Source: Cherry and Dickson (2017)

The next step is to conduct preliminary scoping searches in order to explore the number and nature of studies that could be included in the review. Moreover, it should be checked whether there are any existing published systematic reviews on the topic (Petticrew and Roberts 2006). Inclusion criteria determine the specific attributes that studies must have in order to be included in the review. Equally, exclusion criteria define the attributes that make studies to disqualify from inclusion in a review.

An essential part of the review process is that of quality assessment, since the results and conclusions of the systematic review largely depend on the quality of each individual study included in the review. Moreover, a quality appraisal has further implications as regards the strength of evidence that could be used to inform policy and practice (Greenhalgh and Brown 2017). Quality assessments usually include criteria such as the relevance of the research question, internal and external validity, generalisation of the results, the appropriateness of data analysis and presentation, as well as ethical considerations.

Yet, appraisals in systematic literature reviews are focused primarily on methodological issues, especially reviews of quantitative studies (Petticrew and Roberts 2006). Notwithstanding the appropriateness of specific quality assessment approaches, their rigour and fit depending on the type of research, and the restrictiveness of tools to assess quality, certain criteria are found to be common in quality assessments (Petticrew and Roberts 2006). These criteria extend to include the type of review (peer-reviewed/not peer-reviewed), the publication type (academic journal, professional journal, book chapter, doctoral dissertation), publication date, and journal impact factor amongst others (Jesson et al. 2011).

Following the extraction and presentation of the data from the reviewed studies, these are analysed and synthesised based on various approaches. These approaches depend on the discipline, nature of research enquiry, research design and research strategy, as well as the data analysis techniques of a particular research. Examples are statistical evaluations in the form of meta-analysis, narrative synthesis approaches, as well as various qualitative evidence synthesis methods (Petticrew and Roberts 2006; Cherry et al. 2017).

2.3 Conducting the review

2.3.1 Background

Arctic shipping is an emerging topic within maritime transport research, demonstrating an exponential increase in publications during the last ten years. Lavissière et al. (2021) who conducted a systematic review on Arctic shipping research across various disciplines using a textometric approach, refer to Arctic transport as an emerging field on its own. Lasserre (2014) and Lasserre (2015) identified 26 comparative studies between Arctic and traditional routes from 1991 to 2013, whilst Meng et al. (2016) reviewed 25 studies regarding navigational and commercial perspectives. Ng et al. (2018) provided a literature review on climatic, physical, economic, environmental and social issues of Arctic shipping. Panahi et al. (2021) reviewed the Arctic-related port literature considering several themes, such as, economic, social, connectivity-related, operational, managerial, and environmental amongst others.

However, to date, there has not been any systematic literature review evaluating the economic feasibility of Arctic routes. Moreover, no account has been taken of studies reporting on the environmental assessment of these routes. Further, the aforementioned studies focus on research aspects and do not discuss the research methodological characteristics. The large number of discrepancies and differing assumptions regarding the parameters and results of the studies identified by Lasserre (2014) and Lasserre (2015) stress the need to evaluate the literature in a systematic way in order to identify factors that affect the viability of Arctic routes and add complexity to the route choice decision-making process.

2.3.2 Review Questions

The aim of the systematic review of this Thesis is to evaluate the extant literature regarding comparative studies between Arctic and traditional routes from both economic (costs, profits) and environmental (emissions) perspectives between 1980 and 2021. The current state of the

Arctic shipping literature is evaluated in order to establish a new evidence base, identify research gaps, and suggest areas for future research and methodological approaches.

The following Systematic Review Questions are formulated in order to address the aim of the systematic literature review of the Thesis:

Main Systematic Review Question: According to the extant literature, what is the cost effectiveness, and what is the likely impact on emissions, of using the Arctic routes compared to traditional routes, between 1980 and 2021?

Two further sub-questions are formulated for the purposes of the systematic review:

Systematic Review Question 1: Which research methods and data analysis techniques are employed in order to address the research questions in comparative studies on Arctic shipping literature?

Systematic Review Question 2: What are the emerging issues that need to be addressed?

The Main Systematic Review Question and Systematic Review Question 1 of this systematic literature review are descriptive, whereas the Systematic Review Question 2 is normative. The first two are developed to identify, map and describe the research and methodological issues, whereas the latter is developed to identify research gaps, and to suggest future directions both in research and methodology.

2.3.3 Methods

2.3.3.1 Search strategy

The bibliometric database *Scopus* was used for the initial scoping searches. Title, abstract and keywords of a sample of papers were searched covering all subject areas (fields of study) without specifying the period. The initial keywords used in Scopus were ‘arctic shipping’ OR ‘northern sea route’ OR ‘northwest passage’. Abstracts of a sample of relevant papers were subsequently read and keywords were refined according to the Review Questions. Major ship canals and maritime routes were used as keywords, as well as variations of terms that have similar meanings. Table 2.4 presents the terms searched in the title, abstract and keywords of journal articles in the bibliometric databases *Scopus* and *Web of Science*. The Boolean operator ‘OR’ was used to combine the terms presented in Table 2.4. The wildcard character asterisk (*) was used in both databases to extract studies that contain variations of the terms (e.g. ‘ship’ or ‘shipping’ in the case of ‘ship*’). Braces { } were used to search for exact search terms in *Scopus*, and quotation marks “ ” to search for exact search terms in *Web of Science* according to each database's search rules. Journal articles were searched separately on the website of the *Journal of Maritime Research (JMR)*, since this journal is not covered in *Web of Science* and has been covered in *Scopus* until 2020. Appendix A reports the steps of the searching procedure on *Scopus* and *Web of Science*.

Table 2.4. Keywords used in searches.

Arctic shipping	Nicaragua(n) Canal	Ship* canal(s)
Cape Horn	Northeast Passage	Ship* corridor(s)
Cape of Good Hope	Northwest Passage	Ship* lane(s)
Magellan Strait(s)	Northern Sea Route	Ship* passage(s)
Maritime Canal(s)	Panama Canal	Ship* route(s)
Maritime corridor(s)	Sea canal(s)	Ship* strait(s)
Maritime lane(s)	Sea corridor(s)	Strait(s) of Magellan
Maritime passage(s)	Sea lane(s)	Suez Canal
Maritime route(s)	Sea passage(s)	Transpolar Passage
Maritime strait(s)	Sea route(s)	Transpolar Sea Route
	Sea strait(s)	

2.3.3.2 Inclusion and exclusion criteria

Arctic shipping literature contains studies spanning a broad spectrum of issues including economics, legal, geopolitics, geo-economics, climatic, and technical, and is informed by various disciplinary bases. The inclusion and exclusion criteria applied to the extracted papers from Scopus and Web of Science refer to the type of review (peer-reviewed/not peer-reviewed), language, and relevance to the Systematic Review Questions.

The following inclusion criteria were applied:

- All subject areas, disciplines, and fields of research
- Journal articles or Reviews between 1980 and 2021 (as of April 2021)
- Studies published in English language
- Quantitative studies reporting original results on the economic (costs, profits) or environmental (emissions) assessment of Arctic routes compared to traditional ones
- The basis of the analysis is the firm (shipowner, charterer) or the ship or ships, in case of a fleet in a shipping network

Thus, qualitative research, descriptive studies, surveys, and studies that do not report original findings were excluded from the review. Moreover, studies that report results on cargo flows, networks, shifts in trade and other economic indices, emissions inventories at a macro-level, as well as on macroeconomic factors and variables were also excluded from the review.

Tranfield et al. (2003) argue in favour of including "grey literature" in a systematic review, that is, unpublished studies, conference papers, industry trials, personal communication with known researchers, and internet sources. Yet, the view is adopted in this systematic review that quality is enhanced by including only papers published in peer-reviewed academic journals (David and Han 2004; Newbert 2007; Jesson et al. 2011; Woo et al. 2011; Woo et al. 2012; Shi and Li 2017).

2.3.3.3 Screening and selection, data extraction and quality assessment

The number of papers retrieved from Scopus and Web of Science is 12,003. Of these papers, 9,856 are published in English, whereas 4,174 papers remained after excluding duplicates. This procedure was carried out in Microsoft Excel. Additional duplicate papers were identified whilst carrying out the screening and selection procedure owing to different spelling rules of Scopus and Web of Science referring to the same words and terms. The rest of the papers were excluded based on the application of the inclusion criteria presented in Section '2.3.3.2 Inclusion and exclusion criteria'. The screening and selection process was repeated in order to avoid mistakes and resolve any discrepancies. A total of 40 unique papers were selected for review. Two additional papers were identified by searching the reference lists of these 40 papers. These are Wergeland (1992) and Guy (2006). Moreover, two additional papers were identified by manual searches. One paper is published in a journal which used to be indexed in Scopus and Web of Science (Lu et al. 2014) but is not indexed as of 2021. The other paper is published in an indexed journal but is a commentary to Lasserre (2014) and provides a brief analysis. However, it contains little information in the abstract and does not provide any keywords, but its title includes the title of the paper of Lasserre (2014). Thus, a total of 44 papers were reviewed and analysed based on their methodological and research considerations. Appendix B presents an adapted Prisma flow diagram, which details the screening and selection process (Prisma 2021; Page et al. 2021).

The next step was the identification and extraction of data referring to the study characteristics and outcomes/results of the reviewed papers (Fleeman and Dundar 2017). These data and the methods of analysis and synthesis employed in the systematic review are described in Section '2.3.3.4 Methods of analysis and synthesis'.

A quality assessment of the reviewed studies was carried out (Greenhalgh and Brown 2017). The quality assessment criteria from Pittaway et al. (2004) were applied to the reviewed papers. The following elements are included in the assessment: theory robustness, implications for practice, methodology and data, generalisability, and contribution. The criteria are scales that give a numerical value from 0 (absence) to 3 (high). Appendix C presents the criteria used from Pittaway (2004). Appendix D presents the quality assessment of the papers included in the systematic review. Most of the reviewed papers significantly contributed to the literature since 1980. They developed new knowledge, both in terms of research and methodology. Their findings are primarily generalisable to organisations or settings of similar characteristics. Yet, they are also generalisable to other shipping sectors, given the similarities and interconnections between shipping markets. Similarly, the reviewed papers significantly contribute to practice since their findings are applicable to real world settings and could be used by market participants and practitioners to inform their operations and decision-making. The researchers possess good knowledge of the literature and use relevant theories and concepts to develop their research. Equally, the data and research design used are generally of good quality and the data analysis is rigorous.

2.3.3.4 Methods of analysis and synthesis

The reviewed papers are classified in terms of the number published per year and per journal, country affiliation, author names, paper title, journal title, comparison and scope, transport system, routes, time frame of operations, and origin-destination (OD) pairs. The reviewed papers are also classified based on methodological considerations, such as research methods and data analysis techniques employed in their analysis. Narrative synthesis is employed to analyse the methodological and research considerations, and results of the reviewed papers.

Narrative synthesis is a method of presenting data by using words only. The results, and methodological and research characteristics of the reviewed papers are presented in data tables and figures. Descriptive data (study characteristics) and analytical data (outcomes/results) are synthesised in the textual narrative synthesis by identifying commonalities and differences amongst the reviewed studies (Dickson et al. 2017; Fleeman and Dundar 2017).

2.4 Results

2.4.1 General statistics

Figure 2.1 shows the number of papers published between 1980 and 2021 (as of April) and included in the review. It is noticeable that there are not any papers reporting on comparative analysis between Arctic and traditional routes in 1980-1990. Nevertheless, the lack of research interest during that period could be attributed to the underutilisation of Arctic routes and the lack of interest from the global shipping industry in general. Of the 44 papers reviewed, two were published in the 1990s, five between 2001 and 2010, 33 between 2011 and 2020, and four in 2021. The rising trend of publications appears to be consistent with the view that scholarly research followed the recent developments regarding the use of Arctic routes. An increasing number of destination and transit voyages have been conducted on the NSR since 2011 (CHNL 2021a). Table 2.5 shows the academic journals in which the reviewed papers were published. The 44 papers selected for this review were published in 25 journals between 1992 and 2021.

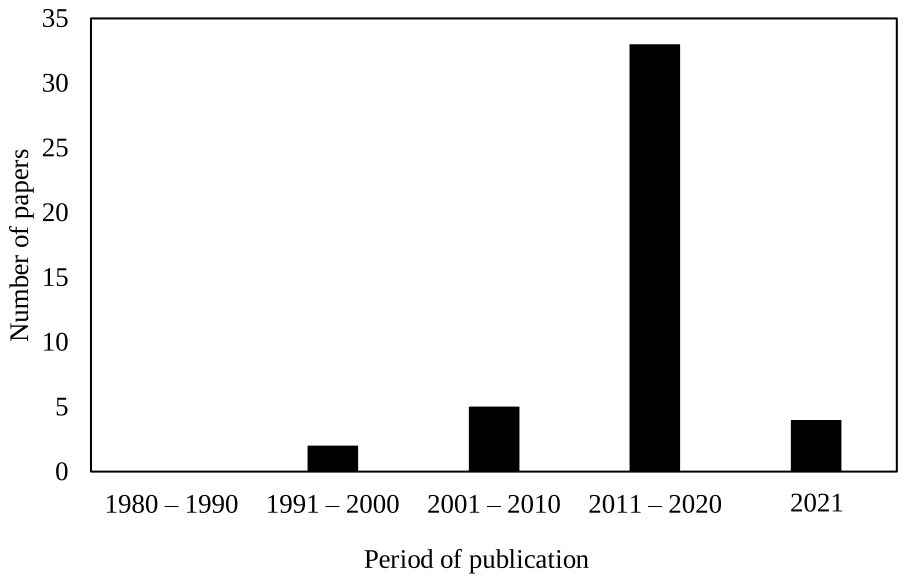


Figure 2.1. Number of papers published between 1980 and 2021.

Maritime Policy & Management and *Transportation Research Part A: Policy and Practice* have the highest number of publications, followed by the *Journal of Transport Geography*, *Transportation Research Part E: Logistics and Transportation Review*, *Maritime Economics & Logistics*, and *Transportation Research Part D: Transport and Environment*, whereas the remaining journals each published one paper between 1992 and 2021.

Table 2.5. Number of papers published per academic journal.

Journal	Number of Papers
Maritime Policy & Management	7
Transportation Research Part A: Policy and Practice	6
Journal of Transport Geography	4
Transportation Research Part E: Logistics and Transportation Review	3
Maritime Economics & Logistics	3
Transportation Research Part D: Transport and Environment	2
The Journal of Navigation	1
Transport Policy	1
International Journal of Production Economics	1
International Journal of e-Navigation and Maritime Economy	1
Journal of Ship Production and Design	1
International Journal of Geographical Information Science	1
Journal of Maritime Research	1
Polar Record	1
International Challenges	1
Journal of Ocean Technology	1
Applied Mechanics and Materials	1
Advanced Science Letters	1
Transportation Research Board	1
Journal of Nuclear Science and Technology	1
Sustainability	1
Polar Research	1
Marine Policy	1
The International Journal of Logistics Management	1
International Journal of Sustainable Transportation	1

Table 2.6 shows the number of papers published, based on the country of affiliation of the first or corresponding author of each paper. Fifteen countries have contributed to Arctic shipping research concerning the economic and environmental assessment of Arctic routes, based on the country of affiliation of the first or corresponding author. China has the biggest contribution, followed by Canada, France, Japan and Norway, whereas Australia, Singapore, the United

Kingdom and the United States of America, including two contributions in which the first or corresponding author is affiliated with more than one countries i.e. China/USA and Finland/Norway, respectively, have the lowest rate of contribution with one paper each. Hong Kong and Taiwan each contributed with three papers, and South Korea and the Netherlands each contributed with two papers, respectively.

Table 2.6. Contribution of papers based on country affiliation.

Affiliation (First or Corresponding Author)	Number of papers
China	10
Canada	5
France	5
Japan	4
Norway	4
Hong Kong	3
Taiwan	3
South Korea	2
The Netherlands	2
Australia	1
China/USA	1
Finland/Norway	1
Singapore	1
United Kingdom	1
United States of America	1

2.4.2 Methodological considerations

The categorisation extended to include the methodological characteristics of the reviewed papers, such as research methods and data analysis techniques. Arctic shipping is a topic within maritime transport research rather than a discipline per se. However, the differing assumptions reported in the reviewed literature regarding cost assessments and factors influencing route choice, as well as the growing trend of addressing the research questions through different methodological perspectives, all stress the need to explore the methodological background of these studies apart from research considerations.

2.4.2.1 Research methods

The categorisation scheme of research methods is adopted from Wacker (1998). In empirical research, data from the ‘real world’ are used to verify the relationships under investigation by using an inductive approach to theory, whereas in analytical research, logic, mathematics and/or statistics are primarily employed by using a deductive approach to theory to reach a conclusion (Wacker 1998). Table 2.7 reports the research methods employed in the reviewed papers. Analytical mathematical methods are reported in 40 papers, whereas two papers report the use of empirical statistical methods and two the use of empirical case studies.

Analytical modelling and simulation are used in order to develop mathematical relationships that explain the behaviour of real-world systems by investigating the performance of dependent variables or models under different conditions (Meredith et al. 1989). Papers which report the use of data analysis techniques such as transport cost models, emissions models, optimisation, game theory models, and mathematical simulation techniques through case examples, belong to the category of analytical mathematical methods.

Empirical statistical research aims to verify theoretical relationships by analysing large samples of data from real business processes (Wacker 1998). Papers which report the use of regression analysis or structural modelling[5] fall under this research method category. Case studies focus on a specific phenomenon with the aim to reveal empirical relationships and usually serve for exploration in the early stages of research. They are also used to examine dependent variables under different scenarios, as well as to provide counter-arguments to prior hypotheses or to come up with new insights in debatable areas (Meredith et al. 1989). The two papers classified under this research method category report the use of interviews, and transport cost models and emissions models in their analysis.

2.4.2.2 Data analysis techniques

Data analysis techniques are used to collect and analyse data as well as to come up with theoretical explanations (Saunders et al. 2019). According to Sachan and Datta (2005), analytical techniques aid the researcher to deal with the summation of large amounts of data, identify causal relationships and explore effects on the outcome based on alternative scenarios. Table 2.7 reports the data analysis techniques employed in the reviewed articles. It should be mentioned that more than one data analysis techniques are reported in some of the reviewed papers. Data analysis techniques which refer to research purposes other than the comparison of competing routes at the micro-economic level of analysis are not included in the review. Optimisation models are reported in four papers and regression analysis is reported in one paper. On the other hand, 38 papers focus on general scenario-based transport cost models rather than employing specific data analysis techniques. Emissions models are also used in nine papers that employ transport cost models, whilst one paper reports the use of both optimisation

[5] Pruyn (2016), which is listed under the empirical statistical research methods category, uses optimisation as part of the structural economic model employed in the analysis. Optimisation is only included in the methodological considerations in Table 2.7.

and an emissions model. Of the two papers classified under the case study research method, one reports the use of interviews, a transport cost model and an emissions model, and one reports the use of a transport cost model and interviews. The interviews in both cases refer to quantitative data collection and analysis. Moreover, other techniques are used along with transport cost models, which aid the primary analysis. These include Monte Carlo simulation in two papers, GIS simulation[6] in one paper, and game theory models in three papers. It should also be mentioned that some papers are informed by climate science models (Wang, Ren et al. 2018; Wang and Zhang 2019; Wang, Liu et al. 2021) or mathematical equations and/or statistical analysis to model the sea ice-ship speed relationship (Faury and Cariou 2016; Xu et al. 2018; Wang et al. 2020; Faury, Cheaitou et al. 2020; Cariou et al. 2021; Gleb and Jin 2021). A list of the reviewed papers based on the methodological considerations is provided in Appendix E.

Woo et al. (2011) argue that some techniques are employed for particular problems and topics, and therefore this could explain the emergence of more purpose specific techniques apart from descriptive statistics in port research during 1980-2009. In a similar vein, it could be argued that scenario-based cost models and, to a lesser extent, optimisation techniques, are prevalent in the literature because of the attention that researchers give to the investigation of the overall competitiveness of Arctic routes over the traditional routes. Thus, they focus on specific aspects and problems, and provide new insights and counter-arguments by capitalising on various modelling approaches. Moreover, researchers from various disciplinary backgrounds have addressed their research questions through more sophisticated techniques. Nevertheless, Arctic shipping is an emerging topic within maritime transport research, and it is expected that new techniques will emerge in the future to address specific research enquiries. Besides, model-based techniques other than transport cost models have been employed extensively since 2011.

[6] GIS simulation: Geographic Information System simulation.

Table 2.7. Methodological considerations of the reviewed papers.

Methodological Characteristics	Categories	Number of papers
Research Methods	Analytical Mathematical	40
	Empirical Statistical	2
	Empirical Case Study	2
Data Analysis Techniques	Transport Cost Model	21
	Transport Cost Model & Emissions Model	9
	Transport Cost Model & Game Theory	3
	Transport Cost Model & Monte Carlo Simulation	2
	Transport Cost Model & Emissions Model & Interviews	1
	Transport Cost Model & Interviews	1
	Transport Cost Model & GIS Simulation	1
	Optimisation Model	4
	Optimisation Model & Emissions Model	1
	Regression Analysis	1

2.4.3 Research considerations

This section describes the results of the review through a narrative synthesis approach. The emphasis lies in the problems investigated and areas explored in the literature. The basic attributes of the reviewed studies, such as routes, transport systems, comparison and scope, time frame of operations, and OD pairs are presented in Table 2.8.

2.4.3.1 Routes, transport systems and OD pairs

The Northern Sea Route (NSR) or Northwest Passage (NWP) are compared with the Suez Canal (SCR) route in 34 papers, and with the Panama Canal route in three papers. The NSR is compared with both the SCR and Panama Canal routes in one paper, whilst one paper reports the comparison of the NSR with the SCR and Cape of Good Hope routes. One paper compares the NSR with all other sea routes globally. One paper compares the NSR, the SCR, the Trans-Siberian Railway, a Sea-Air route, and an All-Air route between Europe and Asia. One paper compares the SCR, the NSR, the New Eurasian Land Bridge, and an All-Air route. One paper compares the NSR with the Trans-Siberian Railway and the SCR. Finally, one paper assesses combined schedules between the NSR (during summer) and any of the SCR, Panama Canal, and Cape of Good Hope routes (during winter).

20 of the 44 papers report the choice of the NSR, whilst the choice of the NWP is reported in four papers. Three papers assess both NSR and NWP, whereas no papers report comparisons between the Transpolar Sea Route (TSR) and other routes. 17 papers examine a combined Traditional Route/NSR route (summer season on the NSR and winter season on the SCR route or on any other route globally) against traditional routes.

Liner shipping is the most studied transport system with 28 papers out of 44, whereas six papers assess dry bulk shipping, six papers study oil tanker shipping, and two papers examine liquefied natural gas (LNG) tanker shipping. Two papers investigate both liner and bulk shipping (one: oil tanker, one: dry bulk carrier). The OD pairs vary widely in terms of the ports chosen by the identified studies. The majority of the reviewed papers focus on OD pairs between Northwest Europe and East Asia, but there is a growing number of studies which include ports globally or from regions other than Europe and East Asia in their analysis.

11 studies include environmental assessments, based on either carbon dioxide (CO_2) emissions or other relevant greenhouse gas (GHG) and non-GHG emissions, whereas three papers use emissions taxes to internalise the environmental costs in the analysis.

Table 2.8. Comparative studies between Arctic and traditional routes.

Author(s) and year	Title	Journal	Comparison and Scope	Transport Systems	Routes	Time frame of operations	Origin-Destination Pairs
Wergeland (1992)	The northern sea route – rosy prospects for commercial shipping?	International Challenges	Transport cost per tonne per month in US$	Liner Shipping (Multi-purpose)	NSR – SCR & Panama Canal	Single voyage	Dutch Harbour (USA) – Hamburg (Germany) Hamburg (Germany) – Yokohama (Japan)
Kondo and Takamasa (1999)	The economic potential of a cassette-type-reactor installed nuclear ice-breaking container ship	Journal of Nuclear Science and Technology	Cost per Twenty-foot Equivalent unit (TEU) per year in US$ & per 20/40-year period Total Shipper's Cost Emissions taxation	Liner Shipping	NSR – SCR	Year-round 20-year period 40-year period	Hamburg (Germany) – Yokohama (Japan)
Guy (2006)	Evaluating the viability of commercial shipping in the Northwest Passage	Journal of Ocean Technology	Cost and profit in US$	Liner & Bulk Shipping (Dry)	NWP – SCR	Liner Shipping: Single voyage Dry Bulk Shipping: Seasonal	Rotterdam (The Netherlands) – Shanghai (China) Arctic – Ports outside Arctic
Somanathan et al. (2007)	Feasibility of a sea route through the Canadian Arctic	Maritime Economics & Logistics	Required Freight Rate (RFR) per TEU in US$	Liner Shipping	NWP – Panama Canal	Year-round	New York (USA) – Yokohama (Japan) St. Johns, Newfoundland (Canada) – Yokohama (Japan)
Somanathan et al. (2009)	The Northwest Passage: A simulation	Transportation Research Part A: Policy and Practice	RFR per TEU in US$	Liner Shipping	NWP – Panama Canal	Year-round	New York (USA) – Yokohama (Japan) St. Johns, Newfoundland (Canada) – Yokohama (Japan)

Author(s) and year	Title	Journal	Comparison and Scope	Transport Systems	Routes	Time frame of operations	Origin-Destination Pairs
Verny and Grigentin (2009)	Container shipping on the Northern Sea Route	International Journal of Production Economics	Cost per TEU in US$	Liner Shipping	NSR SCR Trans-Siberian Railway Sea and air All-air	Year-round	1. Hamburg (Germany) – Shanghai (China) (eastbound stop at Rotterdam, The Netherlands, westbound stops: Pusan, South Korea, Tokyo, Japan) 2. via Dubai, United Arab Emirates (Sea and air) Stop at Frankfurt, Germany (for the Sea and air and All-air options)
Liu and Kronbak (2010)	The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe	Journal of Transport Geography	Profit per year in US$	Liner Shipping	Combined SCR/NSR – Suez Canal	SCR: Year-round Combined SCR/NSR: 3, 6, 9-month season	Rotterdam (The Netherlands) – Yokohama (Japan)
Schøyen and Bråthen (2011)	The Northern Sea Route versus the Suez Canal: cases from bulk shipping	Journal of Transport Geography	Cost per tonne in US$ Emissions assessment	Bulk Shipping (Dry)	NSR – SCR & Cape of Good Hope NSR – SCR	Single voyage	Porsgrunn (Norway) – Shekou (China) Narvik (Norway) – Qingdao (China)

Author(s) and year	Title	Journal	Comparison and Scope	Transport Systems	Routes	Time frame of operations	Origin-Destination Pairs
Xu et al. (2011)	The potential seasonal alternative of Asia–Europe container service via Northern sea route under the Arctic sea ice retreat	Maritime Policy & Management	Cost in US$	Liner Shipping	Combined SCR/NSR – Suez Canal	SCR: Year-round Combined SCR/NSR: Seasonal transit on NSR (One month)	Europe: Antwerp, Rotterdam (The Netherlands), Le Havre (France), Felixstowe (United Kingdom), Bremerhaven, Hamburg (Germany), Murmansk (Russia) Asia: Tianjin, Dalian, Qingdao, Shanghai, Ningbo, Xiamen, Guangzhou, Hong Kong, Yantian (Shenzhen), Chiwan (Shenzhen) (China), Kaohsiung, Keelung (Taiwan), Pusan (South Korea), Tokyo, Yokohama, Nagoya, Osaka, Kobe (Japan)
Song and Zhang (2013)	The economy analysis of sailing in the arctic Northeast Passage	Applied Mechanics and Materials	RFR per tonne in US$	Bulk Shipping (Oil Tanker)	NSR – SCR	Summer season (100 days)	Murmansk (Russia) – Shanghai (China)

Author(s) and year	Title	Journal	Comparison and Scope	Transport Systems	Routes	Time frame of operations	Origin-Destination Pairs
Lasserre (2014)	Case studies of shipping along Arctic routes. Analysis and profitability perspectives for the container sector	Transportation Research Part A: Policy and Practice	Cost per TEU in US$	Liner Shipping	NSR – SCR NWP – SCR	Summer season Six months: (May – October)	1. Rotterdam (The Netherlands) – Shanghai (China)/ Yokohama (Japan) SCR: Intermediate port calls at Malta, Mumbai (India), Singapore
Raza and Schøyen (2014)	The commercial potential for LNG shipping between Europe and Asia via the northern sea route	Journal of Maritime Research	Cost per tonne and per MMBtu (Metric Million British Thermal Unit) in US$	Specialised Shipping (LNG tanker)	NSR – SCR	Round voyage	Hammerfest (Norway) – Tobata (Japan)
Lu et al. (2014)	An Economic Analysis of Container Shipping through Canadian Northwest Passage	International Journal of e-Navigation and Maritime Economy	Cost in US$	Liner Shipping	NWP – Panama Canal	Single voyage	New York (USA) – Busan (South Korea)
Lasserre (2015)	Simulations of shipping along Arctic routes: comparison, analysis and economic perspectives	Polar Record	Cost per TEU in US$	Liner Shipping	NSR – SCR NWP – SCR	Summer season Six months: (May – October) Year-round	1. Rotterdam (The Netherlands) – Shanghai (China)/ Yokohama (Japan) SCR: Intermediate port calls at Malta, Mumbai (India), Singapore

Author(s) and year	**Title**	**Journal**	**Comparison and Scope**	**Transport Systems**	**Routes**	**Time frame of operations**	**Origin-Destination Pairs**
Furuichi and Otsuka (2015)	Proposing a common platform of shipping cost analysis of the Northern Sea Route and the Suez Canal Route	Maritime Economics & Logistics	Cost per TEU in US$ Emissions assessment	Liner Shipping	Combined SCR/NSR – Suez Canal	Year-round on SCR Combined: 105, 135, 165, 195, 225 days on NSR and the rest on SCR	Hamburg (Germany) – Yokohama (Japan)
Chou et al. (2015)	The impact on the operation costs of bulk ship after the opening of the arctic route	Advanced Science Letters	Cost in US$	Bulk Shipping (Dry)	NSR – SCR	Single voyage	Kaohsiung, Keelung (Taiwan)/Shanghai (China)/ Busan (South Korea) – Rotterdam (The Netherlands)
Chang et al. (2015)	Route planning and cost analysis for travelling through the Arctic Northeast Passage using public 3D GIS	International Journal of Geographical Information Science	Cost in US$	Bulk Shipping (Dry)	NSR – SCR	Single voyage	Tokyo (Japan), Busan (South Korea), Shanghai, Hong Kong (China), Kaohsiung (Taiwan) – Rotterdam (The Netherlands)
Cariou and Faury (2015)	Relevance of the Northern Sea Route (NSR) for bulk shipping	Transportation Research Part A: Policy and Practice	Cost in US$ Emissions taxation	Bulk Shipping (Dry)	NSR – SCR	Single voyage	Porsgrunn (Norway) – Shekou (China)
Von Bock und Polach et al. (2015)	A Decision-based Design Approach for Ships Operating in Open Water and Ice	Journal of Ship Production and Design	Comparative Ship Merit Factor	Bulk Shipping (Oil Tanker)	NSR – SCR	Year-round on SCR Combined schedule including seasonal transits on NSR (July-October/ November)	Rotterdam (The Netherlands)– Yokohama (Japan)

Author(s) and year	Title	Journal	Comparison and Scope	Transport Systems	Routes	Time frame of operations	Origin-Destination Pairs
Lindstad et al. (2016)	Economic savings linked to future Arctic shipping trade are at odds with climate change mitigation	Transport Policy	Cost per tonne in US$ Emissions assessment	Bulk Shipping (Dry)	NSR – SCR	N.A.	Asia – Europe (Ports are not specified)
Pruyn (2016)	Will the Northern Sea Route ever be a viable alternative?	Maritime Policy & Management	Cost/charter rate per tonne in US$	Bulk Shipping (Dry)	NSR – SCR	Year-round	Baltic/Hamburg and Le Havre Range – China/Far East (Ports are not specified)
Zhao et al. (2016)	Study on China-EU container shipping network in the context of Northern Sea Route	Journal of Transport Geography	Profit per year in US$	Liner Shipping	NSR – SCR	Year-round	Hamburg (Germany), Rotterdam (The Netherlands), Zeebrugge (Belgium), Felixstowe (United Kingdom), Algeciras (Spain), Qingdao, Shanghai, Ningbo, Yantian, Hong Kong (China)
Zhao and Hu (2016)	Study on economic evaluation of the northern sea route: taking the voyage of Yong Sheng as an example	Transportation Research Record: Journal of the Transportation Research Board	Cost in US$ Emissions assessment	Liner Shipping (Multi-purpose)	NSR – SCR	Year-round & Single voyage	Taicang (China) – Rotterdam (The Netherlands)

Author(s) and year	Title	Journal	Comparison and Scope	Transport Systems	Routes	Time frame of operations	Origin-Destination Pairs
Zhang, Meng, Ng (2016)	Shipping efficiency comparison between northern sea route and the conventional Asia-Europe shipping route via Suez Canal	Journal of Transport Geography	Cost per tonne in US$ and profit per TEU in US$	Liner & Bulk Shipping (Oil Tanker)	NSR – SCR	Round voyage in both cases	Liner Shipping: Shanghai, Shenzhen (China), Singapore, Suez (Egypt), Le Havre (France), Southampton (United Kingdom), Hamburg (Germany), Rotterdam (The Netherlands), Jeddah (Saudi Arabia) Bulk Shipping: Mongstad (Norway) – Mizushima (Japan)
Faury and Cariou (2016)	The Northern Sea Route competitiveness for oil tankers	Transportation Research Part A: Policy and Practice	Cost in US$ and transit time per month	Bulk Shipping (Oil Tanker)	NSR – SCR	Lower Bound (June – February) Higher Bound (July – December)	Murmansk (Russia) – Daesan (South Korea)
Wang et al. 2016	Comments on "Case studies of shipping along Arctic routes. Analysis and profitability perspectives for the container sector"	Transportation Research Part A: Policy and Practice	Cost per TEU in US$ (In-transit inventory costs included)	Liner Shipping	NSR – SCR NWP – SCR	Summer season (six months)	1. Rotterdam (The Netherlands) – Shanghai (China)/Yokohama (Japan) 2. Rotterdam (The Netherlands)– Shanghai (China)/ Yokohama (Japan)

Author(s) and year	Title	Journal	Comparison and Scope	Transport Systems	Routes	Time frame of operations	Origin-Destination Pairs
Lin and Chang (2018)	Ship routing and freight assignment problem for liner shipping: Application to the Northern Sea Route planning problem	Transportation Research Part E: Logistics and Transportation Review	Profit (Unit of measurement not specified)	Liner Shipping	Combined SCR/NSR – Suez Canal	Year-round on SCR Combined schedule including seasonal transits on NSR (July – September)	Tianjin, Dalian, Qingdao, Shanghai, Ningbo, Xiamen, Yantian (China), Pusan (South Korea), Ho Chi Minh (Vietnam), Port Kelang (Malaysia), Jeddah (Saudi Arabia), Algeciras (Spain), Southampton, Felixstowe (United Kingdom), Dunkirk, Le Havre (France), Zeebrugge, Antwerp (Belgium), Rotterdam (The Netherlands), Hamburg (Germany)
Zhu et al. (2018)	The environmental costs and economic implications of container shipping on the Northern Sea Route	Maritime Policy & Management	Transport, environmental, and Global Warming costs per TEU in US$ Emissions assessment	Liner Shipping	NSR SCR New Eurasian Land Bridge All-air	Summer season (180 days)	Rotterdam (The Netherlands) – Shanghai (China)
Xu et al. (2018)	Economic feasibility of an NSR/SCR-combined container service on the Asia-Europe lane: a new approach dynamically considering sea ice extent	Maritime Policy & Management	Cost per TEU in US$	Liner Shipping	Combined SCR/NSR – Suez Canal	Year-round on SCR Combined schedule including seasonal transits on NSR	Shanghai (China) – Rotterdam (The Netherlands)

Author(s) and year	Title	Journal	Comparison and Scope	Transport Systems	Routes	Time frame of operations	Origin-Destination Pairs
Wan et al. (2018)	Energy-Saving Potential and an Economic Feasibility Analysis for an Arctic Route between Shanghai and Rotterdam: Case Study from China's Largest Container Sea Freight Operator	Sustainability	Cost per tonne in US$ and profit per TEU in US$ Emissions assessment	Liner Shipping	NSR – SCR	Summer season (June – October)	NSR: Shanghai, Ningbo (China), Pusan (South Korea), Felixstowe (United Kingdom), Hamburg (Germany), Rotterdam (The Netherlands) SCR: Shanghai, Ningbo, Shenzhen (China), Felixstowe (United Kingdom), Hamburg (Germany), Hong Kong (China), Rotterdam (The Netherlands)
Shibasaki et al. (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	Maritime Policy & Management	Annual and round voyage cost in US$ per cubic metres (m^3)	Specialised Shipping (LNG tanker)	Combined Traditional Route/NSR Traditional Routes: SCR Panama Canal Cape of Good Hope	4, 6 ,9, 12 months	Yamal (Russia), Hammerfest (Norway), Zeebrugge (Belgium), Montoir (France), Bilbao (Spain), Arzew (Algeria), Sabine Pass (USA), Point Fortin (Trinidad and Tobago), Sodegaura (Japan), Pyeongtaek (South Korea), Shanghai (China), Yung An (Taiwan), Map Ta Phut (Thailand), Dahej (India)

Author(s) and year	Title	Journal	Comparison and Scope	Transport Systems	Routes	Time frame of operations	Origin-Destination Pairs
Furuichi and Otsuka (2018)	Examining quick delivery at an affordable cost by the NSR/SCR-combined shipping in the age of Mega-ships	Maritime Policy & Management	Cost per TEU in US$	Liner Shipping	Combined SCR/NSR – Suez Canal	Year-round on SCR Combined: 105, 135, 165, 195, 225 days on NSR and the rest on SCR	NSR: Hamburg (Germany) – Yokohama (Japan) SCR: Yokohama (Japan), Busan (South Korea), Shanghai (China), Hamburg (Germany), Rotterdam (The Netherlands), Felixstowe (United Kingdom)
Wang, Ren et al. (2018)	Investigating the effect of Arctic sea routes on the global maritime container transport system via a generalized Nash equilibrium model	Polar Research	Profit in US$ Ship speed Trade demand (TEU)	Liner Shipping	Combined SCR/NSR – Suez Canal	Year-round on SCR Combined: Three, six and nine month periods on NSR and the rest on SCR	Yokohama (Japan) – Rotterdam (The Netherlands)
Wang and Zhang (2019)	Bi-level Game Model for Interaction between Arctic and Traditional Routes	The Journal of Navigation	Profit in US$ Ship speed Trade demand (TEU)	Liner Shipping	Combined SCR/NSR – Suez Canal	Year-round on SCR Combined schedule including seasonal transits on NSR	Rotterdam (The Netherlands) – Dalian (China)
Ding et al. (2020)	Does a carbon tax affect the feasibility of Arctic shipping?	Transportation Research Part D: Transport and Environment	Cost (including emissions taxation) per TEU in US$	Liner Shipping	NSR – SCR	Single voyage	Shanghai (China) – Rotterdam (The Netherlands)

Author(s) and year	Title	Journal	Comparison and Scope	Transport Systems	Routes	Time frame of operations	Origin-Destination Pairs
Faury, Cheaitou et al. (2020)	Best maritime transportation option for the Arctic crude oil: A profit decision model	Transportation Research Part E: Logistics and Transportation Review	Cost per tonne in US$ Profit per tonne in US$ (total landed price of a tonne of Arctic crude oil)	Bulk Shipping (Oil Tanker)	Combined SCR/NSR – SCR	Year-round on SCR Combined schedule including seasonal transits on NSR	Murmansk (Russia) – Daesan (South Korea)
Keltto and Woo (2020)	Profitability of the Northern Sea Route for liquid bulk shipping under post 2020 sulphur regulations	The International Journal of Logistics Management	Profit per tonne in US$ RFR per tonne in US$	Bulk Shipping (Oil Tanker)	Combined SCR/NSR – SCR	Year-round on SCR Combined schedule including seasonal transits on NSR	Rotterdam (The Netherlands) – Singapore, Shanghai (China), Busan (South Korea), Yokohama (Japan)
Wang et al. (2020)	Feasibility of the Northern Sea Route for oil shipping from the economic and environmental perspective and its influence on China's oil imports	Marine Policy	RFR per tonne in US$	Bulk Shipping (Oil Tanker)	NSR – SCR	Single voyage	Murmansk (Russia), Ras Tanura (Saudi Arabia), Buenaventura (Colombia), Muara (Brunei), Cabinda (Angola), Sudan (Sudan), Tripoli (Libya) – Ningbo (China)
Xu and Yang (2020)	LNG-fuelled container ship sailing on the Arctic Sea: Economic and emission assessment	Transportation Research Part D: Transport and Environment	Profit per TEU in US$ Emissions assessment	Liner Shipping	Combined SCR/NSR – Suez Canal	Year-round on SCR Combined schedule including seasonal transits on NSR	Northwest Europe (Hamburg – Le Havre range) – East Asia Network (Yokohama-Hong Kong range)

Author(s) and year	Title	Journal	Comparison and Scope	Transport Systems	Routes	Time frame of operations	Origin-Destination Pairs
Cariou et al. (2021)	The feasibility of Arctic container shipping: the economic and environmental impacts of ice thickness	Maritime Economics & Logistics	Cost per TEU in US$ Transit Time Emissions assessment	Liner Shipping	NSR SCR Trans-Siberian Railway	Summer/autumn season	Shanghai (China) – Hamburg (Germany)
Tseng et al. (2021)	Northeast passage in Asia-Europe liner shipping: an economic and environmental assessment	International Journal of Sustainable Transportation	Economic and environmental costs in US$ Number of ships used in a fleet	Liner Shipping	Combined SCR/NSR – Suez Canal	Single round trip	SCR: Kobe, Nagoya, Shimizu, Tokyo (Japan), Singapore, Jeddah (Saudi Arabia), Suez (Egypt), Rotterdam (The Netherlands) NSR: Kobe (Japan) – Rotterdam (The Netherlands)
Gleb and Jin (2021)	Evaluating the feasibility of combined use of the Northern Sea Route and the Suez Canal Route considering ice parameters	Transportation Research Part A: Policy and Practice	Cost in US$	Liner Shipping (Multi-purpose/ General Cargo)	Combined SCR/NSR – Suez Canal	Year-round on SCR Combined schedule including seasonal transits on NSR	Yokohama (Japan) – Rotterdam (The Netherlands) Shanghai (China) – Rotterdam (The Netherlands) Shenzhen (China) – Rotterdam (The Netherlands)

Author(s) and year	Title	Journal	Comparison and Scope	Transport Systems	Routes	Time frame of operations	Origin-Destination Pairs
Wang, Liu et al. (2021)	Feasibility of the Northeast Passage: The role of vessel speed, route planning, and icebreaking assistance determined by sea-ice conditions for the container shipping market during 2020–2030	Transportation Research Part E: Logistics and Transportation Review	Profit per TEU in US$ Cost per TEU in US$ Transit Time Trade demand (TEU)	Liner Shipping	Combined SCR/NSR – Suez Canal	Annual Three Scenarios: 2020, 2025, 2030	Shanghai (China) – Rotterdam (The Netherlands)
Wang, Silberman et al. (2021)	Container vessels diversion pattern to trans-Arctic shipping routes and GHG emission abatement potential	Maritime Policy & Management	Cost in US$ Emissions assessment Emissions Trading Scheme (ETS)	Liner Shipping	NSR – Traditional Routes	Single voyage	Containership ports globally

2.4.3.2 Cost and revenue factors

A breakdown of route comparison cost structure and navigational, cost, and revenue factors assumed in the literature is attempted in order to expound the assumptions, based on which the comparative studies determined the competitiveness of Arctic routes. A detailed list of factors and respective premiums affecting ship revenues and costs is provided in Appendix F. The operating cost premiums or increased costs discerned from the reviewed papers refer to *crew*, *insurance*, and *repairs and maintenance* costs. The voyage cost premiums and relevant factors identified refer to *fuel consumption*, *speed*, and *transit fees* (*icebreaking fees*). Further, *capital cost premiums* are reported for ice class ships (ships equipped with an enhanced hull and other arrangements to be able to operate through ice). Moreover, increased *periodic maintenance* costs are reported in the literature and included in the review.

15 studies merely report additional operating costs for either NSR or NWP without providing a more detailed analysis on the specific elements of these costs. Guy (2006) assumes trip charter premiums between 15-200%, reflecting increased operating and capital costs for an ice-strengthened ship. Schøyen and Bråthen (2011) assume a premium of 20% for overall operating costs, whilst Zhang, Meng, Ng (2016), Faury and Cariou (2016), Wang et al. (2020), and Wang, Silberman et al. (2021) use the same premium in their analyses. The operating cost premium assumed in the remaining nine papers ranges from 8% (Tseng et al. 2021) to 9.5% (Cariou and Faury 2015), 14% (Zhao and Hu 2016; Wang, Liu et al. 2021), 16.6% (Keltoo and Woo 2020), 25% (Ding et al. 2020), and 46% (Wang, Ren et al. 2018; Wang and Zhang 2019). Faury, Cheaitou et al. (2020) assume a 5% and 6% premium for ice class IA and IAS Panamax tankers, respectively.

Increased crew costs range from 10% (Liu and Kronbak 2010; Lasserre 2014; Zhao et al. 2016; Zhang, Meng, Ng 2016; Zhu et al. 2018; Wan et al. 2018) to 28% (Song and Zhang 2013). One paper assumes a 10% crew premium for both ice class and non-ice class ships, based on the premise that both ship types operate on NSR (Gleb and Jin 2021). Somanathan et al. (2007) assume increased crew costs by US$ 565 per day. Crew cost premiums are not reported explicitly in sixteen papers (Verny and Grigentin 2009; Xu et al. 2011; Raza and Schøyen 2014; Lu et al. 2014; Furuichi and Otsuka 2015; Chou et al. 2015; Chang et al. 2015; Von Bock und Polach et al. 2015; Lindstad et al. 2016; Pruyn 2016; Wang, Meng, Ng 2016; Lin and Chang 2018; Xu et al. 2018; Shibasaki et al. 2018; Furuichi and Otsuka 2018; Cariou et al. 2021). It is possible that most of these studies assume that manning costs are same regardless of the route, whilst other studies consider differences depending on the route, but these could not be discerned.

The reviewed papers consider Hull and Machinery (H&M), and Protection and Indemnity (P&I) insurance, as well as relevant rates and premiums. The insurance premiums discerned from the review range from 5% (Song and Zhang 2013) to 20% (Zhu et al. 2018; Wang et al. 2020), 25% (Wergeland 1992), 50% (Wan et al. 2018), 50-51.4% (Somanathan et al. 2007; Somanathan et al. 2009), to 62.5% (Liu and Kronbak 2010; Cariou and Faury 2015). Pruyn (2016) assumes premiums of 100% and 200% for P&I and H&M insurance, respectively. Zhao et al. (2016) and Zhang, Meng, Ng (2016) both assume a premium of 25% for P&I insurance, and 100% and 50% for H&M insurance, respectively. Xu et al. (2011) assume the use of non-ice class ships and same insurance costs, regardless of the route. Gleb and Jin (2018) assume a total insurance premium of 50% for both ice class and non-ice class ships, respectively. Lasserre (2014) assumes insurance premiums of 50% and 65% on NSR and NWP, respectively. Lasserre (2015) assumes the same premiums for summer season navigation in both routes, and premiums of 65% and 80% on NSR and NWP, respectively, concerning year-round navigation. Furuichi and Otsuka (2015) and Furuichi and Otsuka (2018) adopt a premium of 10 US$/Gross Tonnes (GT) per year, whereas Shibasaki et al. (2018) assume a 100% premium per GT per year.

Schøyen and Bråthen (2011) assume a premium of US$ 125,000 per voyage for H&M and P&I insurance, whilst Raza and Schøyen (2014) use a H&M premium of US$ 281,250 per round voyage, as well as an insurance premium for ‘increased values’ of US$ 20,250 per round voyage, respectively. Insurance premiums could not be discerned or are not reported in 12 papers, whilst some papers consider average operating cost premiums in their analysis (second paragraph of this section). As regards piracy insurance premiums for voyages on SCR, these refer to various units. Pruyn (2016) assumes a premium of 18 US$ per GT for dry bulk carriers. Furuichi and Otsuka (2015) and Furuichi and Otsuka (2018) assume a premium of 40 US$ per TEU for containerships. Raza and Schøyen (2014) assume a piracy premium of US$ 158,294 per round voyage for LNG tankers.

Premiums for repairs and maintenance (R&M) costs range from 20% (Zhang, Meng, Ng 2016; Wan et al. 2018; Wang et al. 2020), to 23.6% (Wergeland 1992), 24% (Zhu et al. 2018), 25% (Von Bock und Polach et al. 2015), 26% (Song and Zhang 2013) to 100% (Verny and Grigentin 2009; Liu and Kronbak 2010; Zhao et al. 2016). Somanathan et al. (2007) assume increased

R&M costs of US$ 650 per day. 15 papers do not report increased R&M premiums or these could not be identified in their analyses, whilst some papers report average operating cost premiums (second paragraph of this section).

Four studies reporting research on the NWP do not consider icebreaking fees (Somanathan et al. 2007; Somanathan et al. 2009; Lasserre 2014; Lasserre 2015). Eight studies reporting research on the NSR assume discounted icebreaking fees, which are in accordance with some references from practitioners: they range from 3 US$/tonne (ballast) to 6.8 US$/tonne (laden) (Raza and Schøyen 2014), to 5 US$/GT (Furuichi and Otsuka 2015; Furuichi and Otsuka 2018; Von Bock und Polach et al. 2015; Zhang, Meng, Ng 2016; Wang, Silberman et al. 2021) to 7.44 US$/tonne (Lasserre 2014), and 7.5 US$/tonne (Keltto and Woo 2020). Pruyn (2016) assumes a scenario of no fees and a range of 4-19 US$/tonne when fees are applied, Zhao et al. (2016) assume three scenarios based on historic data, whereas Tseng et al. (2021) assume hypothetical fees ranging from US$ 100,000 to US$ 1,000,000 per voyage. Guy (2006) also assumes hypothetical fees, whilst Lu et al. (2014) assume hypothetical transit fees for operations on the NWP, ranging from zero to fees equal to Panama Canal Tolls. Xu et al. (2018) assume icebreaking fees as a percentage of the Suez Canal Tolls, that is, 0% (no fees), 20%, 40%, 60%, 80%, and 100%, respectively.

Some studies use the official Northern Sea Route Administration (NSRA) icebreaking fees, whereas other studies assume discounted and/or no fees in their analyses. Liu and Kronbak (2010) use the official fees and also assume three variant scenarios, that is 50%, 85% and 100% discounted fees. Lasserre (2015) uses the official NSRA fees, and assumes discounted fees based on a rate of 8.2 US$/tonne, as well as zero fees. Wan et al. (2018) and Shibasaki et al. (2018) use the official NSRA fees and also assume discounts of 20% and 50%, respectively. Xu et al. (2011) and Xu and Yang (2020) assume independent navigation in their analyses. 14 papers consider the official NSRA tariffs in their analyses, whilst assumptions on transit fees and/or icebreaking fees are not reported in eight papers.

The average ship speed reported differs across the reviewed papers and depends on various assumptions regarding speed on ice, time frame of operations, navigation zone and season, and scheduling between competing routes. The speeds through ice for oil tankers range from 3-8 knots (Faury, Cheaitou et al. 2020), 3.4-14.5 knots (Faury and Cariou 2016), to 9.4 knots (Zhang, Meng, Ng 2016; Keltto and Woo 2020). Some papers report speeds on NSR per Sea, that is, 10 knots in the Kara Sea and Chukchi Sea, 5-5.23 knots in the Laptev Sea and the East

Siberian Sea during July-October, and 5 knots in all Seas except Kara Sea (5.23 knots) during November (Von Bock und Polach et al. 2015). Wang et al. (2020) report speeds of 12.7 knots for the West Kara Sea, 9.2 knots for the East Kara Sea, 8.2 knots for the Laptev Sea, 7.8 knots for the East Siberian Sea (West), 8.2 knots for the East Siberian Sea (East), and 10.8 knots for the Chukchi Sea.

As regards dry bulk carriers, the speeds assumed range from 6 knots (Guy 2006, worst scenario) to 6.4-12.8 knots (Cariou and Faury 2015), 10-11 knots (Lindstad et al. 2016), 12 knots (Chou et al. 2015), to 9-14.3 knots (Pruyn 2016). Chang et al. (2015) assume that the speed through Chukchi Sea is 12 knots and the speed between the East Siberian Sea and Kara Sea is 6-8 knots.

Raza and Schøyen (2014) use a speed of 12 knots for LNG tankers, and Shibasaki et al. (2018) assume speeds of 6-15 knots through ice for LNG tankers, depending on the navigation zone and season.

Speeds on ice for containerships and general cargo ships range from 3-5 knots (Xu et al. 2018), to 6 knots (Guy 2006, worst scenario), 9.3-9.4 knots (Wang, Ren et al. 2018), 10 knots (Liu and Kronbak 2010; Lu et al. 2014), 11.7 knots (Xu et al. 2011), 12 knots (Wergeland 1992; Zhang, Meng, Ng 2016; Ding et al. 2020; Gleb and Jin 2021), 14 knots (Zhu et al. 2018; Wan et al. 2018), to 17 knots (Verny and Grigentin 2009). Somanathan et al. (2009) simulate speeds of 18.2 knots (February) – 18.4 knots (September). Lasserre (2014) assumes speeds of 14 knots on the NSR and 13 knots on the NWP during the summer season (May-November), whereas Lasserre (2015) assumes the same speeds during the summer season, and a speed of 7 knots on both the NSR and NWP during the winter season, respectively. Furuichi and Otsuka (2015) assume speeds of 12.8 knots during May-July and November-December, and 14.1 knots during August-October, whilst Furuichi and Otsuka (2018) assume speeds of 5.9 knots in June, 10 knots in July, 10.8 knots in August, 10.7 knots in September, 11.2 knots in October, and 11 knots in November, respectively.

Increased fuel consumption rates for ice class ships vary in the literature and depend on whether the factors of ice resistance or the increased weight of an ice-class ship or both are considered in the comparative studies. For ice class IA oil tankers, increased fuel consumption rates, expressed in tonnes per day both on open water and ice, range from 5% (Faury and Cariou 2016), to 7% (Song and Zhang 2013) and 30% (Zhang, Meng, Ng 2016). Faury, Cheaitou et al. (2020) report increased rates of 14% and 60% for ice class IA and IAS Panamax tankers, respectively. Von Bock und Polach et al. (2015) use an increased rate of nearly 40% for a

Double Acting Ship (DAS) ice class IAS Aframax tanker. Keltto and Woo (2020) assume an engine load of 70% on ice for ice class IA Handymax/MR tankers, which implies increased fuel consumption, given that the engine load on open water is assumed at 80% of the installed power at a speed of 14.5 knots. When it comes to dry bulk carriers, increased fuel consumption rates in tonnes per day both on open water and ice are estimated at 5% for ice class IA Handymax bulk carriers (Cariou and Faury 2015) and 17,000-289,000 dwt dry bulk carriers (Pruyn 2016).

As regards containerships and general cargo ships, Liu and Kronbak (2010) assume 67% increased fuel consumption in tonnes per nautical mile for ice class IB ships on ice, whilst Zhao et al. (2016) and Wang, Ren et al. (2018) adopt the same rate. Furuichi and Otsuka (2015) assume increased specific fuel oil consumption (SFOC) of 10%, whereas Wang, Silberman et al. (2021) use a SFOC of 20% on ice. Somanathan et al. (2007) assume 114-122% increased installed engine power for Polar Class 3 (PC3) containerships. When it comes to studies that express increased fuel consumption in tonnes per day, this ranges from 8% (Wan et al. 2018) to 10% (Xu et al. 2018; Xu et al. 2020), and 30% (Zhang, Meng, Ng 2016; Ding et al. 2020) for ice class IA ships. Somanathan et al. (2009) assume 50-59% increased fuel consumption in tonnes per day for PC3 containerships. Lasserre (2014) assumes 8% increased fuel consumption in tonnes per day for ice class IAS ships. Lasserre (2015) assumes the same rate for IAS ships when operating on either NSR or NWP during the whole summer season. As regards year-round operations, a rate of 8% is assumed for ice class IAS containerships operating on the NSR, and 15% (summer) and 12% (winter) for PC4 containerships operating on the NWP (Lasserre 2015). Two papers report increased fuel consumption on ice: Wang, Liu et al. (2021) assume a rate of 4%, and Gleb and Jin (2021) assume rates ranging from 1% (Class II), to 2.5% (ice class IC), 3.4% (ice class IB), 5.1% (ice class IA), 6.3% (ice class IAS), and 7.6% (Arc6/PC5 class). Shibasaki et al. (2018) assume 10% increased fuel consumption on ice for LNG tankers.

Capital cost premiums range from 5% (Song and Zhang 2013) to 20% (Keltto and Woo 2020; Wang et al. 2020), and 30% (Zhang, Meng, Ng 2016) for ice class IA tankers, whereas Von Bock und Polach et al. (2015) assume 35% and 38% premiums for ice class IA and IAS (DAS) tankers, respectively. Premiums for dry bulk carriers range from 5% (Pruyn 2016) to 20% (Schøyen and Bråthen 2011), whilst Shibasaki et al. (2018) assume 20% and 55% for ice class IA and Arc7/PC4 LNG tankers, respectively. As regards capital cost premiums for containerships and general cargo ships, these range from 10% (Furuichi and Otsuka 2015; Xu et al. 2018; Ding et al. 2020; Xu and Yang 2020) to 20% (Liu and Kronbak 2010; Lasserre 2014; Lasserre 2015, for IAS ice class; Zhao et al. 2016; Wan et al. 2018; Wang, Ren et al. 2018; Wang and Zhang 2019; Wang, Silberman et al. 2021), 24% (Zhu et al. 2018), 30% (Somanathan et al. 2007; Somanathan et al. 2009; Lasserre 2015, for PC4 ice class), and 35% (Wergeland 1992). Finally, Gleb and Jin (2021) assume capital cost premiums ranging from 1.2% (Class II) to 4.8% (ice class IC), 10.8% (ice class IB), 19.2% (ice class IA), 30% (ice class IAS), and 43.2% (Arc6/PC5 class).

Six papers consider increased costs of periodic maintenance, that is, the undertaking of regular surveys and dry docking of a ship, instead of routine repairs and maintenance which constitute part of the operating costs. These increased costs range from 20% (Gleb and Jin 2021; Lasserre 2014; Lasserre 2015, for summer season operations on both the NSR and NWP) to 50.3% (Kondo and Takamasa 1999), and 150% (Somanathan et al. 2007; Somanathan et al. 2009; Lasserre 2015, for year-round operations on NWP). Load factors are also reported for both westbound and eastbound cargo flows. These factors range from 30% to 100% with some of the papers assuming lower load factors for eastbound cargoes, considering the dynamics in trade flows between Europe and Asia.

2.4.3.3 Analysis of cost and emissions assessments

The reviewed papers were categorised further according to the results of the Arctic routes' economic feasibility and emissions assessment. 30 papers consider costs/profits only, whereas 14 papers assess costs/profits and emissions. Appendix G and Appendix H present the results of the reviewed papers in terms of cost and emissions assessments, respectively.

15 papers consider the Arctic routes either cost-competitive or profitable, whereas 11 papers consider the Arctic routes unprofitable or not cost-competitive. 21 papers find the Arctic routes to be either competitive or not competitive depending on the assumptions of the basic scenarios in their analyses. The various discrepancies make the cross-comparison of the results rather difficult, especially the differences in the assumed time frame of operations. Figure 2.2 shows clusters of the reviewed papers by considering the critical factor of time frame of operations.

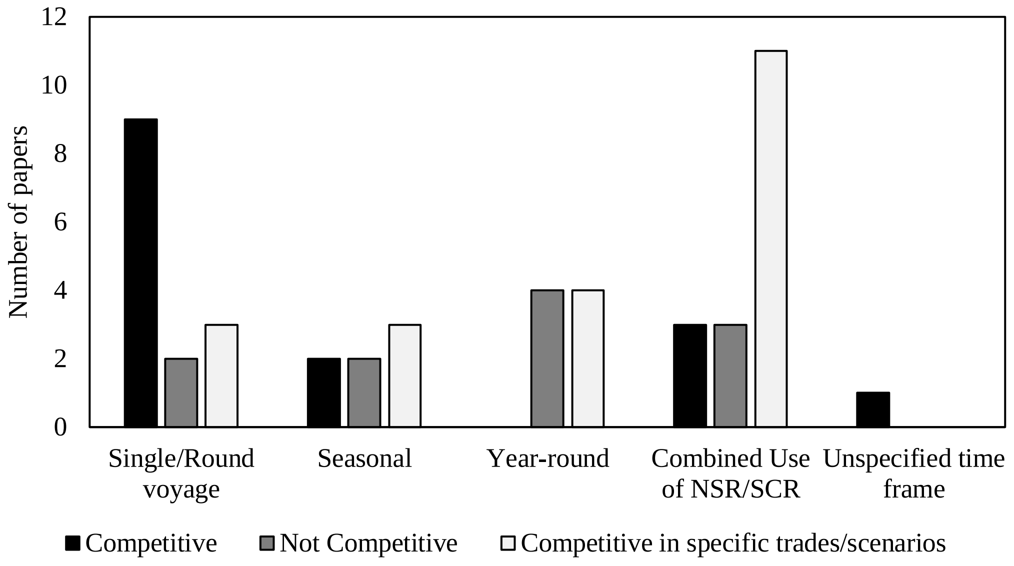


Figure 2.2. Cost and profit assessment results based on the time frame of operations.

The NSR and/or the NWP are shown not to be competitive in four out of eight papers that consider year-round operations, with the rest four papers reporting mixed results. When it comes to papers that consider seasonal operations, two find the Arctic routes uncompetitive, two find them competitive, and three find that they are more competitive than other routes in specific trades and/or scenarios. Papers that assume combined schedules, that is, using the NSR for certain seasonal windows or voyages, and either the SCR or any other traditional routes during the rest of the year or part of the year, report mixed results most of the times (11 papers), with three papers reporting that combined schedules are competitive and three papers asserting that they are uncompetitive compared to using only traditional routes[7].

The Arctic routes are shown to be competitive in most of the papers that consider single/round voyages (nine) as well as in Lindstad et al. (2016), who do not explicitly define the time frame. Of the 14 papers that assess single/round voyages, two find the NSR uncompetitive, whereas three report mixed results.

Overall, Arctic routes were found to be either cost-competitive or profitable in 32% of the papers and unprofitable or not cost-competitive in 23% of the papers, whereas 45% of the papers suggest that they are competitive under specific scenarios or at certain trade routes[8].

[7] Of the 17 papers reporting on combined NSR/Traditional Routes schedules, 14 refer to annual operations, two refer to single voyages, and one assumes three annual long-term scenarios i.e. 2020, 2025, and 2030, respectively.
[8] These percentages refer to the transport systems and/or time frames used per reviewed paper, and not to the total number of 44 papers.

Figure 2.3 presents the results for papers assessing the Arctic routes against liner shipping (including papers reporting research on the general cargo/multipurpose sector), clustered according to the time frame of operations. It is clear from the above analysis and Figure 2.3 that in most of the papers on liner shipping which assume an annual operating period or annual combined NSR/Traditional Routes schedules, Arctic routes tend to be either uncompetitive or demonstrate mixed results. The picture is similar regarding seasonal operations, where three papers report mixed results, and two papers find the NSR to be uncompetitive compared to the SCR.

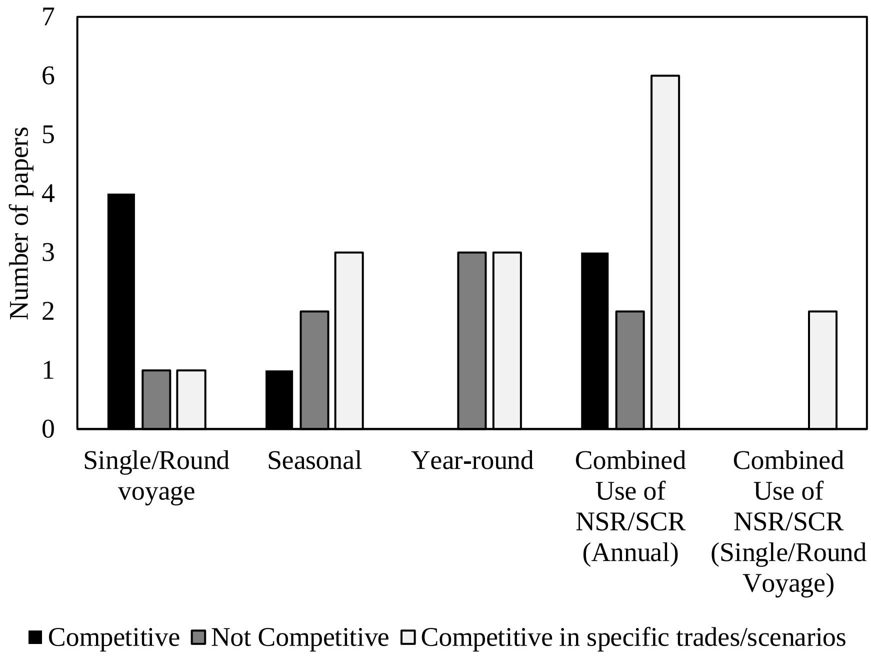


Figure 2.3. Cost and profit assessment results for papers on liner shipping.

In contrast, they are found competitive in most of the papers that assume round or single voyages, mainly for bulk or specialised shipping. Figure 2.4 illustrates results for papers assessing the Arctic routes against bulk (dry and liquid) and specialised shipping (LNG tanker), clustered according to the time frame of operations. A cross-comparison of the various cost components of each study is infeasible due to lack of data and a mismatch on the available variables regarding costs or other factors.

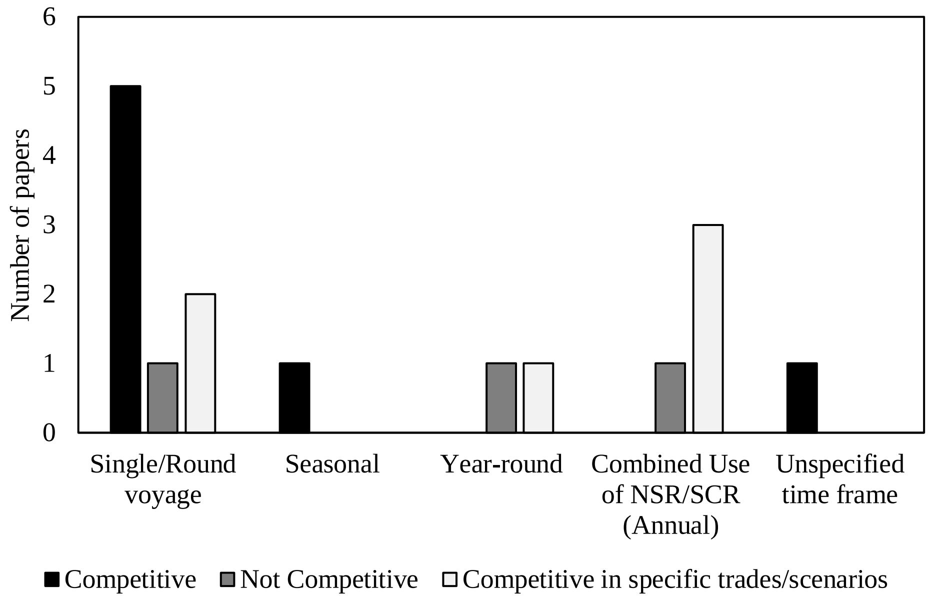


Figure 2.4. Cost and profit assessment results for papers on bulk and specialised shipping.

Of the 14 papers that include emissions assessments in their analyses, six calculate emissions based on fuel consumption (Schøyen and Bråthen 2011; Furuichi and Otsuka 2015; Zhao and Hu 2016; Wan et al. 2018; Xu and Yang 2020; Cariou et al. 2021), three consider emissions taxes (Kondo and Takamasa 1999; Cariou and Faury 2015; Ding et al. 2020), one considers environmental costs in the cost analysis (Tseng et al. 2021), whereas two include emissions assessments based on Global Warming Potential (GWP) Factors and include environmental costs in the analysis (Zhu et al. 2018; Wang et al. 2020). One paper includes emissions calculations and Emissions Trading Schemes (ETS) (Wang, Silberman et al. 2021), and one paper compares emissions output between fuel consumption-based estimates and GWP factors-based assessments for different time frames (Lindstad et al. 2016).

Figure 2.5 shows the results for papers that include emissions comparisons between the Arctic and traditional routes. Of the 14 papers that appraise emissions, five conclude that Arctic routes are more energy efficient than traditional routes (Schøyen and Bråthen 2011; Furuichi and Otsuka 2015; Zhao and Hu 2016; Wan et al. 2018; Xu and Yang 2020), and three find that energy efficiency depends on certain assumptions and scenarios, such as load factors, fuel consumption and transit times when operating through ice (Cariou et al. 2021), distances (Wang, Silberman et al. 2021), and transit fees between competing routes and the ratio of ice class/non-ice class ships in combined SCR/NSR schedules (Tseng and et al. 2021). Out of the three papers that employed GWP factors in their analysis, one concludes that Arctic routes are less energy efficient than if emissions estimations are based solely on fuel consumption conversions (Lindstad et al. 2016). Zhu et al. (2018) find a similar effect of the GWP factors on emissions, whereas air pollution costs are found lower than on traditional routes in their analysis. Yet, they conclude that larger ships and higher load factors when using the NSR can lower both CO_2 emissions and overall environmental costs, that is, the total GWP and pollution costs. Wang et al. (2020) include various OD pairs in their analysis and find that GWP and air pollution cost reductions depend on the OD distances when using the NSR compared to other maritime routes. The NSR is favoured when emissions taxes are considered in the analysis since fuel costs increase when using longer routes (Cariou and Faury 2015; Ding et al. 2020).

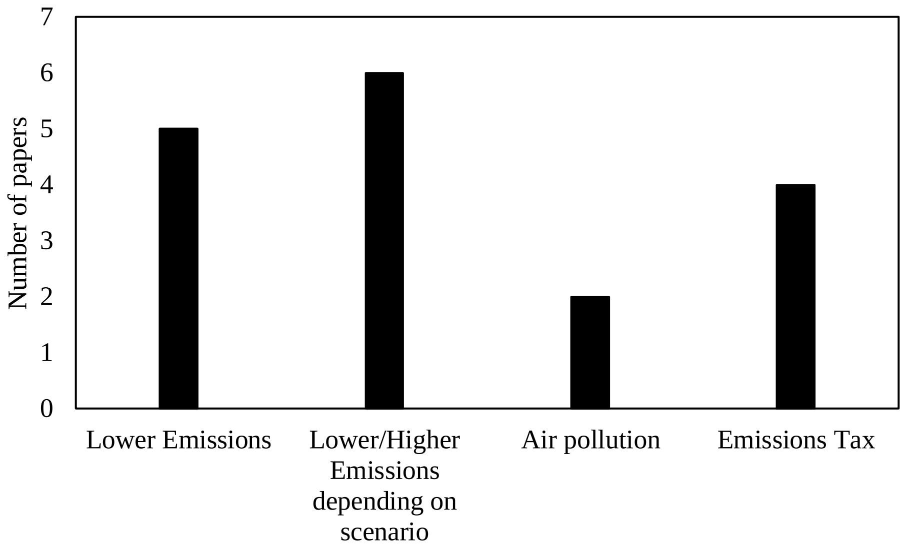


Figure 2.5. Emissions assessment results for all papers.

2.5 Discussion and future directions

2.5.1 Research insights

The number of influential factors which determine maritime route choice extend to include cost, revenue, navigational, and environmental factors amongst others. Important variables are discussed in the following sections in order to understand the interrelations between them, as well as how they affect route choice at the operational, tactical, and strategic levels.

2.5.1.1 Route choice

The systematic review has identified a specific preference for studying the NSR in most of the reviewed papers. This is not surprising when considering the prevailing sea ice conditions and recent infrastructure and project developments in the Arctic region, favouring mainly the NSR amongst others. Studies within climate science investigating the future accessibility of Arctic routes indicate extended navigation seasons for several ship types and for all the Arctic routes (NSR, NWP, TSR) throughout the 21st century. Khon et al. (2010) estimate the navigation season to be 3-6 months for the NSR, and 2-4 months for the NWP for low ice class ships by 2080-2099. Stephenson et al. (2013) project the seasonal navigation period on the NSR to be approximately 103, 113, and 120 days for non-ice class, PC6, and PC3 ships respectively by the end of the 21st century. Khon et al. (2017) project a navigation season of 4 to 6.5 months for non-ice class ships on the NSR by late-century.

Smith and Stephenson (2013) estimate the probability of non-ice class ships to transit the NSR, using September as a benchmark, to be 94-98%, and that for the NWP to be 53-60%, by 2040-2059. Stephenson et al. (2014) find high inter-annual variability of the NSR navigation season, considering sea ice and bathymetry during 2013-2027. Stephenson and Smith (2015) identify a gradual increase in the number of PC6 ship voyages through the TSR by mid-century, whilst the possibilities of using the NWP rise by 2060. In contrast, Laliberté et al. (2016) find both the NWP and TSR to be ice-covered beyond mid-century, whereas regions along the NSR and the Arctic Bridge are projected to be more accessible for non-ice class ships. Their results are in line with Pizzolato et al. (2016) and Liu et al. (2017), who conclude that multi-year ice at the northern sub-route of the NWP will be a significant obstacle for shipping activities in the medium-term. According to Melia et al. (2016), the TSR is projected to become available for non-ice class ships by mid-century, whilst voyages from Europe to the Far East will take 17 days by late-century. Aksenov et al. (2017) identify sea ice extent and thickness as the most determining factors for shipping in the Arctic until 2030-2050, whereas other ice properties (e.g. ice ridging, drift ice, and internal pressure), ocean circulation, winds, currents and waves will mostly affect navigation beyond that period.

Taking into account these findings, future research should also pay attention to the TSR as an alternative route. In addition, further examination of the NWP and alternative sub-routes of the NSR is needed, as these could enable the employment of larger ships. Moreover, the possible opening of the Nicaragua and Kra Canals, the expansion of both Panama and Suez Canals, as well as alternative land-based (e.g. Trans-Siberian Railway, New Eurasian Land Bridges), and other established trade routes, will also have an impact to their northern rivals (Tavasszy et al. 2011; Yip and Wong 2016; Martinez et al. 2016; Zeng et al. 2017; Yuan et al. 2020; Zeng et al. 2020). Figure 2.6 illustrates major sea routes and ship canals as well as several land and multimodal routes.

2.5.1.2 Cost, navigational, and environmental factors

A wide variety of cost, navigational, and environmental factors are identified. This is in line with the findings of Lasserre (2014). The differences extend to include not only the unit of cost and emissions measurement but also navigational factors as well.

The assumed navigation season greatly influences route comparison and the outcomes of the reviewed studies. This implies that Arctic routes could serve as seasonal alternatives for a limited period of about five months (summer/autumn navigation season) rather than offering regular access to ships on an annual basis under the current winter navigational and climatic conditions. Consequently, Arctic routes are currently suitable mainly for dry bulk carriers, tankers, general cargo and specialised ships. A combination of an extended navigation season with low icebreaking fees and high fuel prices significantly increases the competitiveness of the Arctic routes (Liu and Kronbak 2010; Lasserre 2014; Lasserre 2015; Zhao et al. 2016; Xu et al. 2018). The use of small ships on the NSR can be competitive under high fuel prices compared to the use of larger ships on traditional routes (Furuichi and Otsuka 2015). Moreover, the use of smaller ships on the NSR using a low-priced fuel, compared to the use of larger ships on the SCR using a high-priced fuel, also increases the competitiveness of the NSR (Xu and Yang 2020). Further, high load factors, and high average speeds which increase voyage frequency through the Arctic routes, could improve profitability, especially for liner shipping operations (Wergeland 1992; Guy 2006; Lasserre 2014; Lasserre 2015; Gleb and Jin 2021).

The capital cost premium ranges from 10% to 30% in most cases and is identified as an important cost factor amongst others. The importance of an extended navigation season is crucial in order to exploit the advantages of operating on shorter routes by using ice class ships which entail increased capital costs. Besides, operators may seek opportunities to use ice class ships in other ice bound regions with easier ice conditions during the winter season (e.g. Baltic Sea, Sea of Okhotsk), depending on the ice class notation and ship characteristics.

In most of the papers where crew cost premiums are discerned, these are assumed to be 10% higher when operating on Arctic routes. Furthermore, it is widely accepted that insurance costs are higher for ice class ships. However, a common denominator is difficult to find since each voyage on Arctic waters is evaluated individually. According to a survey by Sarrabezoles et al. (2016), most of the insurers stated that H&M premiums range between 25% and 50%, others estimated them between 0% and 25%, whereas only one insurer assumed rates between 50% and 75%. As regards P&I and cargo insurance premiums, a range between 0% to 25% was mentioned most of the times, whilst an almost equal number of respondents estimated cargo insurance premiums around 25-50%. Interestingly, one of the early comparative studies also assumes a cargo insurance rate of 25% (Wergeland 1992).

The ice breaking fees assumed in the reviewed papers can be distinguished in two broad categories. Those, which refer to the official NSRA fees, and those, which refer to discounts, including the category of papers assuming hypothetical fees. This discrepancy stems from the fact that transit fees have been subject to fluctuations related to financial and geostrategic reasons rather than a well-targeted policy during the period 1991-2013 (Gritsenko and Kiiski 2016). Several studies emphasise the importance of relatively low icebreaking fees in order for the Arctic routes to be viable (Liu and Kronbak 2010; Zhao et al. 2016; Lasserre 2014; Lasserre 2015; Furuichi and Otsuka 2015; Lin and Chang 2018; Xu et al. 2018; Tseng et al. 2021; Gleb and Jin 2021). Yet, icebreaking assistance is not compulsory since 2012 (Gritsenko and Kiiski 2016). Nevertheless, insurance companies may require the use of icebreakers for safety reasons and due to increased risks (Sarrabezoles et al. 2016; Fedi et al. 2018; Fedi et al. 2020).

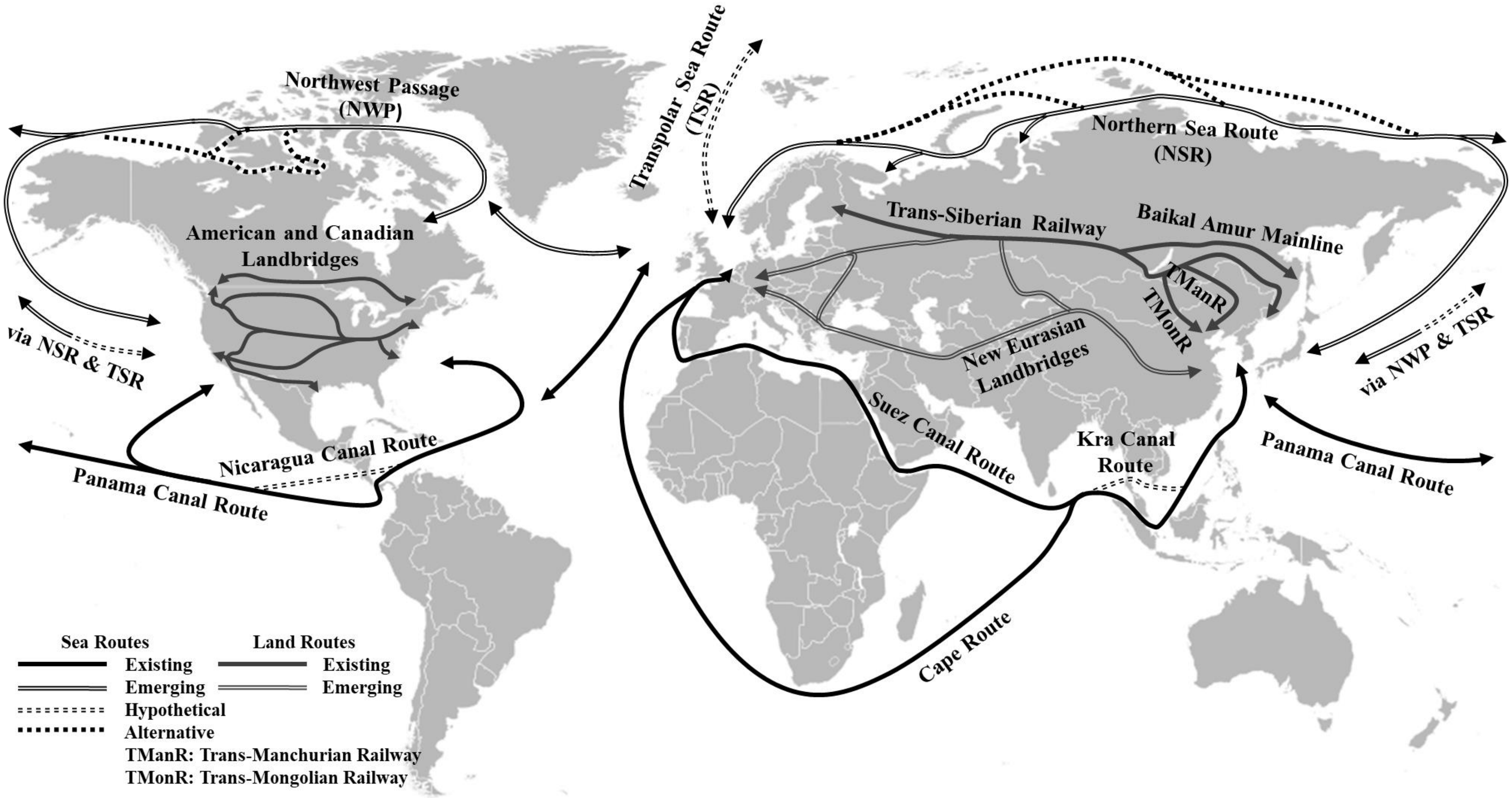


Figure 2.6. Alternative sea and land routes between Eurasia and North America.

Source: Author, based on Rodrigue et al. (2017) and MERICS (2021).

Assumptions on ship speed through ice vary widely in the literature and depend on the modelling approach adopted. The average voyage speed when using any of the Arctic routes depends on the speed realised when operating through ice, since the speed at open water will be the same as in traditional routes. Besides, the variability of ship speed through ice stems from the uncertainty of sea ice and weather conditions per navigation zone and month, and underlines that there are no standards and every case is unique. According to CHNL data, the average speed recorded on the NSR is around 10 knots (CHNL 2021a), which is in line with historic average speeds through NSR (Wergeland 1992; Kitagawa 2001), and operating speeds realised at first-year sea ice in the Bay of Bothnia during the ice season. However, it can be easily reduced to 5-6 knots or even to zero knots depending on local ice and climatic conditions.

Whilst the use of the shorter Arctic routes implies lower fuel costs, this largely depends on transit times and possible delays due to deviation of a ship from its predefined navigational route in order to avoid difficult ice conditions (Faury et al. 2020; Cariou et al. 2021). In addition, most of the papers assume increased fuel consumption owing to greater engine power and additional weight of an ice class ship, whereas other papers also consider additional fuel consumption due to ice resistance. Solakivi et al. (2017) and Solakivi et al. (2018) statistically analysed capital costs and fuel consumption of tankers, bulk carriers, and containerships based on data of the global ice class fleet. Pruyn (2016) suggests that fuel consumption of an unassisted ship could be equal to that at design speed regardless of the speed realised on ice. Similarly, von Bock und Polach et al. (2015) assume that when operating through ice, the fuel consumption at full engine power could be the same as at the design speed on open water. Xu et al. (2018) use mathematical models to estimate the relationship between sea ice thickness and increased fuel consumption when operating through ice on the NSR based on the Finnish-Swedish Ice Class Rules and relevant models. Furuichi and Otsuka (2015), Shibasaki et al. (2018), and Furuichi and Otsuka (2018) assume that fuel consumption is proportional to the speed to the power of two instead of three, when operating either at open water or through ice. Psaraftis and Kontovas (2013) and Psaraftis and Kontovas (2014) claim that the cube law between speed and fuel consumption does not hold at very low speeds for open water navigation, whilst Evans and Marlow (1990) also suggest an exponent of two instead of three. Adland et al. (2020), empirically analysed the speed-fuel consumption relationship and found elasticities ranging from 3.8 (3.7) to 0.7 (1.7) at a speed range between 16 knots and 8.4 (8.2) knots for Aframax and Suezmax tankers, respectively. Future research could shed light on the fuel consumption of an ice class ship both at open water and through ice to improve the quality of cost assessments with respect to overall fuel costs when comparing ice-infested and traditional routes.

As regards the types of fuel used by ships on Arctic routes, Lasserre (2015) suggests that the Intermediate Fuel Oil (IFO) 380 may not be appropriate during winter navigation. The picture becomes more blurred when emissions taxes are introduced (Kondo and Takamasa 1999; Schøyen and Bråthen 2014; Cariou and Faury 2015; Ding et al. 2020; Wang, Silberman et al. 2021), the use of alternative fuels in the Arctic is considered (Wan et al. 2018; Xu and Yang 2020; Wang, Silberman et al. 2021), lower sulphur limits are introduced for operations in the Arctic, and the future ban of heavy fuel oils in the Arctic is realised (IMO 2020; IMO 2021). Moreover, alternative approaches for estimating the environmental impact of maritime operations at different regions might lead to differing results. Lindstad et al. (2016) challenge the assessment of CO_2 emissions that rely merely on fuel consumption conversion to CO_2 amounts when considering operations in the Arctic. They claim that, if region-specific GWP factors are applied, then the use of the NSR generates higher kilograms of CO_2-equivalent per tonne (kg-CO_2-eq/t) than the use of the Suez Canal route even if LNG is used as a fuel. Other studies which employed GWP factors include those of Zhu et al. (2018) and Wang et al. (2020). Moreover, the use of more expensive fuels for operations in the Arctic, such as Marine Gasoil (MGO) compared to the use of low-priced fuels on longer routes, is found to reduce the competitiveness of Arctic routes (Wan et al. 2018).

2.5.1.3 Revenue and market factors

The literature focuses mainly on cost and navigational factors, whilst revenue factors have been overlooked in most cases. Shipowners and operators adjust ship speeds according to market conditions, freight rates, and fuel prices amongst others (Alderton 1981; Evans and Marlow 1991; Psaraftis and Kontovas 2013). Yet, real speeds tend to be less sensitive than theoretical speeds defined solely by fuel prices and freight rate movements. The main reasons include weather factors, organisational and technical constraints, and contractual agreements amongst others (Psaraftis and Kontovas 2013; Psaraftis and Kontovas 2014; Lindstad and Eskeland 2015; Adland et al. 2017; Adland and Jia 2018). For example, speeds for tankers have been around 12-12.5 knots, for dry bulk carriers around 11.2-11.6 knots, speeds for containerships above 8,000 TEU around 16.4 knots, for Liquefied Petroleum Gas (LPG) tankers around 14.3-14.6 knots, and for LNG tankers around 16 knots during 2011-2020 (Refinitiv Eikon 2021).

Various combinations of freight rates and fuel prices may favour one route over the others and this also depends on other factors, such as increased costs, load factors/dwt utilisation, positioning, delays, and transit fees of competing sea routes and ship canals. Moreover, the relationship between speed, freight rates and fuel prices is not often straightforward if other factors such as cargo value and in-transit inventory costs are considered amongst others (Goss et al. 1982). The net effect of these factors upon route choice ultimately depends on the logistical context of the calculations. Commodity prices, distance, freight rates, and proximity to markets play an important role too (Laulajainen 2007; Maxwell and Zhu 2011). Economies of scale and different ship sizes and ice class designs are also important factors, which have not been investigated extensively, especially for ship types other than containerships (Zhang, Meng, Ng 2016; Faury, Cheaitou et al. 2020; Wang et al. 2020; Gleb and Jin 2021).

2.5.1.4 Transport systems

Whilst 30 studies assess the Arctic routes against liner shipping, this system seems to be the most uneconomical and unfeasible to date. Thus, a number of criteria are not satisfied when it comes to carrier port selection: remote geographical location of Arctic ports, lack of proximity to markets and access to hinterlands, regional bottlenecks and limited port infrastructure and services (Lirn et al. 2004; Song and Yeo 2004). Other factors are high uncertainty related to ice and climatic conditions in the Arctic that may result in delays, schedule unreliability and longer transit times (Zohil and Prijon 1999; Notteboom 2006).

Some of the reviewed papers partly tackle these issues by incorporating lower load factors to both eastbound and westbound cargo flows and voyages. Although Arctic routes do not provide for sufficient port calling, they can serve as shorter routes in the long-term, allowing liner operators to either reconfigure their networks or establish separate services through the Arctic. The global geographical focus of liner networks as well as the inherent trend of expansion in secondary markets (Guy 2003; Baird 2006) will possibly trigger the interest of operators possessing large capacity to extend their network in the Arctic by establishing seasonal transits in the short-term and forming regular networks in the long-term (Lee and Kim 2015). Few studies report a network structure in the literature (Xu et al. 2011, Lin and Chang 2018; Wan et al. 2018; Furuichi and Otsuka 2018; Tseng et al. 2021). Future research could shed light on network structure and the feasibility of liner operations from this perspective.

It is evident from this review that bulk (14 papers) and specialised shipping (2 papers) are less studied in the literature compared to liner shipping (30 papers). This neglects the possibility for the Arctic routes to emerge as an alternative option for liquid and dry bulk trades and other cargoes, especially crude oil and oil products, LNG, LPG, and iron ore and other minerals (Jørgensen-Dahl and Wergeland 2013; Bambulyak et al. 2015). Besides, destination and transit voyages historically comprised these cargoes (Armstrong 1952; Granberg 1998; Andreeva 1998; Ragner 2000) and continue to drive traffic from the Arctic to the world markets, with only one pure containership have been recorded to transit the NSR so far (Eguíluz et al. 2016; Zhang, Meng, Zhang 2016; CHNL 2021a; Gunnarsson 2021; Li et al. 2021). The potential for bulk and specialised shipping is also reported in surveys (Lasserre and Pelletier 2011; Lee and Kim 2015; Beveridge et al. 2016; Lasserre et al. 2016). The reefer and general cargo sectors are also largely neglected in the literature. This is in contrast to NSR traffic records, which show that a considerable number of refrigerated cargo ships, as well as a large number of general cargo ships have used the route during the last five years (CHNL 2021a).

2.6.1 Methodological insights

The methods and data analysis techniques identified in the literature are discussed in this section to provide insights on how these could be developed in the future. Data analysis techniques that could aid research on Arctic shipping are also presented, although other techniques could also be appropriate. As a relatively new topic in the maritime transport literature, Arctic shipping, could be addressed by many methods and data analysis techniques used in the social sciences.

2.6.1.1 Operational research and cost modelling approaches

Arctic shipping could be a fertile ground for operational research techniques. Zhao et al. (2016) employ a liner network design on Arctic shipping problems. Lin and Chang (2018) formulate a ship routeing and freight assignment model and consider a multi-port network and a fleet of varying number of containerships to assess the NSR against liner shipping. Tseng et al. (2021) formulate a mixed-integer linear programming model (MILP) to quantify the economic and environmental costs of a multi-port liner network for combined NSR/SCR schedules. Most of the reviewed papers consider the assignment of one ship at single voyages or annual operations. Operational research methods could be used to consider various factors and alternative options related to fleet size, route choice, and number of voyages and networks amongst others (Lin and Chang 2018; Tseng et al. 2021). Contemporary operational tactics, such as ship speed adjustments, adopted to minimise fuel consumption and/or costs or to maximise profits, are very relevant (Psaraftis and Kontovas 2013). Environmental sustainability can also be addressed by employing multi-objective optimisation techniques (Mansouri et al. 2015). Thus, economic and environmental modelling assessments could be informed from all the aforementioned techniques. As Zhao et al. (2016) mention, the majority of operational research methods applied on shipping problems rely on established routes and networks, and do not consider new routes and their impact on maritime operations.

Given that scenario-based transport cost modelling is likely to remain the prevalent approach, it could be developed further to include more assumptions considering not only cost factors but also environmental factors (Lindstad et al. 2016; Faury and Cariou 2016; Xu et al. 2018; Wang and Zhang 2019; Faury, Cheaitou et al. 2020; Cariou et al. 2021; Wang, Liu et al. 2021; Gleb and Jin 2021). Of the 44 papers reviewed, only 11 quantify emissions based on various emissions factors and formulas.

Studies within climate science assessing future accessibility in the Arctic could also aid the modelling approaches with respect to the navigation season, sea ice conditions and transit times to better quantify them. Global climate models projecting ice and weather conditions under different emissions scenarios could be used as inputs (e.g. Wang and Zhang 2019; Wang, Liu et al. 2021). More diversity is needed in terms of scenarios and assumptions to provide fruitful insights and counter-arguments. Arctic maritime operations require cost analysis methods that can deal with the structure and complexity of the issues being involved.

2.6.1.2 Empirical case studies

The discrepancies in hypotheses and assumptions made in the literature regarding navigational, cost, and revenue variables can be attributed to the infancy of Arctic maritime operations, which in turn leads to the lack of relevant data and statistics. Empirical case studies with a focus on the examination of the Arctic routes and interviews with key stakeholders can complement the data reported in databases and other publicly available sources to further refine any modelling approach where there are no, insufficient, or inaccurate statistical data. The identified case studies report empirical data which were obtained through interviews, as well as from records of real NSR voyages (Raza and Schøyen 2014; Zhao and Hu 2016). This type of research could help increase the understanding of Arctic maritime operations. As Wacker (1998) points out, empirical research can verify model-based research amongst others. In particular, case studies provide a deeper understanding of the usually complex operational processes of the real world.

2.6.1.3 Econometric modelling, regression, panel data analysis and other techniques

Statistical analysis techniques such as structural econometric modelling, regression analysis, logit and probit models, panel data analysis, and multi-criteria decision-making models (MCDM) have been widely used in maritime research amongst others (Woo et al. 2013; Talley 2013; Shi and Li 2017). All these techniques could be employed in order to develop models that test various explanatory variables to determine costs, profits and emissions. For instance, Lu et al. (2014) use explanatory variables such as freight rates, distance, time, transit fees, fuel consumption and ship size in order to investigate cost determinants of route alternatives. Pruyn (2016) uses a sophisticated structural model that includes macroeconomic data from sixteen countries, ship sizes, fleet age, freight rates, and transport costs to explore the feasibility of the NSR. Shibasaki et al. (2018) employ a spatial general equilibrium model drawing from macroeconomics to predict changes in LNG trade patterns, and measure economic impacts based on variations of shipping costs. Data analysis techniques such as discrete choice and MCDM models could aid future research by investigating stakeholders' perspectives regarding influential decision-making factors and the potential of Arctic shipping (Moon et al. 2015; Shyu and Ding 2016; Benedyk and Peeta 2016; Wang, Zhang et al. 2018; Tseng and Cullinane 2018; Jiang et al. 2018; Fu et al. 2018; Song et al. 2019; Sur and Kim 2020; Ma et al. 2021).

2.7 Discussion and concluding remarks

The number of comparative studies on Arctic shipping has grown considerably during the last ten years. Lasserre (2014) and Lasserre (2015) provided a review of studies reporting on the feasibility of the Arctic routes, and Meng et al. (2016) surveyed the literature concerning economic and navigational aspects. Ng et al. (2018) provided a literature review on climatic, physical, economic, environmental and social issues of Arctic shipping, whilst Panahi et al. (2021) reviewed the Arctic-related port literature.

This chapter provides the first systematic literature review on comparative studies between Arctic and traditional routes. An evaluation of the literature reporting results on economic and environmental assessments of the Arctic routes is attempted, based on journal articles published between 1980 and 2021. Further, the methodological characteristics of the reviewed papers are identified and analysed. Important factors are identified and discussed, concerning transport systems (bulk, liner, specialised shipping), cost premiums and related factors (crew, insurance, repairs and maintenance, capital costs, periodic maintenance, fuel consumption, speed on ice, icebreaking fees), revenue-related factors (speed on ice, ship size, ice class, dwt utilisation/load factors, in-transit inventory costs, freight rates), navigational factors (route choice, navigation season, speed on ice), and environmental factors (emissions regulations, alternative fuel types, emissions assessment approaches).

The results of this review suggest that Arctic routes are considered more competitive than traditional routes in 15 of the 44 papers which assess their economic potential. On the other hand, they are found to be less competitive in 11 papers, whereas 21 papers report mixed results, depending on the assumptions of the basic scenarios. The Arctic routes are shown to be competitive in nine out of 14 papers that consider single or round voyages, as well as in one paper where the time frame is not defined explicitly. On the other hand, two papers find the NSR uncompetitive, whereas three papers report mixed results. When it comes to papers that consider seasonal operations, two find the Arctic routes uncompetitive, whereas two find them to be competitive, with the rest three reporting that these are more competitive than other routes in specific trades and/or scenarios. The competitiveness of Arctic routes decreases when moving towards year-round operations. More specifically, the Arctic routes are shown not to be competitive in four out of eight papers that consider year-round operations, with the rest four reporting mixed results. Moreover, most of the papers concluding that the Arctic routes are competitive in specific trades or scenarios, assume annual combined NSR/Traditional Routes schedules (11 out of 17). Of these 17 papers, 13 refer to liner shipping with the rest four evaluating bulk or specialised shipping sectors. In contrast, Arctic routes are found competitive in most of the studies that assume round or single voyages, mainly for bulk or specialised shipping. This means that under the current winter navigational and climatic conditions they could serve mainly as seasonal alternatives for a limited period of about five months rather than offering regular access to ships on an annual basis. Consequently, Arctic routes appear to be more suitable for bulk and/or specialised shipping rather than liner shipping in the short to medium-term.

14 studies assess emissions comparing the Arctic with traditional routes, with five papers concluding that Arctic routes are more energy efficient than their traditional rivals, whereas three find that energy efficiency depends on certain assumptions and scenarios, including load factors, ship size, fuel consumption and transit times on ice, distance, transit fees between competing routes, and ship network and allocation of ships between competing routes. The use of GWP factors in the emissions analysis increases the complexity of estimating emissions and environmental costs, especially when comparing transport routes against alternative fuel types and at different time frames. The adoption of emissions taxes favours the use of shorter routes,

and as a result, Arctic routes are advantaged. Yet, the use of fuels in the Arctic which are more expensive than those used in competing routes reduces the competitiveness of Arctic routes.

The findings serve as evidence to inform transport practitioners who operate or willing to operate in the Arctic regarding cost, revenue, and navigational factors, as well as factors related to alternative fuel types, and emissions assessment approaches. Moreover, they provide an understanding of the factors that promote or hinder the competitiveness of the Arctic routes, why and how. The systematic literature review identified several issues that could be addressed in future research. These relate to both research and methodological aspects. Future research could consider route comparisons of the NWP, the TSR and variations of the NSR, as well as other routes, such as the Trans-Siberian Railway and the New Eurasian Land Bridges, and other established or future trade routes. Attention should be paid to revenue attributes, commodity and fuel prices, alternative fuel types and technologies, and how these factors along with Arctic sea ice conditions affect the feasibility of the Arctic routes. More model-based research with robust sensitivity analysis is needed in order to overcome discrepancies in the assumptions regarding cost variables. As regards navigational factors, future research could take into account studies reporting research on climate modelling and variations in Arctic sea ice, the relationship between ice thickness, ship speed, and icebreaker assistance, and the relationship between fuel consumption and sea ice. Sea ice conditions as well as other physical constraints, such as regional bottlenecks, are critical factors that affect the speed or ship size used on Arctic waters, which in turn can affect revenue, transit times, operating and voyage costs, as well as the overall competitiveness of the Arctic routes. Emissions and environmental assessment modelling should focus on GWP factors apart from fuel consumption conversions, on alternative fuel types and technologies, as well as on different scales (e.g. ship/fleet, number of ships per voyage/season/year).

The literature focuses mainly on liner shipping and, to a lesser extent, on bulk shipping. However, bulk (liquid, dry) and specialised shipping (LNG, reefer) will mostly benefit from Arctic routes in the short to medium-term. For liner shipping, more emphasis could be given to network structure/configuration and/or reconfiguration of the existing networks as part of scenario-based modelling approaches.

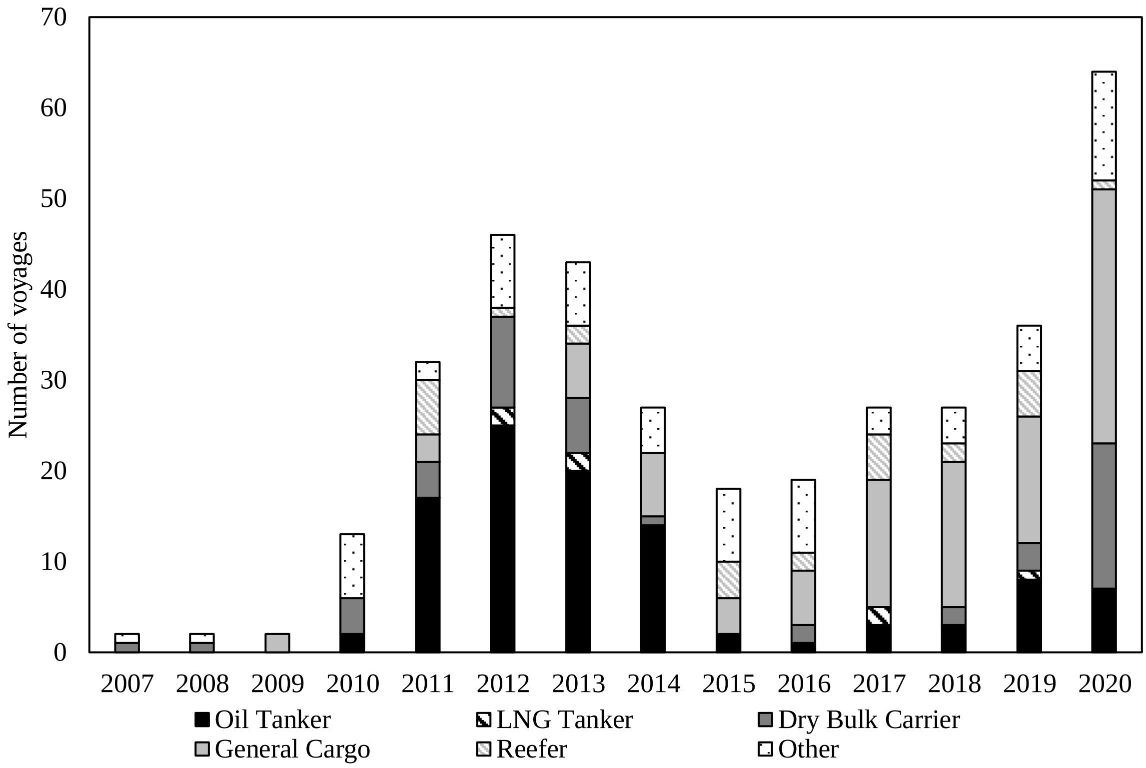
Analytical mathematical methods dominate the literature with empirical statistical research and case study research being used to a lesser extent. With regards to data analysis techniques, the literature shows a particular preference for scenario-based transport cost models. As a relatively new topic in maritime transport literature, Arctic shipping research could be addressed by many methodologies and data analysis techniques used in the social sciences, namely, operational research, case studies, econometric modelling, regression and panel data analysis, as well as discrete choice and MCDM techniques amongst others.

The systematic literature review included studies reporting on cost and emissions assessments of Arctic routes. However, the Arctic shipping literature spans several research areas and topics. A broader review of the literature could include conceptual and descriptive studies, surveys, as well as studies focusing on factors other than costs/profits, such as time/distance effects, ice class ship evaluation, or the overall environmental impact of future shipping traffic volumes in the Arctic.

2.8 Research gaps and Research questions

The choice of the NSR for route comparisons in most of the reviewed papers reflects real practices. Although there have been some exploratory transit voyages by deep-sea cargo ships on the NWP during the last decade, the NSR has been the main route choice for exploratory voyages between Europe, the Arctic, Asia and North America since 2011. This is attributed to the more favourable sea ice conditions along the NSR than on other parts of the Arctic, Russia’s ambitions to develop and promote the NSR, as well as ongoing infrastructure and project developments in the Russian Arctic.

The literature is mainly focused on comparisons between Arctic and traditional routes against liner shipping, and more specifically on containerships. The number of studies reporting results on the competitiveness of Arctic routes against liner shipping dominate the literature (30 papers), compared to studies focusing on bulk (14 papers) and specialised shipping (2 papers). However, container shipping operations require seasonal or annual schedule planning, which is not feasible owing to the presence of sea ice, especially during the current winter/spring navigation season between December to June. Moreover, factors such as revenue-generating port calling, high load factors, and schedule reliability are not satisfied. This is largely confirmed by the results of the systematic review, where Arctic routes are found competitive in most of the studies that assume round or single voyages, mainly for bulk or specialised shipping. These findings are in line with traffic statistics between 2007 and 2020. Figure 2.7 shows the number of transit and destination voyages conducted on the NSR during the summer/autumn seasons (July-November) of 2007-2020. These records include voyages conducted between the Atlantic and the Pacific Ocean through the Arctic (transit traffic), and voyages that originated or terminated within or outside the Arctic (destination traffic).



Sources: NSRA (2016), CHNL (2021a), Bloomberg (2021), Refinitiv Eikon (2021). Note: Other: Non-commercial ships.

Figure 2.7. Number of voyages conducted on the NSR during the summer/autumn seasons of 2007-2020.

Tanker and dry bulk carrier voyages dominated traffic during 2011-2014, whereas general cargo and heavy lift ship voyages comprised most of the traffic during 2017-2020. Yet, dry bulk carrier voyages re-emerged in 2020 amongst others. There has been only one transit of a small containership throughout this period, whilst containers have been only part of the cargo of general cargo ship voyages (Lasserre et al. 2020; Gunnarsson and Moe 2021). Overall, traffic on the NSR rose steeply during 2010-2013, dropped in 2015-2016, gradually increased in 2017-2019, and reached record levels in 2020.

Although the share of each ship type varied throughout this period, there is a distinctive trend across shipping sectors. On the one hand, the share of general cargo and heavy lift ship voyages has gradually increased since 2014 and has remained relatively stable until 2020. Similar observations can be made for other sectors, such as the reefer and the LNG tanker sectors, although records remain low[9]. On the other hand, the share of oil tanker voyages and, to a lesser extent, that of dry bulk carriers, fluctuated considerably between 2011 and 2020. More specifically, the share of oil tanker destination and transit voyages was 53% in 2011, 54% in 2012, 47% in 2013, and 52% in 2014 of the total, whereas it comprised only an average 12% of the total between 2015 and 2020.

Favourable sea ice conditions and distance savings explain only part of the surge in exploratory voyages through the NSR during the last ten years. Other factors, such as the nature of the transport system, geopolitical developments, certain cost and market factors, and commodity price developments, largely determine route choice. General cargo and heavy lift cargo ships are benefitted by using the NSR for voyages between east and west, and this is explained by the consistent use of the route during the last four years. Equally, the use of the NSR for cargoes originating from the Arctic considerably reduces distances for destinations in the Far East, depending on the nature of cargo.

However, commodity price developments, arbitrage opportunities, and geopolitics largely affect route choice for energy commodities along with cost factors, such as marine fuel prices. The marked difference in the number of destination and transit tanker voyages through the NSR between the periods 2011-2014 and 2015-2020 reflects the volatility in commodity and fuel markets, as well as other developments that impacted oil products flows and ultimately route choice from a global perspective. Therefore, this Thesis is focused on the assessment of the NSR against the oil product tanker market, taking into account historic destination and transit traffic records, and developments in the global shipping and energy markets. This Thesis aims to explain the emergence of the NSR as an alternative route for oil product tankers during 2011-2020. Moreover, it aims to explain the economic, navigational and environmental factors which affect its use compared to traditional sea routes between Europe and Asia.

[9] The number of LNG tanker destination voyages has increased since 2017 owing to LNG exports from Yamal LNG. Yet, traffic records from CHNL do not report all of them.

The following **Research Questions** are formulated in order to address the aim of the modelling research of the Thesis:

1. **Why did the NSR emerge as an alternative route for oil product tankers between Europe and Asia since the 2010s?**

Whilst liner shipping economics dominate the Arctic shipping literature, there are a growing number of studies assessing tanker economics from various angles and factors, including economies of scale (Zhang et al. 2016; Wang et al. 2020), seasonal (Song and Zhang 2013) or combined SCR/NSR annual navigation (Von Bock und Polach et al. 2015; Faury, Cheaitou et al. 2020; Keltto and Woo 2020), the impact of sea ice on voyage economics (Von Bock und Polach et al. 2015; Faury and Cariou 2016; Faury, Cheaitou et al. 2020), as well as the impact of emissions taxes and environmental regulations (Keltoo and Woo 2020). The extant literature investigates whether the NSR is a competitive alternative under specific conditions and certain periods of time. However, there have not been studies that aimed to explain quantitatively why the NSR emerged as an alternative route for oil product tankers since the 2010s, and how cost and market factors affected its use between 2011 and 2020. Moreover, crucial economic factors which are coupled with inherent strategic and geopolitical issues encompassing the tanker trades and affect routeing patterns have not been addressed.

2. **How do cost and market factors affect the use of the NSR for oil product tankers?**

Currently, there is a very limited understanding as to how fuel price levels, icebreaking fees, and ship size affect the use of the NSR in the context of oil tanker shipping. Furthermore, distances based on both historic voyage patterns and major oil products flows have not been explored. The impact of commodity prices and in-transit inventory costs have not been addressed. Moreover, route choice in the wider context of oil products trades has not been considered.

3. **How does ship speed on ice affect the feasibility of the NSR for oil product tankers?**

Whilst the sea ice – ship speed dependency has been thoroughly investigated by employing historic sea ice thickness data to determine tanker speeds on the NSR (Faury and Cariou 2016; Faury, Cheaitou et al. 2020), there have not been studies that used data regarding ship speed on ice from actual tanker voyages conducted on the NSR, and therefore providing an alternative approach to the literature.

4. **How do different approaches to ship speed choice and cost modelling affect the feasibility of the NSR for oil product tankers?**

As regards the methodological perspectives, there have not been any studies on tanker shipping that employed ship speed optimisation in the modelling approach. Further, speed data reflecting real practices have not been considered, with tanker design speeds being the default assumption in all studies. Moreover, all papers rely on data from previous studies regarding operating and capital cost factors, and most of the secondary data used in the literature are not up-to-date.

5. **How do emissions regulations and alternative operational modes and fuel types affect the feasibility of the NSR compared to the traditional routes for oil product tankers?**

Although the use of LNG as an alternative fuel type is considered in recent studies concerning liner shipping (Ding et al. 2020; Xu and Yang 2020), the literature on tankers has so far focused only on the use of Very Low Sulphur Fuel Oil (VLSFO) (Keltoo and Woo 2020; Wang et al. 2020). Moreover, there have not been studies that considered the future ban on the use of heavy fuel oils in the Arctic (IMO 2020).

3. Methodology

This chapter presents the methodology used to address the research questions of the Thesis. The Research Philosophy is outlined, which includes the Ontology, Epistemology, Axiology, and the Approach to Theory. The Research Design, Research Strategy, Nature of the Research, and Data Analysis Techniques are then described. The Quality of the Research Design is described and ways of addressing Reliability, Validity and Ethics of the research design of this Thesis are presented. The fundamental relationships between costs and output are presented drawing from classical microeconomic theory of costs. Cost and profit functions, and optimal levels of output are described analytically, drawing from classical maritime economics theory. Finally, the modelling approach is outlined and the modelling cases are presented.

3.1 Research Philosophy

The research scheme of this Thesis is informed by Saunders et al. (2019), who provide a guide on research methodology extending from the research philosophy to the data analysis and ethical considerations.

The development of knowledge presupposes certain beliefs and assumptions, both of which constitute the research philosophy of a study. Ontology refers to theories about the fundamental nature of reality, perceptions about the world, and the research objects of a study. Epistemology refers to theories of what is known, and how it is known, in other words, what is acceptable and reliable knowledge. Axiology refers to the ethics and values in research (Saunders et al. 2019; Bell et al. 2019).

The research philosophy of a study naturally leads to a choice of a set of beliefs which guides the researcher throughout the research process, from the ontology and epistemology to the research strategy and data analysis techniques. The two opposing ontologies are those of objectivism and subjectivism. Objectivism adopts the assumptions of natural sciences, where the experiences and interpretations of the researcher do not influence other social actors or the settings in the social world. There is only one reality experienced in the same way by all social actors. Physical phenomena are universal, enduring in character and independent from the social actors' values (Saunders et al. 2019). Subjectivism adopts the assumptions of the arts and humanities. Subjectivity means that perceptions and actions make and shape the social reality, and that there exist multiple realities that are created by social actors, beyond which there is not a universal reality. Subjectivists are interested to research different narratives and views to understand the different social realities, and at the same time they cannot separate themselves from their own values (Saunders et al. 2019).

The ontologies of objectivism and subjectivism refer to the epistemologies of positivism and interpretivism, respectively (Bell et al. 2019). Positivism holds that social phenomena can be observed directly and can be measured to produce law-like generalisations. Interpretivism, which is the opposite of positivism, rejects the assumption that social actors can be researched in the same way as research objects are investigated in natural sciences due to the fact that human beings and their institutions create meanings. These meanings cannot be measured directly assuming a stance outside of the specific context in which they are created and studied (Saunders et al. 2019; Bell et al. 2019). Table 3.1 presents a comparison between the two epistemologies, and respective approaches to Axiology and Methods.

The Approach to Theory is the next step towards building the Research Design and defining the Research Strategy. A basic distinction is made between theory testing and theory building. If the research starts with an established theory, the conclusions are meant to be informed and being valid depending on the premises of the theory. This is a deductive approach to theory. On the other hand, an inductive approach is followed when the conclusions are supported by the observations, since there is a gap between the theory and the initial premises made and the conclusions derived (Saunders et al. 2019). A third approach refers to the abductive approach to theory (retroduction), where the research process moves back and forth between deduction and induction. This approach is initiated by an observation of a ‘surprising fact’, which is investigated further to build theory (Saunders et al. 2019).

Table 3.1. Comparison between Positivism and Interpretivism.

Positivism			
Ontology **(nature of reality or being)**	**Epistemology** **(what constitutes acceptable knowledge)**	**Axiology** **(role of values)**	**Typical methods**
Real External Independent One true reality (universalism) Granular (things) Ordered	Scientific method Observable and measurable facts Law-like generalisations Numbers Causal explanation and prediction as contribution	Value-free research Researcher is detached, neutral and independent of what is researched Researcher maintains objective stance	Typically deductive Highly structured Large samples Measurement Typically quantitative methods of analysis, but a range of data can be analysed

Source: Saunders et al. (2019).

Table 3.1. Comparison between Positivism and Interpretivism (continued).

Interpretivism			
Ontology **(nature of reality or being)**	**Epistemology** **(what constitutes acceptable knowledge)**	**Axiology** **(role of values)**	**Typical methods**
Complex, rich Socially constructed through culture and language Multiple meanings, interpretations, realities Flux of processes, experiences, practices	Theories and concepts too simplistic Focus on narratives, stories, perceptions and interpretations New understandings and worldviews as contribution	Value-bound research Researchers are part of what is researched Subjective Researcher interpretations key to contribution Researcher reflexive	Typically inductive Small samples, in-depth investigations, qualitative methods of analysis, but a range of data can be interpreted

Source: Saunders et al. (2019).

The epistemology of positivism is adopted in this Thesis, which is underpinned by the ontology of objectivism. The research examines the economic feasibility of the Northern Sea Route compared to established sea routes and ship canals. The purpose is to measure economic variables in order to derive conclusions concerning route comparisons for the organisation of the deep-sea oil tanker sector. Mathematical models are employed drawing from classical maritime economics theory. A deductive approach to theory is followed in order to establish generalisations (Blaikie 2011). The generalisability is made from the general to the specific, and data collection and analysis are used to evaluate propositions related to existing theories (Saunders et al. 2019). As regards axiological considerations of the research, the author of this Thesis is impartial against the facts observed, and decisions are based on objective criteria. The facts are value-free, that is, there is not any intervention in the conduct of the research such that could impose a subjective view (Williams and May 1996; Collis and Hussey 2009).

3.2 Research Design, quality and ethical considerations

3.2.1 Research Design

The research design can be defined as a broad plan of how to answer the research questions of the Thesis (Saunders et al. 2019). Bell et al. (2019) who use the term ‘research strategy’ instead of ‘research design’ refer to it as a ‘general orientation’ to the conduct of research. Saunders et al. (2019) emphasise on the clear objectives contained in the research design, which are derived from the research questions, the specification of sources, the data collection and analysis procedures, the ethical considerations, as well as the constraints and limitations throughout the conduct of the research process (access to data, time, funding, location).

The three main types of research design are the quantitative research design, the qualitative research design, and the mixed-methods research design. Although different types of data can be used and analysed by adopting any of these research designs, a basic distinction is made between numeric data and non-numeric data (such as words, images, recordings) (Saunders et al. 2019). Numeric data are generally used in a quantitative research design and non-numeric data are used in a qualitative research design. Further, a quantitative research design is typically associated with positivism and a deductive approach to theory. Equally, a qualitative research design is typically associated with interpretivism and an inductive approach to theory. According to Saunders et al. (2019), these classifications should not be too rigid since quantitative research could adopt an inductive approach to theory and vice versa. Similarly, quantitative research designs may be used under an interpretivist epistemology. The basic distinction is between data that relate to the attributes of research objects (things, people, organisations), and data that are derived from peoples’ opinions (Saunders et al. 2019). Further distinctions could be made based on the number of data analysis techniques used in a research. A mono-method study refers to a single data analysis technique, whereas a multi-method study to more than one techniques of the same nature, that is, quantitative only or qualitative only (Saunders et al. 2019). The multi-method research design should not be confused with the mixed-methods research design, which is a mix of both quantitative and qualitative research (Creswell and Creswell 2017).

Two distinctive research designs are adopted in this Thesis. A research design based on a systematic literature review and a multi-method quantitative research design. The first design refers to the systematic review of the literature. The second design refers to the development of cost models, and the use of optimisation techniques, secondary data sources, and email communication.

3.2.2 Quality of the research design

A brief introduction to concepts and measures is provided before proceeding to the definitions of validity and reliability. According to Bailey (1994), a concept is defined as a mental image or perception, a variable is a concept which can take on more than one value along a continuum, whereas a constant is a concept which has only a single, fixed, value. Variables are usually numbers but can also have categories signified by words (Bailey 1994). Bell et al. (2019) define concepts as the building blocks of theory in business research. Some of the concepts they mention are structure, agency, productivity, competitive success, organisational development, knowledge, and employment relations amongst others. A measure is a number assigned to a concept or variable (Bailey 1994). In this Thesis, the Required Freight Rate is the measure used to capture the concept of cost effectiveness.

Measurement in quantitative research reflects the ontology of objectivism and the epistemology of positivism. More specifically, it reflects that there exists an external reality and in order to develop acceptable and reliable knowledge, social phenomena should be observed directly and measured. According to Bell et al. (2019), a measure allows the identification and distinction of *fine differences* between entities related to the research enquiry. It is a *consistent device* to make such distinctions even if a concept varies in time. It also enables *more precise estimates of the degree of relationship* between concepts.

Measurement is closely related to the notions of validity and reliability. More specifically, when a concept is employed in quantitative research, it has to be measured. The quality of scientific enquiry is of particular importance for a research design. According to Saunders et al. (2019), reliability and validity determine the quality of a research in quantitative research in the social sciences. *Validity* refers to the integrity of research, its processes and conclusions, the appropriateness of the measures applied to concepts, either variables or constants, and the generalisability of the findings (Bell et al. 2019; Saunders et al. 2019). *Reliability* refers to consistency and replication (Saunders et al. 2019).

There are three main categories of validity, namely, measurement validity, internal validity and external validity. *Measurement validity* is concerned with whether the measures employed in the research to examine a concept actually measure what they are intended to measure. There are several ways to address measurement validity in a quantitative research (Bailey 1994; Bell et al. 2019; Saunders et al. 2019). Different ways may apply to different methods/strategies or data analysis techniques employed in a research. This Thesis focuses on measurement validity ways which are appropriate for cost modelling and optimisation techniques, secondary data sources, and email communication. These include face validity, content validity, and criterion validity (concurrent and predictive validity). *Face validity* refers to whether a measure reflects the content of a concept, in other words whether a measure appears to make sense (Bell et al. 2019; Saunders et al. 2019). *Content validity* refers to whether a measure provides adequate coverage of the research questions (Saunders et al. 2019). Criterion validity refers to whether a measure is valid for measurement of a concept either in the present (*concurrent validity*) or in the future (*predictive validity*) (Bailey 1994).

Internal validity refers to whether the findings of a research are attributed to the methods, data analysis techniques and assumptions used rather than other, irrelevant factors (Bell et al. 2019; Saunders et al. 2019). In particular, internal validity in quantitative research refers to the validity of causal relationships between variables (Bell et al. 2019). *External validity* refers to the generalisability of the findings of a research to other relevant research contexts (Bell et al. 2019; Saunders et al. 2019). *Ecological validity* refers to the applicability of the findings in natural occurring social settings, in other words, in the real world (Bell et al. 2019). Internal validity, external validity and ecological validity are addressed in the research design of this Thesis.

Another way to address validity is validation. According to Saunders et al. (2019), *validation* refers to verification of data, methods, and findings in order to establish that these are valid, credible and authentic. Saunders et al. (2019) describe two validation techniques, namely, triangulation and participant or member validation. *Triangulation* refers to the use of more than one source of data and/or data analysis techniques in order to confirm that the data, and data collection methods are valid, credible and authentic. They propose the use of a multi-method quantitative study, multi-method qualitative study or a mixed methods study in order to achieve the purpose of triangulation. *Participant* or *member validation* refers to the procedure of sending the collected research data to the informants in order to confirm that they are accurate and valid by allowing them to make comments and corrections. Triangulation and participant validation are addressed in the research design of this Thesis.

Reliability is further categorised in internal and external reliability based on the premises of consistency and replication, respectively. *Internal reliability* refers to consistency and stability in a research. *External reliability* refers to replication by using the same methods, data analysis techniques, and assumptions to reproduce the research and obtain the same findings (Saunders et al. 2019). This Thesis focuses on reliability ways which are appropriate for cost modelling and optimisation techniques, secondary data sources, and email communication. These include internal reliability, external reliability, and the use of 'alternative form' (Saunders et al. 2019). The *alternative form* refers to the comparison of informants' responses to alternative forms of the same question or questions (Saunders et al. 2019).

As regards cost modelling and optimisation techniques, the validity is considered by using the criteria of internal and external validity, ecological validity, face validity, content validity, and criterion validity (concurrent and predictive validity). Reliability is considered by addressing internal reliability and external reliability. Moreover, validation is considered by employing triangulation.

As regards secondary data sources, one needs to consider the overall suitability of the data to the research questions and objectives. The overall suitability is considered by addressing measurement validity and coverage (Saunders et al. 2019). Measurement validity is established by any of the ways mentioned above. *Coverage* concerns to what extent the secondary data cover the population and time period about which the data are needed, and whether they contain data variables that enable answering the research questions (Saunders et al. 2019). Moreover, one needs to consider the precise suitability of the data for data analysis. The precise suitability is established by addressing validity and reliability, and measurement bias (Saunders et al. 2019). *Measurement bias* occurs due to deliberate distortion of data, either on purpose or for other reasons. It can also occur due to changes in the way the data are collected, or when the data analysis techniques developed to collect, compile or analyse the secondary data do not truly measure the concepts (Saunders et al. 2019). Finally, the costs and benefits of obtaining and using secondary data sources are evaluated (Saunders et al. 2019). *Costs* refer to both time and financial costs needed to locate and obtain the data. *Benefits* from using the secondary data refer to the extent to which they will enable answering the research questions and meet the research objectives (Saunders et al. 2019). Moreover, validation is considered by employing triangulation.

Appropriate ways to address validity and reliability of email communication relate to those applied in questionnaires. These include face validity, content validity, and criterion validity (concurrent and predictive validity) (Saunders et al. 2019). Moreover, validation is considered by addressing participant validation. Reliability is considered by using the 'alternative form' (Saunders et al. 2019).

The validity and reliability of measures employed to capture concepts are very important in quantitative research. This is especially true for newly developed measures. Yet, researchers also employ measures which have already been validated in previous research and collect data on concepts which have been investigated in previous research. According to Bell et al. (2019), if a measure is not reliable, then it is not valid. More specifically, if a measure is not consistent over time, it lacks validity.

The analysis in this Thesis is informed by undertaking a systematic review of the literature, which provides deep insights as to what works, how it works, and whether certain methods are the most appropriate for what is being studied.

The highly structured nature of the research enquiry by means of employing mathematical models and logic, which are commonly used to address the problem under investigation in the area of maritime economics, establishes the internal validity and measurement validity of the modelling research of this Thesis. The use of authoritative secondary data sources ensures the internal reliability and the external reliability, along with the consistency and replicability of the modelling approach. Moreover, the measurement validity is significantly improved by using unique primary data and insights from a shipowner who conducted a considerable number of destination and transit oil product tanker voyages on the Northern Sea Route in 2011-2020.

Notwithstanding the small number of destination and transit tanker voyages conducted on the Northern Sea Route so far, the primary and secondary data obtained enhance the quality of the research design and establish the ecological validity of the findings. The research findings are derived from a coherent and applied methodology, the uniqueness of the data employed, the validation procedures applied and the quality of the research design. The research findings ensure the external validity, that is, the generalisability of the findings, to organisations of similar characteristics, given the global nature of shipping and the way market developments affect all market participants. Tables 3.2 and 3.3 present the quality criteria of validity and reliability employed in the research design of this Thesis, and the ways these are addressed. The quality criteria and processes employed refer to Saunders et al. (2019) and Bell et al. (2019).

Table 3.2. Quality criteria of Validity employed in this Thesis.

Quality criterion	Cost modelling and optimisation	Secondary data sources	Email communication
Face Validity	Required Freight Rate (RFR) approach is a well-established way for route comparisons and break-even analysis of operations RFR modelling is informed by the literature (academic and industry literature)	Secondary data appear to reflect the content of the variables Secondary data are relevant The reputation of the organisations further enhances face validity	Primary data appear to reflect the content of the variables Primary data are relevant The tanker shipowner who provided primary data conducted a considerable number of destination and transit oil product tanker voyages on the Northern Sea Route in 2011-2020 This further enhances face validity
Content Validity	RFR models contain all variables required for cost assessment and comparison	Secondary data sources provide data variables which enable the adequate coverage of the research questions	The list of survey questions contains questions which enable the adequate coverage of the research questions of the Thesis The survey questions are formulated based on careful definition of the research and drawing from both the academic and industry literature
Criterion Validity (Concurrent and Predictive Validity)	RFR models are used in the research to establish past, present, and future cost assessments Basic Scenarios and Sensitivity Analysis provide or predict outcomes based on past, present, and future conditions	Secondary data sources provide data variables and timeseries which enable the measurement of variables in the past and present Measurement for predictions depends on data analysis techniques, scenarios, and sensitivity analyses, which the secondary data inform	Primary data sources provide data which enable the measurement of variables in the past and present Measurement for predictions depends on data analysis techniques, scenarios, and sensitivity analyses, which the primary data inform

Table 3.2. Quality criteria of Validity employed in this Thesis (continued).

Quality criterion	Cost modelling and optimisation	Secondary data sources	Email communication
Validation (Triangulation and Participant Validation)	Triangulation: Multi-method research design which includes four data analysis techniques Authoritative sources from both the academic and industry literature are used to develop valid cost modelling approaches	Triangulation: Several secondary data sources are used to confirm the validity of the data and comparisons are made across databases and other sources These data sources refer to cost, market, and navigational factors	Triangulation: The tanker shipowner who provided primary data conducted a considerable number of destination and transit oil product tanker voyages on the Northern Sea Route in 2011-2020 Participant validation: Data were sent to informant for further validation and amendments, if any
Internal Validity	RFR approach is a well-established way for route comparisons and break-even analysis of operations in both theory and practice Explanatory variables are valid for cost assessment in the context of route comparison	Procedures used to collect, compile or analyse the data cannot be confirmed Data analysis techniques are assumed to truly measure the concepts, given the reputation of the organisations	N.A.
External Validity	The findings are generalisable to organisations of similar characteristics High level of generalisability to other contexts and organisations if relevant data are used	Secondary data can be used in research in order to generalise to organisations of similar characteristics	N.A.
Ecological Validity	Findings are validated and confirmed by NSR traffic records in 2011-2020	Secondary data are collected from naturally occurring social settings	N.A.

Table 3.2. Quality criteria of Validity employed in this Thesis (continued).

Quality criterion	Cost modelling and optimisation	Secondary data sources	Email communication
Overall suitability (Coverage and Measurement Validity)	N.A.	Coverage: Secondary data cover the population about which the data are needed Time period varies for some of the data variables but not very significantly Data variables enable answering the research questions Unwanted data can be excluded Sufficient data remain for analysis after unwanted data are excluded in all cases Measurement validity referring to overall suitability are presented in the respective fields of this Table	N.A.

Table 3.2. Quality criteria of Validity employed in this Thesis (continued).

Quality criterion	Cost modelling and optimisation	Secondary data sources	Email communication
Precise suitability (Validity and Reliability)	N.A.	Validity and reliability referring to precise suitability are presented in the respective fields of this Table	N.A.
Precise suitability (Measurement bias)	N.A.	Purpose of secondary data collection and compilation is for use by researchers, market participants, policy makers, academics Measurement bias from deliberate distortion of data: This type of measurement bias is difficult to detect Triangulation with other independent sources to ensure validity, where a high degree of confirmability is achieved Changes in the way data are collected or measured: This type of measurement bias is difficult to detect Use of the same source for same data is consistent throughout the methodological process and calculations to ensure consistency and avoid discrepancies Documented changes did not report any changes in the way data are collected or measured	N.A.

Table 3.2. Quality criteria of Validity employed in this Thesis (continued).

Quality criterion	Cost modelling and optimisation	Secondary data sources	Email communication
Precise suitability (Measurement bias) (continued)	N.A.	Appropriateness of the data analysis techniques developed to collect, compile or analyse the secondary data to be able to truly measure the concepts This type of measurement bias is difficult to detect Data analysis techniques are assumed to truly measure the concepts, given the reputation of the organisations Triangulation with other independent sources to confirm validity, where a high degree of confirmability is achieved	N.A.
Cost and Benefits	N.A.	Financial costs to obtain most of the data were low Most databases and sources are available by the University Time taken to locate and obtain the data is short Significant benefits derived from obtaining and using the data Secondary data enable answering the research questions Familiarity of type and user-friendly type of data files: Microsoft Word Microsoft Excel Overall benefits significantly outweigh the costs to locate and obtain the data	N.A.

Table 3.3. Quality criteria of Reliability employed in this Thesis.

Quality criterion	Cost modelling and optimisation	Secondary data sources	Email communication
Internal Reliability	Use of Microsoft Excel software ensures consistency of calculations Stability is promoted by writing detailed accounts of the methodological procedure Calculations are checked and repeated at different time periods to avoid flaws and mistakes	Procedures used to collect, compile or analyse the data cannot be confirmed Procedures are assumed to be rigid and accurate, given the reputation of the organisations	N.A.
External Reliability	Employment of replication by using the same methods, data analysis techniques and assumptions to compare new findings with initial ones	Survey data and large data from everyday market transactions are considered reliable and credible, given the reputation of the organisations	N.A.
Alternative form	N.A.	N.A.	Data collection is repeated at different time periods to confirm consistency Questions referring to same data are repeated or asked in alternative form

3.2.3 Ethical considerations of the research design

As regards ethical considerations, the author of this Thesis complies with the rules and good academic conduct as these are defined by Cardiff University. Further, the author complies with the rules and code of ethics defined and operationalised through the ethical review of the research proposal and the research enquiry. Anonymity, integrity, responsibility, and confidentiality are addressed by the author and are of utmost importance throughout the research process.

The ethical considerations extend to include aspects of all data analysis techniques employed in this Thesis. As regards sources related to cost modelling and optimisation, all relevant academic and industry literature is cited throughout the Thesis and full references are provided in the reference list. The same also applies for all sources used during the conduct of the research. All secondary data were obtained ethically through the use of relevant databases provided by the University. The access to secondary data is allowed and no permission is required to obtain the data. Moreover, personal data related to assistance or when requesting further information and clarifications on the secondary data are anonymised.

Consent forms are provided to the participants of this research regarding email communication, where the aims of the study are clearly defined and confidentiality and anonymity is ensured concerning any commercial data and other related data to be collected and analysed. A consent form is provided in Appendix I, based on which data were obtained by a shipowner of ice class oil product tankers who conducted a considerable number of destination and transit voyages on the Northern Sea Route in 2011-2020. There is no relationship between the author of this Thesis and the primary and secondary sources from which these data were obtained. Table 3.4 presents sources of primary and secondary data, and sources related to methodological aspects of this Thesis. Table 3.5 presents the ethical aspects considered in the research design of this Thesis.

Table 3.4. Sources of primary and secondary data and sources related to methodological aspects of this Thesis.

Data	Sources
Distances	Dataloy (2021), Mulherin (1996)
Operating Costs	BDO (2021)
Capital Costs	Evans and Marlow (1990), Solakivi et al. (2018), Sovcomflot (2018), Riviera (2020), The Motorship (2020b), Clarksons (2021)
Cost Premiums	Tanker Company (2018), Tanker Company (2019), Tanker Company (2020)
Fuel Prices, Commodity Prices	MAN Energy Solutions (2018), BP (2020), SEA LNG (2020), Capital IQ (2021), Refinitiv Eikon (2021), OPEC (2021), DNV (2021c)
ICE Gasoil Futures Prices	Bloomberg (2021)
Oil Products Trade Data	IEA (2021c)
Transit Fees (Canal Tolls and Icebreaking Fees)	Falck (2012), NSRA (2014), Gritsenko and Kiiski (2016), Tanker Company (2018), Leth Agencies (2021a), Leth Agencies (2021b), Leth Agencies (2021c), Bank of Russia (2021), IMF (2021a), IMF (2021b), ARCTIS (2021c)
Interest Rates	Alizadeh and Nomikos (2009), Giannakoulis (2016), Petrofin (2017), FED of St. Louis (2021)
Voyage and Speed Records	NSRA (2016), Clarksons (2021), Refinitiv Eikon (2021), Bloomberg (2021), CHNL (2021a), CHNL (2021b), ARCTIS (2021a)
Tanker Characteristics	MAN Diesel and Turbo (2013a), MAN Diesel and Turbo (2013b), MAN Diesel and Turbo (2013c), Trafi (2017a), Clarksons (2021)
Port Characteristics	IHS Maritime (2015)
LNG Infrastructure Characteristics	DNV (2021b), Clarksons (2021)

Table 3.4. Sources of primary and secondary data and sources related to methodological aspects of this Thesis (continued).

Methodology	Sources
RFR modelling approach	Metaxas (1971), Alderton (1981), Goss et al. (1982), Evans and Marlow (1990), Barrass (2004), Dykstra (2005), McQuilling (2012), MAN Diesel and Turbo (2013a), ICS (2014), ICS (2015), Fagerholt and Psaraftis (2015), Fagerholt et al. (2015), Lindstad and Eskeland (2015), Shibasaki et al. (2018), Solakivi et al. (2018), Psaraftis and Kontovas (2014), IMO (2016a), IMO (2018), Fulwood (2019), IMO (2020), IMO (2021), Heather (2020), BP (2020), IGU (2020), Clarksons (2021)
Speed upper and lower limits	Lindstad et al. (2011), Trafi (2017a)
Fuel Consumption function and related factors	Barrass (2004), Psaraftis and Kontovas (2013), MAN Diesel and Turbo (2013a), MAN Diesel and Turbo (2013c), Psaraftis and Kontovas (2014), Solakivi et al. (2018), Riviera (2018), Tanker Company (2019), MAN Energy Solutions (2019a), MAN Energy Solutions (2019b), MAN Energy Solutions (2020), The Motorship (2020b), MAN Energy Solutions (2021), Clarksons (2021), DNV (2021a)
Tonnes per Centimetre Immersion (TPC) estimation	Barrass (2005), Stopford (2009), MAN Diesel and Turbo (2013a), MAN Diesel and Turbo (2013c)
Fuel and Energy-related Conversions and Factors	IMO (2016b), Platts (2017a), Platts (2017b)

Table 3.5. Ethical aspects considered in the research design of this Thesis.

Cost modelling and optimisation	Secondary data sources	Email communication
All sources used in the research process are cited throughout the Thesis and are provided in the reference list	All data are obtained ethically No permission required to obtain the data There is no relationship between the author of this Thesis and the sources from which data were obtained Personal data related to assistance or when requesting further information and clarifications on the secondary data are anonymised	All data are obtained ethically There is no relationship between the author of this Thesis and the sources from which data were obtained Data obtained via email communication are anonymised Compliance with the rules and good academic conduct as these are defined by Cardiff University Compliance with the rules and code of ethics defined and operationalised through the ethical review of the research proposal and the research enquiry Consent forms are provided to the participants Aims of the study clearly defined and confidentiality and anonymity ensured concerning any commercial data and other related data A consent form is provided in Appendix I

3.3 Nature of the Research

According to Saunders et al. (2019), the purpose of a research can be either exploratory, explanatory, descriptive or evaluative. It can also be any combination of these purposes. Exploratory research refers to the exploration of a topic, a conduct of literature searches or unstructured interviewing. Descriptive research intends to describe research objects, situations, data, or people. It can be regarded as an intermediate step between an exploratory study and an explanatory study. Explanatory research aims to establish causal relationships and explain relationships between variables. Evaluative research aims to investigate what works and how well it works (Saunders et al. 2019).

A combined research purpose is adopted, which is reflected in the exploratory, evaluative and explanatory nature of each research stage of this Thesis (Saunders et al. 2019). The exploratory stage refers to the preliminary scoping searches of studies to be included in the systematic literature review. The evaluative stage refers to the systematic literature review, which aims to find what works and how it works and is concerned with the economic and environmental efficiency of the Arctic sea routes. The explanatory stage refers to modelling research, where highly structured data analysis techniques are used to explain relationships between transport costs and other economic variables.

3.4 Research Strategy

A research strategy is a plan to answer the research questions and constitutes a methodological link between the research philosophy and choice of data analysis techniques (Saunders et al. 2019). Bell et al. (2019) who use the term ‘research design’ instead of ‘research strategy’ refer to it as a framework for data collection and analysis. Positivism and quantitative research dominate maritime economics literature (Woo et al. 2013; Shi and Li 2017). Mathematical analysis and economic analysis are found to be amongst the prevalent research strategies in maritime economics research (Woo et al. 2013; Talley 2013). Woo et al. (2011) reports similar findings regarding seaport research, with positivism being by far the dominant epistemology, whilst mathematical research strategy ranks high amongst the research strategies adopted in the literature.

Wacker (1998) distinguishes between analytical and empirical research strategies. He refers to them as ‘types of theory-building research’, whilst Woo et al. (2011) who uses Wacker’s scheme calls them ‘research strategies’. The terms ‘method’ and ‘strategy’ can be used interchangeably, given that Saunders et al. (2019) and Wacker (1998) use these terms to define the same concept[10]. The term 'method' is also used in the categorisation scheme of research methods identified in the systematic literature review of this Thesis. According to Wacker (1998), analytical research can be further categorised between analytical conceptual, analytical mathematical, and analytical statistical. Empirical research can be further categorised between empirical experimental, empirical statistical, and empirical case study.

A systematic literature review strategy and an analytical mathematical research strategy are adopted in this Thesis (Dickson et al. 2017; Saunders et al. 2019). The systematic review strategy is used to synthesise and evaluate the body of comparative studies on Arctic shipping according to specific procedures and criteria. The analytical mathematical research strategy is used to develop models in order to study how relationships between variables behave under different conditions (Wacker 1998). More specifically, the type of analytical mathematical research strategy adopted in this Thesis is *descriptive (positive)* analytical modelling (Meredith et al. 1989). Positive analytical modelling seeks to describe how a real-world system works by using mathematical models.

3.5 Data Analysis Techniques

Data analysis techniques are used to collect and analyse data as well as to come up with theoretical explanations (Saunders et al. 2019). Four data analysis techniques are used to answer the research questions. First, cost models are developed to compare maritime routes based on specific relationships between numerical variables. Second, optimisation techniques are used, that is, differential equations in order to optimise specific variables with respect to other variables. Third, secondary data sources are used from databases, the literature, industry reports, and websites to obtain numerical data. Fourth, email communication with companies which have operated oil tankers on the NSR is conducted to obtain numerical data (cost premiums and other cost-related data), given that these data are not available in secondary sources.

[10] Other researchers define the terms 'Strategy', 'Design', and 'Method' differently. 'Strategy' in Bell et al. (2019) is defined as 'Design' in Saunders et al. (2019), and vice versa. The term 'Method' is synonymous to 'Data Analysis Technique' in both Bell et al. (2019) and Saunders et al. (2019), whereas in this Thesis it has the meaning of 'Methodology', following Wacker (1998) and Meredith et al. (1989) who use the two terms interchangeably, or 'Strategy', following Woo et al. (2011).

3.6 Cost theory

3.6.1 The relationship between costs and output

The aim of a shipowner is to maximise the daily profit by producing at the optimal level of output. The output of a ship can be defined as the miles navigated or tonne-miles produced for a given period, and therefore the shipowner will choose an optimal speed which maximises profit (Metaxas 1971; Evans 1988; Evans 1994). It is assumed that shipowners own and operate oil tankers in perfect competitive markets or *like* perfect competitive markets, that is, there is a freight rate level defined by supply and demand for all shipowners, and there is a tendency for the market to reach an equilibrium point between supply and demand in the long-run (Zannetos 1966; Veenstra and De La Fosse 2006)[11]. Thus, shipowners only control the costs at which they produce and decide the level of their output. The costs of a ship in the short-term period include voyage and operating costs, whereas in the long-term period they include voyage, operating, and capital costs. Thus, the total cost, TC, equals the sum of fixed costs, FC, (operating costs or operating and capital costs, depending on the time frame), and variable costs, VC (voyage costs):

$$TC = FC + VC \tag{1}$$

The output in miles navigated for a given period determines the level of costs for the shipowner. The average total cost, ATC, defines the cost per unit of production, Q, and can be further expressed as the sum of the average fixed cost, AFC, and average variable cost, AVC:

$$ATC = \frac{TC}{Q} \tag{2}$$

$$AFC = \frac{FC}{Q} \tag{3}$$

$$AVC = \frac{VC}{Q} \tag{4}$$

[11] Whilst it is generally assumed that the tanker markets operate under a perfect competitive model, there have been studies which point to structural changes that have led to a growing market concentration, as well as to the influence that charterers exert in the market (e.g. Adland and Strandenes 2007; Lun et al. 2013; Merikas et al. 2014; Adland et al. 2016; Goulielmos 2018). Yet, spot tanker markets are considered to function under nearly perfect competitive conditions at an aggregate level. Researchers have long emphasised on continuous supply adjustments to volatile demand fluctuations towards establishing a long-run equilibrium, rather than focusing on stable equilibria per se. Various economic, political, social, physical, and technological factors ensure that such equilibria only occur very rarely and that the adjustment process is rather continuous (Tinbergen 1959a; Tinbergen 1959b; Koopmans 1939; Gripaios 1959; Thorburn 1960; Bes 1963; O’Loughlin 1967; Cufley 1970; Metaxas 1971; Stopford 2009).

And:

$$ATC = AFC + AVC \quad (5)$$

The marginal cost, MC, defines the change in total cost that occurs from a change in production by one more unit of production. Thus, it determines the changes in production arising from incremental, *marginal*, shifts in the output. This relationship is shown below, with the Greek letter Δ denoting the change in a variable:

$$MC = \frac{\Delta TC}{\Delta Q} \quad (6)$$

Figure 3.1 shows the relationship between the ATC, AFC, AVC, and MC cost curves in the short-term period. All cost curves are U-shaped, implying first an increasing and then a decreasing marginal product, which reflects the law of diminishing returns (Evans and Marlow 1990)[12].

[12] In economics, the law of diminishing returns states that as more units of a factor of production are added in a production process, the output is incrementally decreased, whilst holding all other factors of production constant. Thus, the marginal product of each additional unit of this factor of production will decline as more units are added after a certain point, ceteris paribus. The U-shaped cost curves show that in the short-term diminishing returns lead to rising marginal costs (Samuelson and Nordhaus 2009).

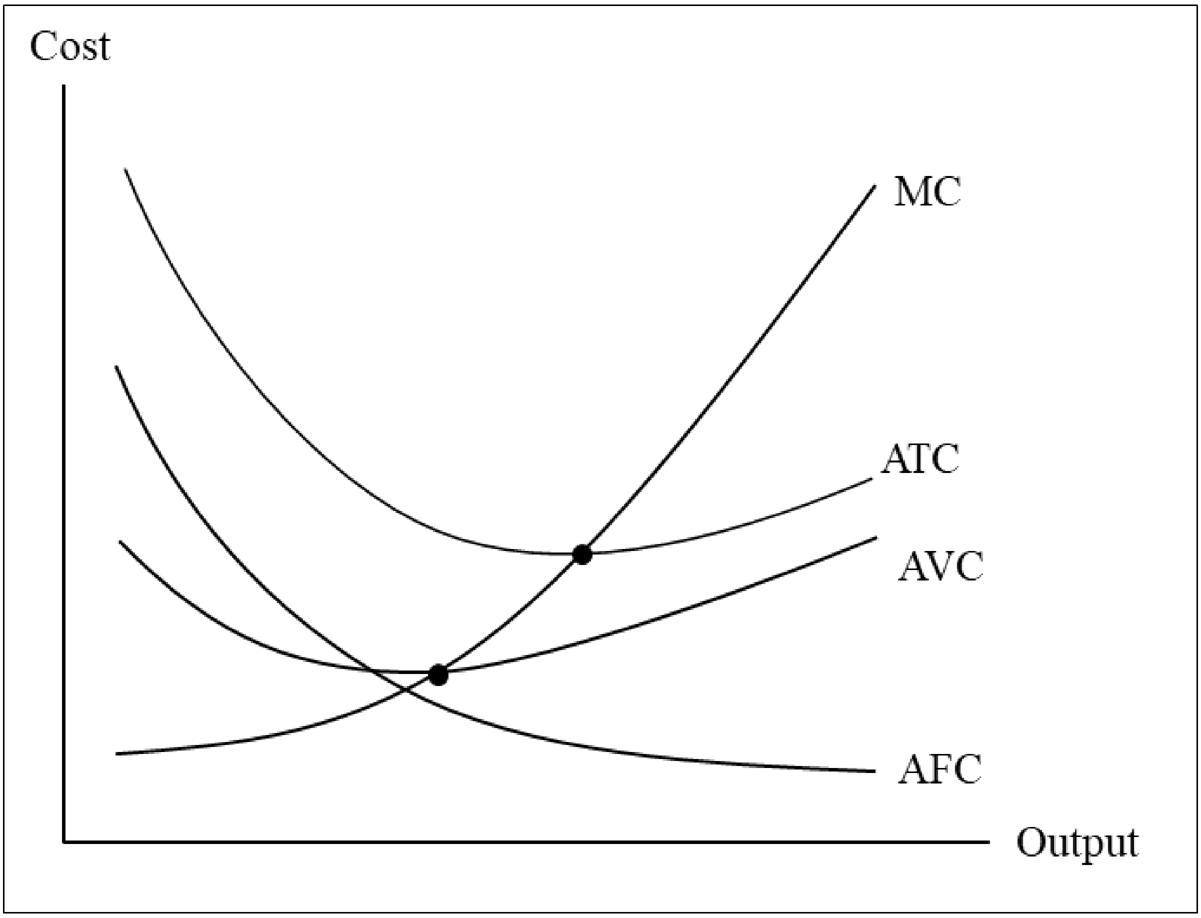


Figure 3.1. ATC, AVC, AFC, and MC cost curves.

Several observations can be made regarding the relationship between costs and output. First, the average fixed cost curve, AFC, gradually decreases when moving towards a higher output, since fixed costs are spread over more units of production. Fixed costs decline rapidly first, and then at a slower rate, which shows that fixed factors can be utilised to increase output and reduce costs at low levels of production until reaching a point beyond which further output increases do not lead to significant cost reductions. Second, the average variable cost curve, AVC, first falls and then rises, owing to the law of diminishing returns. Third, the average total cost curve, ATC, which reflects the average variable cost and average fixed cost curves, first decreases as both the average variable costs and average fixed costs decline, and then increases, since the rise in average variable costs influences the average total cost curve more than the declining average fixed costs. The lowest point of the average variable cost curve defines the minimum cost per unit of output that occurs at the *optimal* speed level in the short-term period. Equally, the lowest point of the average total cost curve defines the minimum cost per unit of output that occurs at the *optimal* speed level in the long-term period. In both cases, the marginal cost curve intersects the average variable cost and average total cost curves at their lowest points i.e. at the minimum cost per unit of output. Fourth, the marginal cost curve, MC, increases with the increase in variable costs and output. Marginal costs are always found lower than average variable costs and average total costs when these are falling, but always higher than both, when these are rising.

Figure 3.2 shows the relationship between the ATC and MC cost curves in the short and long-term periods. Whilst the most efficient level of output in the short-term period is determined by a mix of fixed and variable costs, in the long-term period all costs become variable. Thus, the long-term average total cost curve is different than the short-term average total cost curve. All short-term ATC cost curves are above the long-term ATC cost curve due to higher costs in the short-term period. The long-term ATC cost curve comprises many scales of production due to the fact that all factors of production and corresponding costs are variable. Economies of scale exist until the lowest point of the long-term ATC cost curve since total costs fall with increasing output. Diseconomies of scale exist at the point where total costs start rising with increasing output. Constant returns to scale are found in between economies and diseconomies of scale, where total costs do not vary with the output[13]. Figure 3.2 shows the various scales that can be chosen in the short-term period and corresponding levels of cost per unit of output, which may not necessarily be the minimum. For example, the scale of output in the short-term ATC cost curve located at the left side can increase further, since total costs decrease as output increases, and $ATC > MC$. On the other hand, the scale of output in the short-term ATC cost curve located at the right side is large, and as a result total costs increase as output increases, and $ATC < MC$.

[13] Whilst diminishing returns and marginal products refer to short-term period, returns to scale are a characteristic of the long-term period. Thus, increasing, decreasing, or constant returns to scale occur when an increase in inputs of all factors of production leads to a proportionally higher, lower, or equal increase in output (Samuelson and Nordhaus 2009).

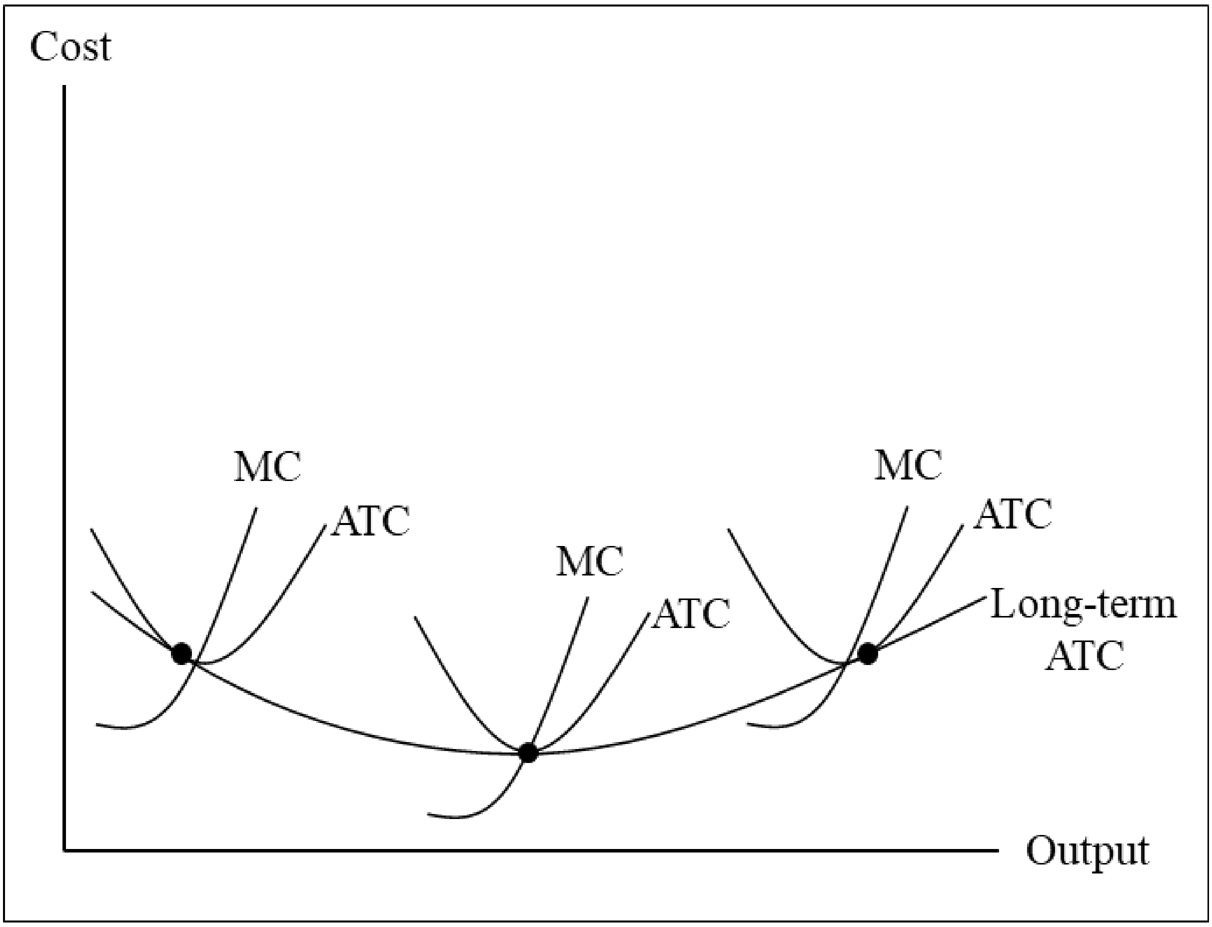


Figure 3.2. Relationship between short-term and long-term ATC and MC cost curves.

3.6.2 Marginal cost and the optimal speed

The central point of the analysis revolves around the effect of marginal cost and optimal speed adjustments. It is assumed that the output of a tanker for a given period is the ship-mile, and therefore the only way to adjust the number of ship-miles, or the distance navigated per time, is by increasing or decreasing its operating speed. Following Evans and Marlow (1990), the variable cost function, $VC(S)$, is defined as the summation of voyage and operating costs for a given voyage time:

$$VC(S) = \left(\frac{D}{S}\right) \cdot \left(C_o + P_F \cdot F_d \cdot \left(\frac{S}{S_d}\right)^a\right) \quad (7)$$

With a fuel consumption function (Barrass 2004; Dykstra 2005; MAN Diesel and Turbo 2013a):

$$F(S) = F_d \cdot \left(\frac{S}{S_d}\right)^a \quad (8)$$

Where D, is the distance, S, the speed, C_o, the operating costs, P_F, the fuel price, S_d, the design speed, and F_d, the corresponding fuel consumption. The fuel consumption function, $F(S)$, is assumed to be cubic, and therefore the exponent a is approximated at three (3). Port time and port-related costs are excluded for simplicity. By differentiating the variable cost function, VC, with respect to distance, D, the marginal cost, MC, is obtained, which is the rate of change of the variable cost, VC, with respect to distance, D (Metaxas 1971; Evans and Marlow 1990):

$$MC = \frac{\partial VC}{\partial D} = 3 \cdot P_F \cdot \frac{F_d}{S_d^3} \cdot S^2 \quad (9)$$

The marginal cost varies with the speed raised to the power of two (2) and gives the cost of navigating (producing) an additional ship-mile for a given period of time.

The average variable cost, AVC, is defined as the summation of operating and voyage costs divided by the output, in which case is the ship speed S:

$$AVC = \frac{C_o}{S} + P_F \cdot \frac{F_d \cdot S^2}{S_d^3} \quad (10)$$

The optimal speed at which the cost per unit of output is minimised, is found when:

$$AVC = MC \quad (11)$$

By substituting the AVC and MC functions, the result is the optimal speed, which gives the minimum cost per period of time:

$$S^* = \left(\frac{C_o \cdot S_d^3}{2 \cdot P_F \cdot F_d}\right)^{1/3} \quad (12)$$

This optimal ship speed depends on operating costs and fuel prices, all else being equal.

When it comes to the long-term period, all costs are considered, including capital costs, which reflect the opportunity cost of capital through the interest rate, amongst others[14]. Whilst in the short-term period freight rates may be lower than total costs, in the long-term period all costs must be covered in order for the shipowner to continue operating in the freight market.

The total cost function, $TC(S)$, is defined as the summation of voyage, operating, and capital costs for a given voyage time:

$$TC = \left(\frac{D}{S}\right) \cdot \left(C_o + C_c + P_F \cdot F_d \cdot \left(\frac{S}{S_d}\right)^a\right) \quad (13)$$

[14] Metaxas (1971) also includes the cost of land, which shipowning companies may acquire and use for their operations, to define the opportunity costs amongst alternative investment options. Moreover, the normal profit includes not only the owners' salaries, but also other imputed opportunity costs related to production factors used, which are not being compensated for the provided time and services.

Where D, is the distance, S, the speed, C_o, the operating costs, C_c, the capital costs, P_F, the fuel price, S_d, the design speed, and F_d, the corresponding fuel consumption. The fuel consumption function, $F(S)$, is assumed to be cubic, and therefore the exponent a is approximated at three (3). Port time and port-related costs are excluded for simplicity. By differentiating the variable cost function, VC, with respect to distance, D, the marginal cost, MC, is obtained, which is the rate of change of the total cost, TC, with respect to distance, D (Metaxas 1971; Evans and Marlow 1990):

$$MC = \frac{\partial TC}{\partial D} = 3 \cdot P_F \cdot \frac{F_d}{S_d^3} \cdot S^2 \tag{14}$$

As in the case of the variable cost function, the marginal cost varies with the speed raised to the power of two (2) and gives the cost of navigating (producing) an additional ship-mile for a given period of time.

The average total cost, ATC, is defined as the summation of all costs, divided by the output, in which case is the ship speed S:

$$ATC = \frac{C_o}{S} + \frac{C_c}{S} + P_F \cdot \frac{F_d \cdot S^2}{S_d^3} \tag{15}$$

The optimal speed at which the cost per unit of output is minimised, is found when:

$$ATC = MC \tag{16}$$

By substituting the ATC and MC functions, the result is the optimal speed, which gives the minimum cost per period of time:

$$S^* = \left(\frac{(C_o + C_c) \cdot S_d^3}{2 \cdot P_F \cdot F_d}\right)^{1/3} \tag{17}$$

This optimal speed determines the minimum cost in the long-term period or in other words the *break-even point* of operations. This optimal ship speed depends on operating and capital costs, and fuel prices, all else being equal. The solutions for all functions and calculations presented in the Section '3.6.2 Marginal cost and the optimal speed', are included in Appendix J.

The higher speed level observed in the case of the long-term optimal speed is explained by the fact that a higher required freight rate is necessary in order to compensate for the increased costs, which now include capital costs, along with operating and voyage costs. Mathematically, this is reflected in the long-term period optimal speed equation, where the denominator remains constant, but the nominator is higher than in the short-term period optimal speed equation.

3.6.3 Approaches to speed optimisation

Generally, ship speed is optimised at the design stage of a ship, where the nature of the service and technical characteristics determine its design speed, and lower and upper speed boundaries (Barrass 2005; MAN Diesel and Turbo 2013a). Moreover, the state of the hull, safety, and weather conditions also affect the operating speed (Alderton 1981; Barrass 2005; MAN Diesel and Turbo 2013a). Allowing for these constraints, ship speed can be optimised with respect to economic factors.

The two main ways of determining the unit of output depend on the criterion of maximisation. For a shipowner who operates in the spot market, the freight rate is defined in US$ per tonne based on the Worldscale (WS) indices, whilst the time charter equivalent (TCE) rate is defined in US$ per day. On the one hand, the profit per day is maximised at a speed where profit reaches its maximum point. This speed depends on the level of prevailing freight rates, port time and port-related costs, and potential delays. On the other hand, the profit per tonne is maximised at a speed where the cost per tonne reaches its minimum point. This speed depends on fixed costs and fuel prices. Alderton (1981) refers to the first speed as the *most profitable speed* (MPS), and to the second speed as the *least cost speed* (LCS), respectively. In other words, the first speed is a profit maximising speed, whereas the second speed is a cost minimising speed.

Figure 3.3 shows the relationship between cost and the two optimal speeds. The profit maximising speed departs from the cost minimising speed level in accordance with freight rate levels. The closer the profit maximising speed is on the cost minimising speed level, the more the market reaches the long-run equilibrium point between supply and demand. In this point revenue equals cost, and the shipowner earns a 'normal profit'[15]. On the other hand, the more the profit maximising speed level deviates from the cost minimising speed level, the higher the excessive profit, that is, the 'economic profit' made in the freight markets owing to a departure of the freight rate level from its long-run equilibrium point.

[15] Evans and Marlow (1990) and Evans (1994) assume normal profits even in the short-term period, that is, AVC = MC. Although this state can be achieved in the short-term period under certain conditions, normally, freight rates fluctuate around costs and result in economic profits during the short-term period (Metaxas 1971; Stopford 2009).

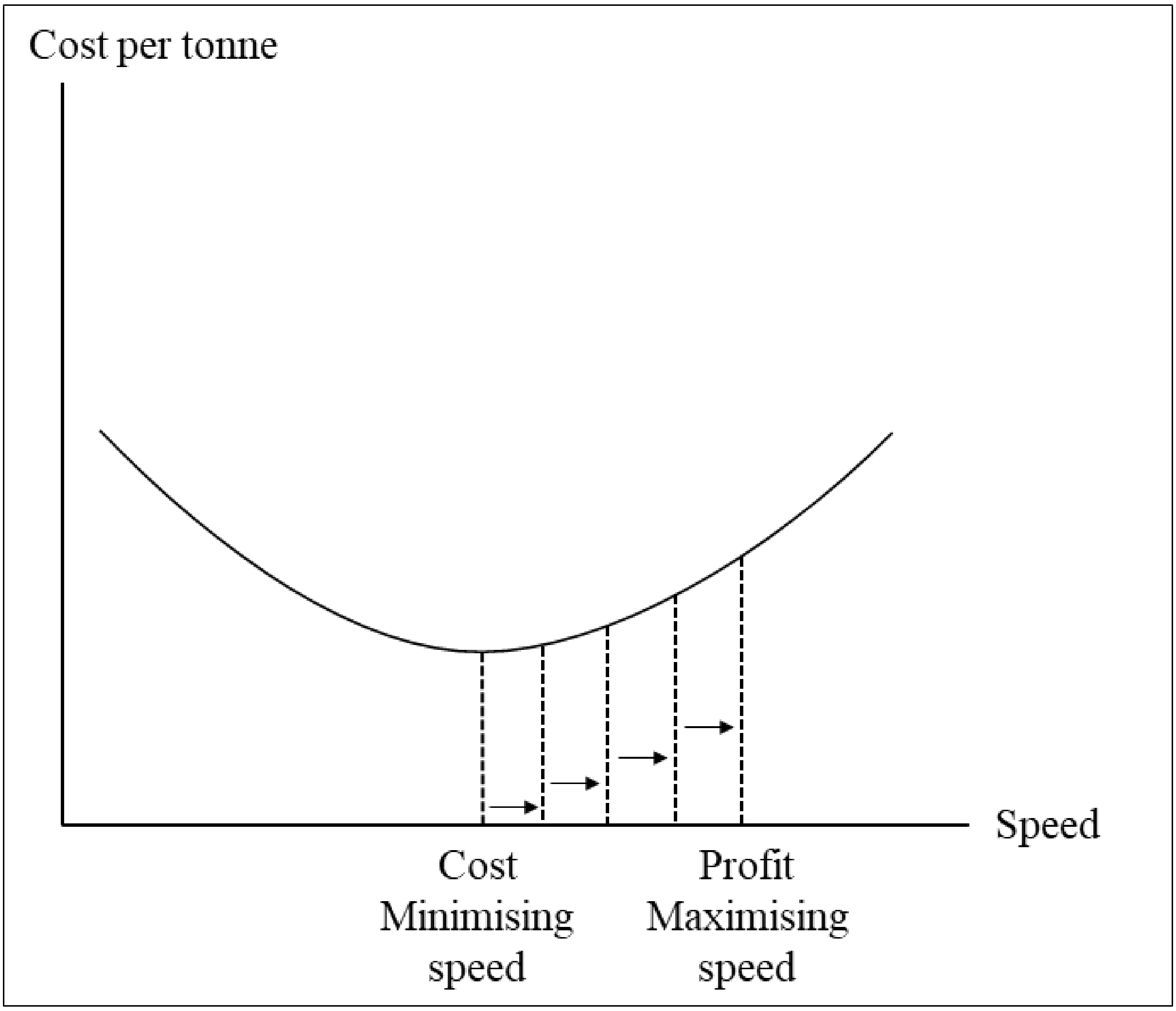


Figure 3.3. Cost minimising speed and profit maximising speed, based on Alderton (1981).

The cost minimising speed which considers both the value of ship and cargo carried on board is referred as the *least cost inventory speed* (Alderton 1981). Goss et al. (1982) refer to the opportunity cost of cargo in-transit, which can be quantified by using a relevant interest rate and the price and quantity of cargo. Figure 3.4 shows the relationship between optimal laden speed, optimal ballast speed, and optimal laden speed with in-transit inventory. The optimal laden speed is lower than optimal ballast speed due to higher resistance and fuel consumption when a ship is laden, i.e. loaded with cargo (Psaraftis and Kontovas 2014; Lindstad and Eskeland 2015). The optimal laden speed with in-transit inventory is higher than both the optimal ballast speed and the laden speed. This indicates that the optimal laden speed is sensitive to the value of cargo, depending on the interest rate and the price of the cargo. The difference between the laden speed and the laden speed with in-transit inventory depends on fuel price levels, and on the interest rate and the price of the cargo, all else being equal.

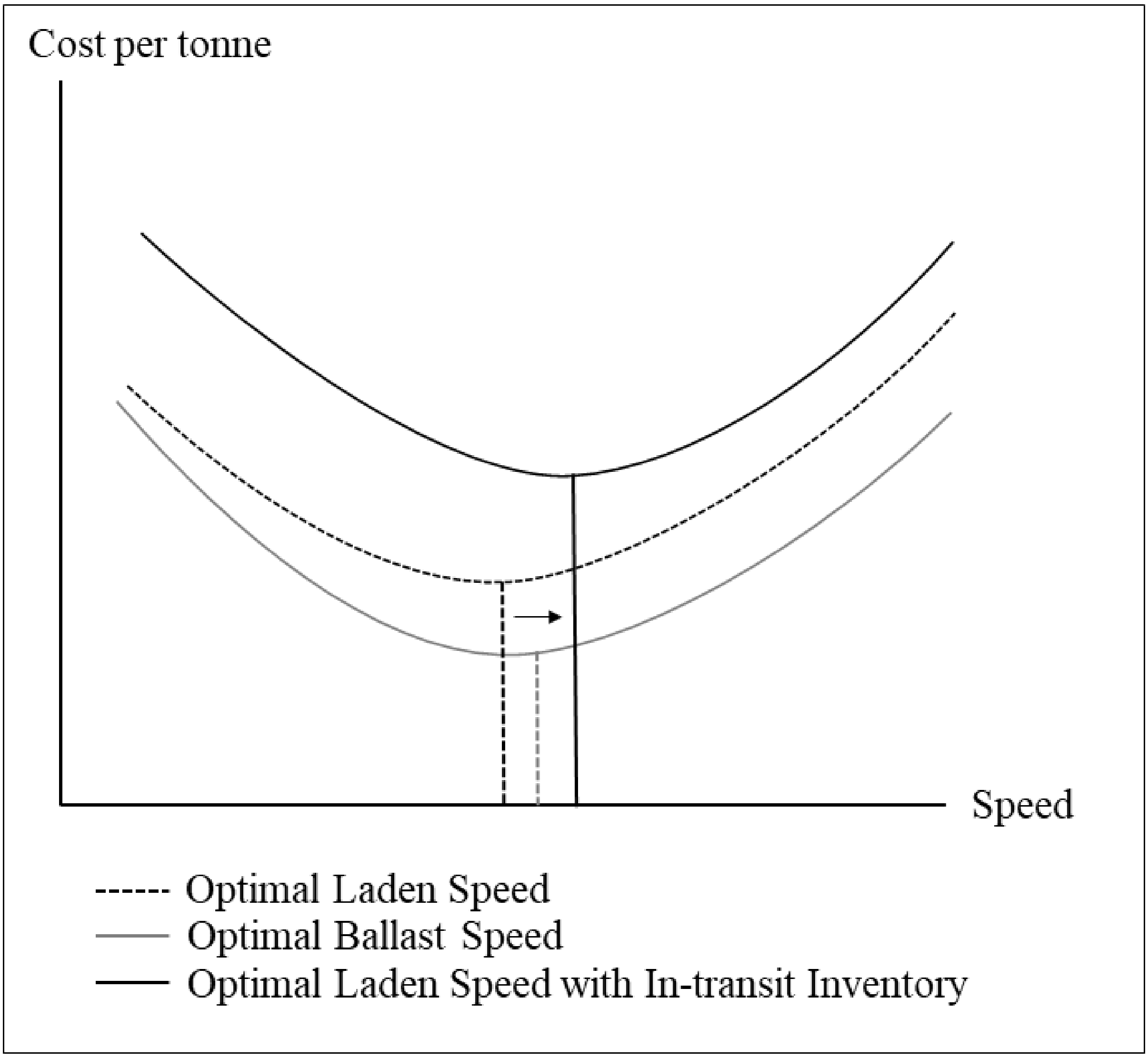


Figure 3.4. Optimal laden, ballast, and laden with in-transit inventory speeds.

These optimal speeds are found based on general profit and cost functions. A closed-form fuel consumption function is presented which includes payload[16] to determine fuel consumption based on cargo weight. This is an alternative to the fuel consumption function presented in Section '3.6.2 Marginal cost and the optimal speed', and takes into account laden and ballast voyages, respectively. Let $F(S, \nabla)$ denote the fuel consumption as a function of speed, S, and payload, P, with, F_d, denoting the fuel consumption at the design speed, S_d, depending on the fuel type and, ∇, and, L, the displacement and lightweight of a tanker, respectively (Barrass 2004; Psaraftis and Kontovas 2013; Psaraftis and Kontovas 2014; MAN Diesel and Turbo 2013a):

[16] The payload is the weight of cargo, fresh water, fuel, lubricating oil, stores, water ballast, crew and effects, and baggage and passengers, and is measured in metric tonnes (Barrass 2005; Stopford 2009).

$$F(S,\nabla) = F_d \cdot \left(\frac{S}{S_d}\right)^{a} \cdot \left(\frac{P+L}{\nabla}\right)^{2/3} \tag{18}$$

Following Evans and Marlow (1990), for both cost and profit functions in their simplest form, port time and port-related costs are ignored, and the cubic rule between speed and fuel consumption is retained.

Let π denote profit:

$$\pi = \frac{FR \cdot W - C_T}{\left(\frac{D}{S \cdot 24}\right)} - C_o - F(S,\nabla) \cdot P_F \tag{19}$$

FR, is the freight rate in US$ per tonne, W, the cargo in metric tonnes (m.t.), D, the distance for a one-way laden voyage in nautical miles (n.m.), C_o, the daily operating costs in US$ per day, C_T, any transit costs in US$, and, P_F, the price of fuel in US$ per tonne.

The aim is to maximise, π, by differentiating Equation (19) with respect to speed, S, and setting the partial derivative equal to zero:

$$\frac{\partial \pi}{\partial S} = 0 \tag{20}$$

The optimal profit speed becomes:

$$S_\pi^* = \left(\frac{24 \cdot (FR \cdot W - C_T) \cdot {S_d}^3 \cdot \nabla^{2/3}}{3 \cdot D \cdot F_d \cdot P_F \cdot (P+L)^{2/3}}\right)^{1/2} \tag{21}$$

The profit maximising speed depends on freight rates, transit fees, and fuel prices, all else being equal.

Let C denote cost:

$$C = \frac{1}{W} \cdot \left[\left(\frac{D}{S \cdot 24}\right) \cdot \left((F(S,\nabla) \cdot P_F) + (C_o + C_c)\right) + C_T\right] \tag{22}$$

W, is the cargo in m.t., D, the distance for a one-way laden voyage in n.m., C_o and C_c, the daily operating and capital costs in US$ per day, C_T, any transit costs in US$, and, P_F, the price of fuel in US$ per tonne.

The aim is to minimise cost, C, by differentiating Equation (22) with respect to speed, S, and setting the partial derivative equal to zero:

$$\frac{\partial C}{\partial S} = 0 \tag{23}$$

The optimal cost speed becomes:

$$S_C^* = \left(\frac{(C_o+C_c)\cdot {S_d}^3\cdot \nabla^{2/3}}{2\cdot F_d\cdot P_F\cdot (P+L)^{2/3}}\right)^{1/3} \quad (24)$$

The cost minimising speed depends on operating and capital costs, and fuel prices, all else being equal. This speed determines the minimum cost in the long-term period, in other words, the *break-even point* of operations. It is the same speed found in Section '3.6.2 Marginal cost and the optimal speed', when $ATC = MC$. Moreover, when the freight rate equals the cost per tonne, $FR = C$, in Equation (19), the profit per tonne becomes zero, and the profit maximising speed equals the cost minimising speed, $S_\pi^* = S_C^*$. This is the point where normal profits are realised i.e. revenue equals cost.

When including in-transit inventory costs in the cost function:

$$W \cdot P_C \cdot \frac{r}{365} \quad (25)$$

Where, P_C, is the average price of a tonne of cargo in US$ per tonne, multiplied by cargo quantity, W, and a relevant interest rate, r, which is divided by 365 to express the in-transit inventory cost per day.

The cost function becomes:

$$C = \frac{1}{W} \cdot \left[\left(\frac{D}{S\cdot 24}\right) \cdot \left((F(S,\nabla) \cdot P_F) + (C_o + C_c) + \left(W \cdot P_C \cdot \frac{r}{365}\right)\right) + C_T\right] \quad (26)$$

And by differentiating Equation (26) with respect to speed, S, and setting the partial derivative equal to zero:

$$\frac{\partial C}{\partial S} = 0 \quad (27)$$

The optimal cost speed becomes:

$$S_C^* = \left(\frac{\left((C_o+C_c)+\left(W\cdot P_C\cdot \frac{r}{365}\right)\right)\cdot {S_d}^3\cdot \nabla^{2/3}}{2\cdot F_d\cdot P_F\cdot (P+L)^{2/3}}\right)^{1/3} \quad (28)$$

This cost minimising speed depends on operating and capital costs, the price of cargo and the interest rate, and fuel prices, all else being equal. It is higher than the cost minimising speed without in-transit inventory cost by the total cost of the inventory in-transit that appears in the nominator of the equation.

The solutions for Equation (21), Equation (24), and Equation (28) and calculations are included in Appendix J.

3.6.4 Cost assessment approach

Notwithstanding the freight rate fluctuations in the short-term period, as well as the dynamic adjustments of supply and demand in the long-term period, the cost minimising optimal speed establishes the break-even point of operations, in other words, the required freight rate (RFR). Assessments of both profits and costs based on profit maximisation and cost minimisation, respectively, would provide a two-way approach to maritime route comparison. However, the non-existence of a spot market for tanker trades via the Northern Sea Route (NSR) as of today, as well as the lack of freight rates or lumpsum rates of voyages conducted in 2011-2019, prevents the use of profit-based comparisons. Had there been any rates available, the difficulty of discerning the ice class premiums[17] could have increased the methodological difficulties. Besides, ice class freight premiums, even for established ice class tanker trades, such as the Baltic Sea tanker trades during the ice season, tend to fluctuate depending on supply and demand conditions (Clarksons 2005; Clarksons 2006; Clarksons 2007). Thus, a cost-based approach which establishes the RFR against competing route alternatives, is more appropriate for long-term planning than one which aims to maximise profit (Alderton 1981; ICS 2015).

3.6.5 Required freight rate functions

The RFR analysis of this Thesis is based on the RFR that minimises the cost per tonne from the shipowner's perspective. The methodological approach has two objectives. First, the cost assessment is based on *speed optimisation* which minimises the RFR of a route alternative. Second, the cost assessment is based on *real speeds*, drawing from Automatic Identification System (AIS) speed data. On the one hand, the cost per tonne reaches its minimum when speed is optimised with respect to cost and market factors subject to engine technical boundaries. On the other hand, real ship speeds tend to depart from optimal points determined by market factors owing to organisational and technical constraints, ship, and voyage-specific variables, as well as weather factors amongst others (Psaraftis and Kontovas 2014; Lindstad and Eskeland 2015; Adland et al. 2017; Adland and Jia 2018). Moreover, speed through ice on the NSR may not be optimised with respect to cost and market factors as on open water. The reason is that speed through ice primarily depends on sea ice conditions and may not equal the optimal speed. Thus, it has to be approximated based on either physical factors, such as ice thickness, or on real speeds recorded on the NSR. The assumptions for ship speed through ice on NSR in this Thesis are informed by AIS speed data of historic oil product tanker voyages conducted on the NSR.

[17] Ice class premiums are applied on ice class trades to compensate for increased operating costs and repairs and/or maintenance costs of ice class ships.

The assumptions for real speeds in this Thesis are informed by AIS speed data of voyages conducted between ports of major oil products trades.

The distinction between *optimal*, and fixed, *real* speeds is illustrated in the following RFR functions:

$$RFR = \frac{1}{Weight} \cdot \big(Voyage\,Time \cdot (Operating\,Costs + Voyage\,Costs + Capital\,Costs)\big) \quad (29)$$

The RFR is a function of all costs multiplied by the voyage time in days, and divided by the payload (total weight) to determine the cost in US$ per tonne. Different values of payload correspond to different tanker sizes, and therefore to scale economies that can be achieved by using larger tankers in the long-term period.

Further, the voyage time can be defined as the distance in nautical miles divided either by the theoretical, *optimal* speed, or by a fixed, *real* speed, based on data from actual voyages:

$$RFR = \frac{1}{Weight} \cdot \left(\left(\frac{Distance}{Optimal\,Speed}\right) \cdot (Operating\,Costs + Voyage\,Costs + Capital\,Costs)\right) \quad (30)$$

$$RFR = \frac{1}{Weight} \cdot \left(\left(\frac{Distance}{Fixed\,Speed}\right) \cdot (Operating\,Costs + Voyage\,Costs + Capital\,Costs)\right) \quad (31)$$

3.6.6 RFR modelling and speed optimisation as a modelling approach

The findings of the systematic literature review show that analytical mathematical research methods and general transport cost models are prevalent in the literature. Although established ways to estimate costs are used in the literature, there are no studies which employ a RFR approach based on speed optimisation. The RFR is a fundamental cost modelling approach, which is used both in practice and the literature when comparing voyages or alternative routes. Moreover, speed optimisation from a cost-based perspective based on analytical techniques determines the minimum RFR. Not only optimal speeds are considered, but also fixed speeds are used in the analysis to enable comparisons of the outcomes based on theoretical and real speeds. In addition, data of real ship speeds through ice on NSR are factored in the RFR models to provide a new approach to the literature. Most of the studies have focused on theoretical approaches of sea ice-ship speed dependency and used historic ice thickness data to determine tanker speeds on the NSR.

3.6.7 Modelling Cases

1. *The role of distance, fuel prices, icebreaking fees and ship size.* The feasibility of the NSR is assessed against the Suez Canal route (SCR) in the first modelling case. The factors considered are distance, fuel prices, average ship speed through ice on NSR, icebreaking fees, ice damage repairs, ship size, varying capital and operating costs, and fuel types. The analysis explains the emergence of the NSR as an alternative route for oil product tankers between Europe, the Russian Arctic and Northeast Asia since 2010. First, costs are assessed during 2011-2014 and 2015-2017, reflecting developments of major cost and market factors which affected route choice. Second, costs are assessed for the years 2018, 2019, and 2020, respectively. The analysis is undertaken at the tactical/operational level for single voyages during the summer/autumn season. A RFR model is developed based on speed optimisation to assess the minimum cost per tonne from the shipowner's perspective. The data and assumptions for capital costs, voyage costs, and speed on ice vary on an annual basis during 2011-2020, reflecting historic market conditions and respective cost structure for competing routes.

2. *The role of commodity prices, in-transit inventory, and alternative operational modes*. The feasibility of the NSR is assessed against the SCR and Cape of Good Hope routes in the second modelling case. The factors considered in the analysis are distance, fuel prices, average ship speed through ice on NSR, icebreaking fees, ice damage repairs, commodity prices and in-transit inventory costs, and fuel types and operational modes. The analysis in this modelling case complements the analysis in the first modelling case by considering in-transit inventory costs and addressing market structure and route choice in the wider context of oil product tanker flows, drawing from AIS data of voyages conducted between the Far East and Europe in 2011-2020. Not only is the NSR compared with SCR, but also the Cape route is included to explain route choice for oil product tanker trades between Northeast Asia and Europe. The cost-based analysis explains route choice depending on two distinct states of the market. First, it explains the choice of shorter routes when cargo value is important, and fuel and commodity prices are high. Second, it explains the choice of longer routes when cargo value is not critical, and fuel and commodity prices are low. The analysis is undertaken at the tactical/operational level for single voyages during the summer/autumn season. The analysis reflects real practices of Long Range 2 (LR2) product tanker voyages carrying jet fuel/kerosene or gasoil/diesel, drawing from actual cargo movements between east

and west. A RFR model is developed to assess the cost per tonne from the shipowner's perspective. The methodological approach has two objectives. First, the cost assessment is based on speed optimisation to minimise the RFR of a route alternative. Second, the cost assessment is based on real speeds, drawing from AIS data of LR2 tanker voyages between Northeast Asia and Northwest/Southwest Europe.

3. *The role of ship speed on ice and alternative fuel types for seasonal navigation.* The feasibility of the NSR is assessed against the SCR for seasonal navigation operations in the third modelling case. The factors considered are distance, fuel prices, ship speed through ice on NSR, seasonal navigation, icebreaking fees, commodity prices and in-transit inventory costs, and fuel types and operational modes. The analysis in this modelling case complements the analysis in the first and second modelling cases by developing seasonal navigation scenarios and considering AIS speed data of historic tanker voyages conducted on NSR to determine the varying speed through ice on NSR. The analysis assesses seasonal navigation between ports located in the Baltic Sea, Northwest Europe and Northeast Asia during the summer/autumn season. The analysis is undertaken at the strategic level (choice of oil products/commodities and routes as an expert-based scenario). LR2 tanker voyages of naphtha and jet fuel/kerosene cargo are assumed in the analysis, based on major oil products trades and historic tanker voyages conducted on NSR between east and west. A RFR model is developed, based on speed optimisation, to assess the minimum cost per tonne from the shipowner's perspective. The methodological approach considers ship speed through ice per month, navigation zone and voyage direction. The analysis is informed by AIS data which contain real hourly speed data of historic tanker voyages conducted on NSR.

4. The role of distance, fuel prices, icebreaking fees, and ship size

The feasibility of the Northern Sea Route (NSR) is assessed against the Suez Canal route (SCR) in this chapter. The factors considered are distance, fuel prices, average ship speed through ice on NSR, icebreaking fees, ice damage repairs, ship size, varying capital and operating costs, and fuel types. The analysis explains the emergence of the NSR as an alternative route for oil product tankers between Europe, the Russian Arctic and Northeast Asia since 2010. First, costs are assessed during 2011-2014 and 2015-2017, reflecting developments of major cost and market factors which affected route choice. Second, costs are assessed for the years 2018, 2019, and 2020, respectively. The analysis is undertaken at the tactical/operational level for single oil product tanker voyages during the summer/autumn season.

A required freight rate (RFR) model is developed based on speed optimisation to assess the minimum cost per tonne from the shipowner's perspective. The data and assumptions for capital, navigational, and voyage costs vary on an annual basis during 2011-2020, reflecting historic market conditions and respective voyage cost structure for competing routes.

Different fuel types are considered to address current emissions reductions policies, such as, the Emission Control Areas (ECAs) policy and the IMO sulphur limit. The choice of fuel type reflects changes in emission regulations, both in local (ECAs) and global (IMO sulphur limit) levels throughout the period between 2011 and 2020. The use of High Sulphur Fuel Oil (HSFO) is considered for the period between 2011 and 2014. The use of HSFO is assumed outside ECAs and the use of Marine Gasoil (MGO) within ECAs for the period between 2015 and 2019. The use of Very Low Sulphur Fuel Oil (VLSFO) instead of HSFO is assumed outside ECAs along with MGO within ECAs for the year 2020. Both primary and secondary data are employed in the analysis regarding cost, market, and navigational factors.

4.1 Introduction

After the first experimental transit of a non-Russian flagged merchant ship (*MT Uikku*) through the NSR in 1995 (Brigham and Armstrong 1996), exploratory destination and transit voyages increased from two in 2007 to 43 in 2013. A rapid decline in traffic and use of the route mainly for product tanker voyages linking Russian ports in 2014 was followed by a steady recovery during 2015-2019, and a record high of 64 transit and destination voyages in 2020 (ARCTIS 2021a; NSRA 2016; CHNL 2021a). Although the NSR offers shorter geographical distances up to around 60% depending on origin-destination (OD) pairs (Mulherin 1996), reductions in transport costs and transit times depend on a number of factors. Physical factors (ice conditions, harsh climate), and safety concerns largely determine the use of the NSR for sea transport. Moreover, navigational and cost factors, such as variability in ship speed through ice, increased operating costs and capital costs as well as geopolitical developments and market conditions significantly affect the use of the NSR.

Studies assessing the economic feasibility of Arctic shipping have increased considerably since 2011, with liner shipping being the most studied transport system, and the NSR, the most studied route in the literature. On the other hand, less attention has been paid to bulk shipping, and more specifically to oil tankers (Song and Zhang 2013; Von Bock und Polach et al. 2015; Zhang, Meng, Ng 2016; Faury and Cariou 2016; Faury, Cheaitou et al. 2020; Keltto and Woo 2020; Wang et al. 2020). However, on average, 51% of the exploratory destination and transit voyages during 2011-2014 involved oil product tankers of various sizes, followed by a sharp decline to 12% between 2015 and 2020. Although, this is attributed to various economic and geopolitical factors, it shows that the potential of the NSR both for destination and international transit traffic mainly lies with bulk (liquid and dry) and specialised (e.g. Liquefied Natural Gas – LNG, Liquefied Petroleum Gas – LPG) shipping, rather than liner shipping in the short to medium-term.

The extant literature investigates whether the NSR is a competitive alternative under specific conditions and certain periods of time. There is a very limited understanding as to how distance, fuel price levels, icebreaking fees and ship size affect the use of the NSR in the context of oil tanker shipping (Zhang, Meng, Ng 2016; Wang et al. 2020). Moreover, alternative fuel types for oil product tankers with reference to historic periods have not so far been explored. Further, crucial economic factors coupled with inherent strategic and political issues encompassing the tanker trades and affecting routeing patterns have not been addressed.

The analysis aims to assess the feasibility of the NSR for oil product tanker trades between Northwest Europe, the Russian Arctic, and Northeast Asia at the tactical/operational level during the summer/autumn season. A RFR analysis is established to assess the break-even point for competing routes from the shipowner’s point of view. It considers the use of the NSR compared to the SCR drawing from historic NSR oil product tanker voyages to inform the choice of OD pairs. It aims to demonstrate quantitatively why the NSR was a competitive alternative for oil product tankers during 2011-2014 and how cost and market factors affected its competitiveness during 2015-2017 and during 2018-2020, respectively. Speed optimisation is employed to minimise the RFR for competing routes. Moreover, the RFR model is informed by Automatic Identification System (AIS) data to determine the ship speed through ice on the NSR. The analysis considers distance, fuel types and prices, varying operating costs and capital costs, icebreaking fees, ship size, and average ship speed through ice on NSR, depending on the historic period of operations.

4.2 Developments between 2011 and 2020

The NSR witnessed an increase in destination and transit traffic during the period 2007-2013. Several factors contributed to the extensive use of the route for destination and transit voyages. The sea ice retreat in the Arctic, high fuel price levels during 2011-2014, and a competitive icebreaking tariff policy until 2013, induced non-Russian operators to explore the NSR as an alternative to traditional sea routes and ship canals, such as the Suez and Panama Canal routes (Gritsenko and Kiiski 2016). These developments also coincided with the launch of Russia's new 'Arctic Strategy 2020' in 2009, concerning the further development of the NSR (ARCTIS 2021b). Another equally important reason behind this surge in destination and transit traffic was the increased number of piracy incidents off the Gulf of Aden during the period 2009-2014, resulting in increased insurance premiums and risk when transiting through the SCR (Tanker Company 2018). A large number of oil product tankers ranging from 47,000 to 162,000 deadweight (dwt) tonnes conducted transit and destination voyages via the NSR between 2011 (31%) and 2014 (33%) (NSRA 2016; CHNL 2021a; Bloomberg 2021; Refinitiv Eikon 2021). These tankers transported jet fuel/kerosene, gasoil/diesel, condensate, naphtha, and fuel oil between the Russian Arctic, Europe, and Asia (NSRA 2016; CHNL 2021a).

A redirection of condensate and naphtha flows from ports in the Barents and White Seas to ports in the Baltic Sea resulted in a sharp decline of destination voyages in 2014 (Bambulyak et al. 2015; Tanker Company 2018). Moreover, geopolitical factors negatively impacted transit voyages as well (Shapovalova et al. 2020). Oil product tanker voyages comprised mostly ballast voyages and fuel oil supply voyages between Far East Russian ports and Russian ports in the Baltic or in the Russian Arctic (CHNL 2021a; Bloomberg 2021; Refinitiv Eikon 2021).

The decline of interest since 2015 is associated with the fall in global oil prices and a drop in piracy insurance premiums, which reduced the economic potential of the NSR, since both fuel costs and oil products commodity prices declined, respectively. Moreover, a lower RFR has not been sufficient to cover potential ice damage repairs. The official icebreaking fees have declined due to the depreciation of the Russian Rouble since 2015, but they are still higher than the discounted offered before 2013. The NSR being a shorter route lost its comparative advantage for tanker voyages between the Atlantic and the Pacific Ocean, especially during 2015-2017 and in 2020. Not only did the cost differential between the NSR and other traditional sea routes and ship canals narrow due to lower transport costs by using the latter, but also low oil products prices and hence a lower value of cargo on board meant that transit time was not very important.

Developments in emission regulations both in local and global levels have also impacted and will continue to impact route choice as much as economic and geopolitical factors affect routeing patterns. The most recent fuel oil sulphur limit within ECAs (0.1% mass by mass) was established in 2015 (IMO 2021)[18]. Following the International Maritime Organisation (IMO) 2020 regulation on the reduction of the maximum level of sulphur content in marine fuels from 3.5% to 0.5% mass by mass (IMO 2016a), VLSFO became the main marine fuel globally. MGO is used primarily when operating in ports and within ECAs. HSFO can still be used with the aid of exhaust gas cleaning systems (scrubbers) which are able to remove sulphur oxides (SO_x) from the exhaust gas before these are emitted to the atmosphere. Moreover, the Initial IMO greenhouse gas (GHG) Strategy (IMO 2018), and a future ban on the use of heavy fuels (HSFO, VLSFO) for operations in the Arctic (IMO 2016a) will significantly affect costs and operations alike. Thus, economic, geopolitical and regulatory changes are expected once again to affect route choice patterns, and therefore the use of ship canals and sea routes accordingly.

4.3 Modelling

4.3.1 Modelling approach

The minimum cost per tonne is the long-run equilibrium point between supply and demand, where revenue equals cost (Alderton 1981). Classical maritime economic theory holds that the (theoretical) optimum speed which minimises the cost per tonne is not affected by short-term freight rate volatility, port time or delays, and therefore is more appropriate for long-term planning than one which aims to maximise profit (Alderton 1981; Evans and Marlow 1990). A cost-based route comparison aims to establish the break-even point for a route and includes fixed and variable cost factors, including operating and capital costs for different ship types and technologies, fuel costs, transit fees, and other voyage-related costs.

The RFR model incorporates various fuel types to reflect operations during 2011-2020 for competing sea routes. First, the use of HSFO is considered for the period 2011-2014. Second,

[18] ECAs (SO_x and Particulate Matter emissions only) constitute the Baltic and the North Sea areas in Europe, and the North American and US Caribbean Sea areas in North America as well as the Hawaiian Islands area (IMO 2021).

the use of HSFO is assumed outside ECAs and the use of MGO within ECAs during 2015-2019 (IMO 2021). Third, the use of VLSFO is considered instead of HSFO outside ECAs for the year 2020 (IMO 2021).

The fuel consumption is a function of speed, fuel type, operational mode and payload (Barrass 2004; MAN Diesel and Turbo 2013a; Psaraftis and Kontovas 2013; Psaraftis and Kontovas 2014).

The fuel consumption function can be expressed as:

$$F_{FO}(S^*, \nabla) = F_{FO\ d} \cdot \left(\frac{S^*_{FO}}{S_d}\right)^{a} \cdot \left(\frac{P+L}{\nabla}\right)^{2/3} \quad (1)$$

The exponent a depends on the actual speed (Adland et al. 2020) and is approximated at three (3) in this study (Psaraftis and Kontovas 2014).

The objective is to minimise the total RFR per voyage of a route alternative (either RFR_{NSR} or RFR_{SCR}):

$$min \sum RFR \quad (2)$$

where $\sum RFR$ denotes the sum of the RFR for all legs of a voyage in either of the two routes.

The $\sum RFR$ of each voyage is a function of fuel consumption and optimal speed, distance, total cost inputs and cargo carrying capacity of a tanker for each leg:

$$RFR = \frac{1}{W} \cdot \left[\left(\frac{D_{SCR,NSR}}{S^*_{FO} \cdot 24}\right) \cdot \left((F_{FO}(S^*_{FO}) \cdot P_{FO}) + (C_o + C_c)\right) + C_{TI}\right] \quad (3)$$

Equation 4 presents the RFR for a ballast voyage between the unloading port and the repair dockyard when ice damage repairs are factored in the model. This RFR includes only fuel, operating and capital costs. MGO is used along with either HSFO or VLSFO, depending on the OD pair and the ECAs mileage for a yard located in Europe or in China, in the Yangtze River Delta area (UK P&I 2015; Dataloy 2021).

$$k \cdot RFR = \frac{1}{W} \cdot \left[\left(\frac{D_B}{S^*_{FO\ B} \cdot 24}\right) \cdot \left((F_{FO}(S^*_{FO\ B}) \cdot P_{FO}) + (C_o + C_c)\right) + C_R\right] \quad (4)$$

subject to

$$\underline{S} \leq S^* \leq \overline{S} \quad (5)$$

Table 4.1 reports the parameters and variables used in Equations (1) – (15).

Table 4.1. Parameters and variables used in the model.

Parameters:	**Description**
P	weight of cargo, fresh water, fuel, lubricating oil, stores, water ballast, crew and effects, and baggage and passengers in metric tonnes (m.t.)
W	average weight of cargo in m.t.
$\sum_{i=1}^{n} D_{SCR}$	total SCR distance in nautical miles (n.m.)
$\sum_{i=1}^{n} D_{NSR}$	total NSR distance in n.m.
$D_{1,SCR}, \dots, D_{n,SCR}$	SCR distance legs in n.m.
$D_{1,NSR}, \dots, D_{n,NSR}$	NSR distance legs in n.m.
D_B	distance for a ballast voyage from an unloading port to a repair yard in days
P_{FO}	fuel oil price in US$ per tonne
C_R	cost of ice damage repairs in US$
C_o, C_c	operating costs in US$ per day, capital costs in US$ per day
C_{TI}	transit costs (canal tolls or icebreaking fees) and insurance premiums in US$
S_d	design speed in knots
$\overline{S}$	upper speed in knots
$\underline{S}$	lower speed in knots
$F_{FO\ d}$	fuel consumption at design speed in tonnes per day
L	lightweight of a product tanker in tonnes
∇	displacement of a product tanker in tonnes

Table 4.1. Parameters and variables used in the model (continued).

Variables	Description
S^*_{FO}, $S^*_{FO\ B}$	optimal speed for laden voyage and optimal speed for a ballast voyage to a repair yard in knots
k	binary variable, equal to 1 when ballast voyages for repairs are considered, and 0 otherwise
$\sum_{i=1}^{n} T_{SCR}$	total SCR transit time in days
$\sum_{i=1}^{n} T_{NSR}$	total NSR transit time in days
$T_{1,SCR}, \dots, T_{n,SCR}$	SCR transit time for each leg in days
$T_{1,NSR}, \dots, T_{n,NSR}$	NSR transit time for each leg in days
T_B	transit time for a ballast voyage from an unloading port to a repair yard in days
RFR_{SCR}, RFR_{NSR}	required freight rate (RFR) for the SCR and NSR routes in US$ per tonne
ΔRFR	RFR differential

The number 24 denotes the hours per day, which is used in Equations (3) and (4) to obtain voyage time in days. The term $\frac{1}{W}$ transforms RFR to RFR in US$ per tonne, whilst the terms $\left(\frac{D_{SCR,NSR}}{S^*_{FO}\cdot 24}\right)$, $\left(\frac{D_B}{S^*_{FO\ B}\cdot 24}\right)$, calculate the days at sea for each leg and voyage, respectively. The speed range is defined between 5 and 16 knots. A minimum speed of 5 knots is assumed for an ice class IA tanker (Finnish-Swedish ice class rules) as the speed below which it cannot navigate independently (MAN Diesel and Turbo 2013b; Trafi 2017a; Solakivi et al. 2018), and a maximum speed of 16 knots for all tankers, where the design speed falls between 90-95% of the maximum speed depending on ship size (Lindstad et al. 2011). Port-related costs and time, as well as cargo handling are assumed the same for either route choice. Auxiliary fuel requirements are assumed to be satisfied by the use of the main engine, which depends on the ship and engine set up (Tanker Company 2019).

Repair costs, C_R, which are the result of ice damages, along with the RFR of a ballast voyage to visit a repair yard, following a laden voyage, are included when $k = 1$ or 0 otherwise. According to Tanker Company (2018) and Tanker Company (2020), ice damages occurred in 20% of their voyages through NSR, whilst proceeding with slow speed through ice on the NSR could reduce the risk of damages[19]. Thus, ice damage repairs are included in the sensitivity analysis to assess how the RFR is affected when these are factored in the model.

Partial differentiation of Equations (3), and (4) with respect to speeds $S^*_{FO}, S^*_{FO\,B}$, is carried out to obtain optimal speeds. The partial derivatives are set equal to zero, that is, $\frac{\partial RFR}{\partial_{S^*_{FO}}} = 0$, $\frac{\partial RFR}{\partial_{S^*_{FO\,B}}} = 0$, with optimal speeds subject to lower limit, $\underline{S}$, and upper limit, $\overline{S}$ respectively.

Equation 6 refers to the optimal speed for laden voyages, whilst equation 7 refers to the optimal speed of ballast voyages to a drydock following a laden voyage:

$$S^*_{FO} = \sqrt[a]{\frac{(C_O+C_C)\cdot {S_d}^{a} \cdot \nabla^{2/3}}{(a-1)\cdot(F_{FO\,d}\cdot P_{FO})\cdot(P+L)^{2/3}}} \tag{6}$$

$$S^*_{FO\,B} = \sqrt[a]{\frac{(C_O+C_C)\cdot {S_d}^{a} \cdot \nabla^{2/3}}{(a-1)\cdot(F_{FO\,d}\cdot P_{FO})\cdot(P+L)^{2/3}}} \tag{7}$$

Appendix K presents the calculations for equations (6) and (7). Equations (3) and (4) are solved by substituting the optimal speeds obtained from Equations (6) and (7) to give the minimum RFR for each leg of a certain OD.

These optimal speeds depend on fixed costs, fuel prices, and payload. Moreover, speeds through ice are assumed to not vary with respect to cost and market factors due to the influence of sea ice on ship speed, and therefore could be determined based on recorded speeds of tanker voyages through NSR (for assumptions on the average speed through ice: Section '4.3.2.5 Speed through ice on the NSR').

The total distance and time of each individual leg for a route alternative depends on ECA zones, fuel types and prices. They can be expressed as:

$$\sum_{i=1}^{n} D_{NSR} = D_{1,NSR} + \ldots + D_{n,NSR} \tag{8}$$

$$\sum_{i=1}^{n} T_{NSR} = T_{1,NSR} + \ldots + T_{n,NSR} \tag{9}$$

$$\sum_{i=1}^{n} D_{SCR} = D_{1,SCR} + \ldots + D_{n,SCR} \tag{10}$$

19 Other options that reduce the risk of damages could include the use of special ice coating. However, this option is considered in Chapter 6, as it is more appropriate when an ice class tanker operates on ice for a whole season (Tanker Company 2019). The number of voyages is not given in absolute value due to confidential reasons.

$$\sum_{i=1}^{n} T_{SCR} = T_{1,SCR} + \ldots + T_{n,SCR} \tag{11}$$

The optimal speed per voyage for a route alternative is defined as:

$$S_{FO}^{*} = \frac{\sum_{i=1}^{n} D_{NSR}}{\sum_{i=1}^{n} T_{NSR} \cdot 24} \tag{12}$$

$$S_{FO}^{*} = \frac{\sum_{i=1}^{n} D_{SCR}}{\sum_{i=1}^{n} T_{SCR} \cdot 24} \tag{13}$$

Whereas the optimal speed concerning ballast voyages from an unloading port to a dockyard are defined as:

$$S_{FO\ B}^{*} = \frac{D_B}{T_B \cdot 24} \tag{14}$$

The RFR differential between the NSR and SCR is defined as:

$$\Delta RFR = RFR_{SCR} - RFR_{NSR} \tag{15}$$

This speed optimisation approach is in line with Fagerholt et al. (2015), and Fagerholt and Psaraftis (2015), where distinct voyage legs and respective optimal speeds can be defined owing to different fuel types and prices, and environmental policies.

4.3.2 Assumptions and data

4.3.2.1 Origin – Destination pairs and routes

The choice of OD pairs is based on representative ports, distance savings, and tankers that operated through NSR and were involved in the transport of major oil products commodities during 2011-2020. Table 4.2 shows the number of oil products tanker destination and transit voyages on the NSR per tanker size between 2011 and 2020. 49 of the 52 voyages concerning tankers below 39,000 dwt comprised destination voyages between Russian ports. Most of these voyages involved fuel oil supplies linking different geographic regions in Russia (CHNL 2021a). In contrast, only 10 of the 43 destination and transit voyages of large tankers operated between Russian ports. Thus, small tankers and OD pairs for destination and transit voyages linking Russian ports are not considered since they are beyond the scope of this study.

Table 4.2. Number of voyages per tanker size during 2011-2020.

Large Tankers (40-162,000 dwt)	
Destination	Transit
Russian Arctic – Far East (17)	Far East – Europe (8)
Russian Arctic – Southeast Asia (3)	Baltic Russia – Far East Russia (3)
Far East Russia – Russian Arctic (3)	Far East Russia – Baltic Russia (3)
Russian Arctic – Far East Russia (1)	Baltic Russia – Far East (2)
Arctic Europe – Southeast Asia (1)	Europe – Far East (2)
Small Tankers (Below 39,000 dwt)	
Destination	Transit
Russian Arctic – Far East Russia (30)	Europe – Far East Russia (2)
Far East Russia – Russian Arctic (19)	Canada – Far East (1)

Sources: NSRA (2016), CHNL (2021a), Bloomberg (2021), Refinitiv Eikon (2021). The statistics include a crude oil tanker which transported jet fuel/kerosene from South Korea to the ARA region in 2018.

Table 4.3 shows the number of destination and transit voyages of large tankers on NSR per commodity during the 2011-2018 summer/autumn seasons. Most of the voyages comprised condensate cargo, followed by jet fuel/kerosene and naphtha, and gasoil/diesel cargo. Five voyages were in ballast i.e. they transited without cargo. All but one voyage of heavy fuel oil were conducted between Russian ports. Thus, heavy fuel oil is not considered in the analysis.

Table 4.3. Number of destination and transit voyages of large tankers (47-162,000 dwt) on NSR per commodity during 2011-2018.*

Commodity – Voyage type	Number
Condensate	19
Jet Fuel/Kerosene	6
Naphtha	5
Heavy Fuel Oil	5
Gasoil/Diesel	2
Ballast	5

*There have not been any large product tanker voyages in 2019 and 2020.

Table 4.4. shows the number of OD pairs per commodity transported by large tankers (47-162,000 dwt) during 2011-2018. Appendix L presents all OD pairs per tanker name, ice class, region, country, port, and cargo size and type. Most of the times condensate cargo was transported from the port of Vitino, Russia, in the White Sea, to South Korean ports. Jet fuel/kerosene and gasoil/diesel cargoes were mostly shipped from ports in South Korea to the Amsterdam-Rotterdam-Antwerp (ARA) region in Northwest Europe. Naphtha was mainly

shipped from either Mongstad, Norway, or Ust-Luga, Russia, in the Baltic to ports in the Far East.

Table 4.4. Number of OD pairs per commodity transported by large tankers (47-162,000 dwt) during 2011-2018.*

Commodity and OD pairs	
Condensate	Naphtha
Russian Arctic – South Korea (10) Russian Arctic – China (6) Russian Arctic – Thailand (1) Russian Arctic – Malaysia (1) Norway – Thailand (1)	Russian Baltic – South Korea (2) Norway – Japan (1) Norway – Taiwan (1) Russian Arctic – Japan (1)
Jet Fuel/Kerosene	Gasoil/Diesel
South Korea – ARA (3) South Korea – Finland (3)	South Korea – ARA (2)

Sources: NSRA (2016), CHNL (2021a), Bloomberg (2021), Refinitiv Eikon (2021). *There have not been any large product tanker voyages in 2019 and 2020. The statistics include a crude oil tanker which transported jet fuel/kerosene from South Korea to the ARA region in 2018.

The geographical implications on costs and economies of scale for alternative routes are investigated by assuming three OD pairs after considering historic NSR transit and destination voyages of large tankers during the 2011-2018 summer/autumn seasons. The choice of OD pairs is a combination of representative distance savings, representative number of voyages per commodity, and port characteristics which can accommodate the tanker sizes chosen for the modelling case. Appendix L includes a comparative distance analysis between NSR and SCR and provides notes on the choice of OD pairs. Using the NSR as a basis for comparison, the Vitino-Daesan pair is considered a representative short-haul and the Yeosu-Rotterdam pair a long-haul in terms of distance. The pair of Mongstad-Mizushima lies in between them and is considered as a medium-haul. Figure 4.1 illustrates OD pairs and sea routes between Europe and Asia. Table 4.5 presents distances, including distance legs within ECAs. Table 4.6 presents distances between unloading ports and repair yards. Appendix M presents port characteristics.

Table 4.5. OD pairs and distances.

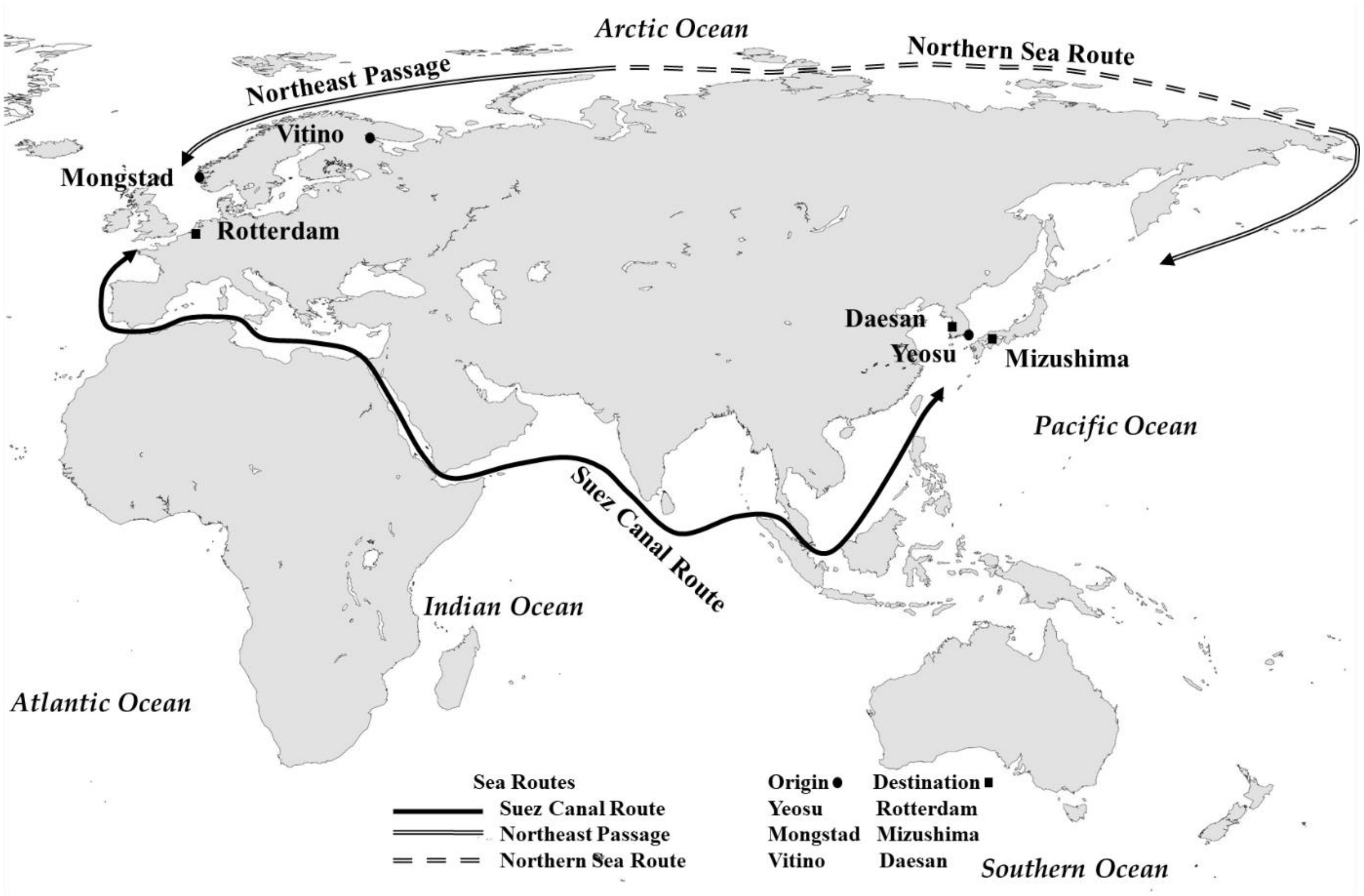
Origin – Destination (OD) Distance (n.m.)	Suez Canal (SCR)	Northern Sea Route (NSR)	Difference between NSR – SCR
Yeosu – Rotterdam (Long-Haul)	10,872 (ECAs: 413)	7,276 (ECAs: 629)	-33%
Mongstad – Mizushima (Medium-Haul)	11,605 (ECAs: 912)	6,668 (ECAs: 84)	-43%
Vitino – Daesan (Short-Haul)	12,943	6,487	-50%

Source: Dataloy (2021). The distance through NSR is assumed 2,059 n.m. and refers to the deep-water high-latitude route north of the New Siberian Islands, based on the majority of historic NSR voyages (Bloomberg 2021).

Table 4.6. Distances between the unloading ports and repair yards.

From destination port to repair yard	Distance (n.m.)
Rotterdam – Lindo Havn	636 (distance is within ECAs)
Mizushima – Qushan	698 (ECAs: 91*)
Mizushima – Ulsan	295
Mizushima – Singapore	2,665
Daesan – Qushan	477
Daesan – Ulsan	414
Daesan – Singapore	2,536

Source: Dataloy (2021). *Maximum sulphur limit of 0.5% (mass by mass) for marine fuels used in the Yangtze River Delta area since 2019 (UK P&I 2015).



Source: Author, based on Equirectangular projection (NASA 2021).

Figure 4.1. OD pairs and route alternatives.

Traffic data reported on the website of CHNL show that the route north of the New Siberian Islands was used extensively during 2016-2019 (CHNL 2021b). AIS data from Bloomberg (2021) were subsequently used to track oil product tanker voyages recorded on CHNL (2021a) and provided by NSRA (2016) referring to the period 2011-2019. The data show that almost all oil product tankers used the high-latitude route north of the New Siberian Islands between 2011 and 2019 (Bloomberg 2021). Therefore, the deep-water high-latitude route north of the New Siberian Islands is chosen to inform the RFR model with respect to distance comparisons. Moreover, this route is suitable for large tankers, given that the route through the Sannikov Strait imposes draught restrictions (13 metres depth), which limit the use of the NSR to only small and medium ship sizes (Mulherin 1996). On the other hand, there is a trade-off between bathymetry in the Sannikov Strait and difficult ice conditions on the high-latitude route north of the New Siberian Islands (Stephenson et al. 2014).

4.3.2.2 Cost and navigational factors

The tanker sizes chosen in the analysis are Medium Range (MR), Long Range 1 (LR1), Long Range 2 (LR2), and Long Range 3 (LR3)/Suezmax based on the analysis in Section '4.3.2.1 Distances and routes'. The LR3 size is chosen to facilitate the analysis of economies of scale, although only one tanker of this size was used on the NSR during 2011-2020. Currently, oil products trades involving such tanker sizes are limited, but they could be used in heavy fuel oil or crude oil trades as well. The ice class IA is chosen for the comparison between ice and non-ice class ships, as this ice class currently represents the majority of the global ice class fleet (Trafi 2017b; Solakivi et al. 2018). The ice class IA is also in line with the majority of the tankers that used the NSR from 2011 to 2019 (NSRA 2016; CHNL 2021a). Generally, an ice class IA ship is capable of navigating on first-year ice with a maximum thickness of 1.0 metre (MAN Diesel and Turbo 2013b; Trafi 2017a).

Table 4.7. Tanker characteristics and newbuilding prices.

Tanker Size	DWT (Tonnes)	Design Speed (knots)	Fuel Tank Capacity HSFO/VLSFO* (tonnes)	Newbuilding price (Million US$)
LR3 Tanker	162,362	15.0	3,150	74.6
LR2 Tanker	117,055	14.9	2,415	62.0
LR1 Tanker	74,158	15.0	2,130	48.0
MR Tanker	47,842	14.9	1,616	40.0

Sources: Clarksons (2021), Appendix N. *Assumed to be the same as HSFO.

The technical characteristics and prices of these tankers are presented in Tables 4.7, and 4.8, respectively. The fuel consumption in tonnes per day at the design speed for each engine set-up is obtained from Clarksons (2021). More specifically, assumptions on fuel consumption for ice class tankers refer to values of the ice class tankers which operated on NSR in 2011-2014, whereas assumptions on fuel consumption for ordinary tankers refer to global average values during the same period. Detailed assumptions are provided in Appendix N. HSFO gives higher consumption than VLSFO and MGO owing to its lower energy density, whereas MGO gives the lowest consumption.

Table 4.8. Fuel consumption at design speed.

	Fuel Consumption (tonnes per day)		
Tanker Size	HSFO	VLSFO	MGO
	Ordinary Tankers		
LR3 Tanker	62.2	60.7	58.6
LR2 Tanker	47.1	46.0	44.3
LR1 Tanker	42.3	41.3	39.8
MR Tanker	33.9	33.1	31.9
	Ice Class Tankers		
LR3 Tanker	67.0	65.4	63.1
LR2 Tanker	50.5	49.3	47.5
LR1 Tanker	42.5	41.5	40.0
MR Tanker	34.4	33.6	32.4

Sources: Clarksons (2021), Appendix N. Fuel type conversions are based on calorific values (heating values) from IMO (2016b): From HSFO to MGO: MGO = HSFO · (40,200/42,700), from MGO to VLSFO: VLSFO = MGO · (42,700/41,200).

Operating costs and capital costs assumed in the analysis are presented in Tables 4.9 and 4.10, respectively. Appendix O1 presents the method which is used to calculate capital costs. This method is also used to calculate capital costs for tankers in Chapters 5 and 6, although based on different assumptions.

Table 4.9. Operating costs for MR – LR3 tankers.

Route	Year						
	2011-2013	2014	2011-2014	2015-2017	2018	2019	2020
	LR3 Tanker						
SCR	9,452	9,452	9,452	9,071	8,813	8,537	8,726
NSR	9,947	9,947	9,947	9,560	9,298	9,011	9,216
	LR2 Tanker						
SCR	8,264	8,264	8,264	7,785	7,386	7,143	7,302
NSR	8,706	8,706	8,706	8,211	7,797	7,542	7,715
	LR1 Tanker						
SCR	8,409	8,409	8,409	8,043	7,860	7,709	7,883
NSR	8,859	8,859	8,859	8,489	8,302	8,144	8,333
	MR Tanker						
SCR	7,868	7,868	7,868	7,590	7,284	7,076	7,209
NSR	8,299	8,299	8,299	8,017	7,698	7,480	7,627

Sources: Author, based on BDO (2021).

Most of the ice class tankers which operated on the NSR during 2011-2019 were ordered in 2004-2005 and were delivered three years later, i.e. in 2007 (Clarksons 2021). Thus, the newbuilding prices of 2004 are used to estimate capital costs for each tanker size, which are assumed to be repaid in 10 years from the date of delivery i.e. 2017. This assumption facilitates the cost comparison between alternative routes for tankers with varying cost structures across time. The same logic applies to operating costs, fuel prices, and ship speed on ice, which are assumed to vary on an annual basis between 2011 and 2020. Moreover, a cost comparison between tankers with and without capital costs after 2017 is included in the analysis to explain how optimal speeds and costs are affected for competing routes.

Table 4.10. Capital costs for MR – LR3 tankers.

Route	Year			
	2011-2013	2014	2011-2014	2015-2017
	LR3 Tanker			
SCR	16,876	16,876	16,876	16,876
NSR	22,006	22,006	22,006	22,006
	LR2 Tanker			
SCR	14,025	14,025	14,025	14,025
NSR	18,289	18,289	18,289	18,289
	LR1 Tanker			
SCR	10,858	10,858	10,858	10,858
NSR	14,159	14,159	14,159	14,159
	MR Tanker			
SCR	9,049	9,049	9,049	9,049
NSR	11,799	11,799	11,799	11,799

Sources: Calculations based on Appendices O1 and O2.

Oil product tankers usually do not utilise their maximum capacity, partly due to the low density of certain oil products and partly due to smaller than the ship's dwt cargo sizes (Stopford 2009). Cargo sizes used in the analysis as well the difference between the draught and draught when loaded, based on TPC, are presented in Table 4.11. These are based on average cargo size carried by ice class product tankers operated on NSR in 2011-2019 (CHNL 2021a).

Table 4.11. Cargo sizes and draught.

Tanker Size	Tanker Size on NSR (DWT tonnes)[a]	Cargo Size on NSR (tonnes)[a]	Tonnes per Centimetre Immersion (TPC)	Draught (metres)	Draught when loaded (metres)[b]
LR3 Tanker	162,362	120,843	118.0	16.3	13.4
LR2 Tanker	113,074	87,139	98.0	15.4	13.0
LR1 Tanker	73,828	60,662	67.3	14.3	12.9
MR Tanker	47,327	35,943	52.1	12.5	10.7

Sources: [a]NSRA (2016), CHNL (2021a), [b]calculations based on Appendix N.

Increased costs for ice class tankers refer to premiums in capital, operating and voyage costs. Whilst the literature on comparative studies of Arctic routes has increased considerably since 2011, so has the difficulty of identifying valid parameters regarding certain cost and operational factors. Minimal shipping activity in the Arctic regarding transits coupled with operations in harsh climate, sea ice, and the relatively small ice class fleet globally, increase the variability of estimates, and underline the difficulty of obtaining a global view on Arctic shipping economics. Solakivi et al. (2018) and Solakivi et al. (2019) recently attempted to address this gap by statistically analysing and determining increased costs of ice class containerships, and bulkers and tankers respectively.

A capital cost premium of 30.4% for a new ice class IA tanker is assumed based on Solakivi et al. (2018) (also Table 4.7). A tanker company with extensive experience on the NSR provided the following premiums: maximum insurance premium at US$ 50,000, costs for books and charts at US$ 20,000 per voyage, increased daily crew costs in US$ by 10%, higher rate for ice piloting at US$ 1,000 per day and US$ 5,000 for travel expenses (Tanker Company 2018). Additional insurance premiums for piracy and armed guards when operating off the Gulf of Aden are approximated at US$ 60,000 in 2011-2014 and US$ 24,000 in 2015, whereas these are estimated at US$ 10,500 per round voyage during 2018-2020 (Tanker Company 2018).

A fixed cost of US$ 180,000 is assumed for ice damage repairs and relevant costs if these occur for any voyage from Rotterdam, after discharing a cargo, to a repair yard in Odense, Denmark. Similarly, ice damage repairs are estimated at US$ 120,000 in any repair yard located at the Yangtze River Delta area, and US$ 168,000 for any voyage either from Mizushima or Daesan to a repair yard in either Singapore or Ulsan, South Korea (Tanker Company 2020). Moreover, additional costs are assumed for the voyage between the unloading port to a yard (Section '4.3.1 Modelling approach'). The premiums are valid regardless of tanker size (Tanker Company 2018). Moreover, a lumpsum of US$ 190,000 owing to ship-to-ship (STS) transfer operations for Suezmax/LR3 tankers is included when loading nearby the port of Vitino, Russia.

4.3.2.3 Fuel Prices

Table 4.12 presents the assumptions on fuel oil prices used in the analysis. They refer to average prices in Rotterdam and Singapore, which are used as proxies for the OD pairs in the analysis. Similar to capital costs, operating costs, and ship speed on ice, fuel oil prices vary depending on the scenario, in order to facilitate the cost comparison between alternative routes for tankers with varying cost structures across time.

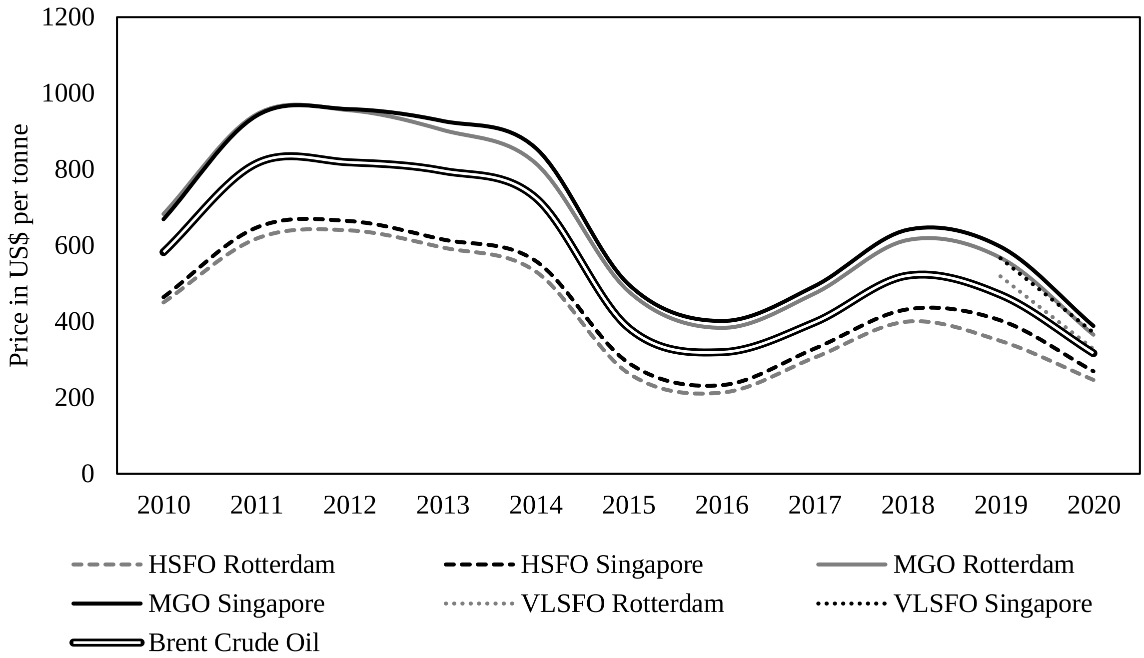
Table 4.12. Average fuel oil prices in Rotterdam and Singapore during 2011-2020.

Fuel Type & Price in US$/t	2011-2013	2014*	2011-2014	2015-2017	2018	2019	2020
HSFO	600	600	600	260	400	380	350
MGO	900	900	900	450	630	580	380

Source: Clarksons (2021). *HSFO and MGO fuel prices during 2014 were 546 US$/t and 837 US$/t, respectively. Yet, the 2011-2013 average value is used for that year, since the results are not affected significantly.

Figure 4.2 illustrates annual fuel oil prices in the two major oil and fuel oil hubs of Rotterdam and Singapore between 2010 and 2020. The figure includes the price of the most important benchmark crude oil globally, the Brent[20], and the prices of HSFO, VLSFO, and MGO, in Rotterdam and Singapore, respectively. Both the crude oil and fuel oil prices demonstrate significant volatility and all fuel oil prices are highly correlated with the price of Brent crude oil (Gjølberg and Johnsen 1999; Lindstad and Eskeland 2015).

[20] Tamvakis (2005) provides a general overview of oil benchmarks in his book. The Intercontinental Exchange recently published three short reports on crude oil benchmarking and the significance of Brent crude oil for the global oil markets (ICE 2021a; 2021b; 2021c).



Source: Clarksons (2021).

Figure 4.2. Brent crude oil and marine fuel oil prices between 2010 and 2020.

The Brent crude oil price rose by 40% during 2011 and remained at very high levels until September 2014. It significantly declined by 47% during 2015 and dropped by a further 17% in 2016. It then increased by 24% and 31% in 2017 and 2018, respectively, only to contract again by 10% and 33% during 2019 and 2020, respectively. Fuel oil prices followed similar price developments between 2010 and 2020. They reached all-time highs in 2012 with the price of HSFO at 640 US$/t in Rotterdam and 664 US$/t in Singapore, and the price of MGO at 955 US$/t in Rotterdam and 958 US$/t in Singapore, respectively. It can be seen that MGO is the most expensive fuel, followed by VLSFO and HSFO.

4.3.2.4 Transit fees and icebreaking assistance

Suez Canal Tolls depend on the type of ship, routeing direction (northbound, southbound), the Suez Canal Net Tonnage (SCNT) of a ship, its draught and beam, laden or ballast condition, and are determined by the special drawing rights (SDR) exchange rates. The Suez Canal tariff rates and average USD per SDR rates during July-November 2011-2020 are used to calculate the Suez Canal Tolls (IMF 2021a; Leth Agencies 2021a)[21]. Additional costs, such as tugs, mooring, pilotage, and disbursements were calculated by using an online calculator from Leth agencies (Leth Agencies 2021b).

[21] The average SDR rates in July-November are used for an equal comparison with the NSR summer/autumn season.

According to the latest rules of the Northern Sea Route Administration (NSRA), icebreaking assistance depends on the prevailing ice and climatic conditions (Gritsenko and Kiiski 2016). Unescorted voyages may occur when sea ice and climatic conditions are favourable. This is evident in the voyage records of the 2011-2020 summer/autumn navigation seasons (CHNL 2021a). However, there are limited data regarding icebreaking assistance operations in general. The long-term trend of sea ice extent and thickness in the Arctic exhibit anomalies of negative values (Parkinson and Comiso 2013; Lindsay and Schweiger 2015).

However, there exists high inter-annual variability and uneven distribution of sea ice conditions in the Russian Arctic, especially in the Laptev Sea, East Siberian Sea, and East Kara Sea in the medium-term (Stephenson et al. 2014). In addition, ship operators may be advised to use icebreaking escort owing to insurance policy requirements (Sarrabezoles et al. 2016; Fedi et al. 2018; Fedi et al. 2020). Thus, icebreaking assistance is assumed in the analysis when operating on the NSR. Icebreaking fees depend on the ice class of a ship, gross tonnage, number of escorting zones and period of navigation (summer/autumn: July-November, winter/spring: December-June), and are determined by the US Dollar – Russian Rouble (USD/RUB) currency exchange rates (NSRA 2014; Bank of Russia 2021).

Discounted icebreaking fees are assumed to reflect a flexible tariff policy during 2011-2013, whereas official fees are assumed during 2015-2020, following the introduction of the latest tariffs in 2014 (NSRA 2014). Discounted fees are also considered for the year 2014, assuming a flexible tariff policy similar to that during 2011-2013 since high fuel prices that year could have still incentivised operators to use the NSR as an alternative. Moreover, two additional scenarios are formulated to assess how the NSR RFR would have been affected, assuming official fees in 2011-2013 based on the tariff regime of the same period, and official fees during 2014, the year where the latest tariff rates were introduced (NSRA 2014). The practice of negotiated tariffs is well documented in the literature (Lasserre 2014; Lasserre 2015; Gritsenko and Kiiski 2016; Moe and Brigham 2016) and is also confirmed by the industry (Falck 2012; Tanker Company 2018). Besides, tariff rates during 2011-2013 as well as the latest ones introduced in 2014 were and are based on maximum rates, implying that these are negotiable (ARCTIS 2021c; NSRA 2014; Gritsenko and Kiiski 2016; Moe and Brigham 2016). The NSRA icebreaking fees and Suez Canal Tolls are presented in Table 4.10. Appendix P presents the assumptions and calculations for transit fees.

Table 4.13 presents the transit fees assumed for both SCR and NSR, respectively. It can be seen from Tables 4.12 and 4.13 that there exists an inverse relationship between the USD/RUB exchange rate and fuel oil prices. The reason is that the USD/RUB exchange rate is usually high at low crude oil prices and vice versa, indicating an inverse relationship between them – these relationships are illustrated in Figures 5.13 and 5.14 in Chapter 5 (Beckmann and Czudaj 2013; Yang et al. 2017; Shibasaki et al. 2018; Chuffart and Hooper 2019).

Table 4.13. NSRA icebreaking fees and Suez Canal Tolls for MR – LR3 tankers.

	Year						
Transit Fees in USD	2011-2013	2014	2011-2014	2015-2017	2018	2019	2020
NSRA Tariff Rate	530.0	446.8	Discounted Fees	446.8	446.8	446.8	446.8
USD/RUB Rate	31.4	39.1	33.2	62.1	65.8	64.4	75.1
	LR3 tanker						
NSR Fees	2,039,232	1,019,730	604,215	642,137	606,761	619,582	531,574
SCR Fees (Southbound)	409,143	409,143	409,143	408,609	407,799	401,301	411,979
SCR Fees (Northbound)	409,761	409,761	409,761	409,227	408,418	403,872	412,597
	LR2 tanker						
NSR Fees	1,470,476	735,175	435,695	462,949	437,445	446,688	383,239
SCR Fees (Southbound)	370,626	370,626	370,626	370,315	369,579	364,476	375,576
SCR Fees (Northbound)	371,208	371,208	371,208	370,897	370,161	365,058	376,195
	LR1 tanker						
NSR Fees	1,023,675	482,693	303,310	303,957	287,212	293,281	251,622
SCR Fees (Southbound)	245,374	245,374	245,374	240,862	240,369	236,974	243,210
SCR Fees (Northbound)	245,931	245,931	245,931	241,419	240,926	237,531	243,767
NSRA Tariff Rate	530.0	536.21	Discounted Fees	536.21	536.21	536.21	536.21
	MR tanker						
NSR Fees	606,540	387,229	179,715	243,570	230,152	235,015	201,633
SCR Fees (Southbound)	190,050	190,050	190,050	183,001	182,628	180,119	184,663
SCR Fees (Northbound)	190,484	190,484	190,484	183,435	183,062	180,553	185,097

Sources: Calculations based on Appendix P.

4.3.2.5 Speed through ice on the NSR

There exists high uncertainty regarding the operating speed on ice, which is largely determined by sea ice thickness, sea ice concentration, ice ridges, ice floes and icebergs amongst others (Löptien and Axell 2014; Aksenov et al. 2017). Ship speed through ice depends on navigation season, month and zone, as well as on the ice class of a ship (Stephenson et al. 2014; Faury and Cariou 2016; Faury et al. 2020; Cheaitou et al. 2020; Cariou et al. 2021). This means that speed through ice may not be optimised with respect to cost and market factors as on open water, and therefore it has to be approximated based on either physical factors, such as ice thickness, or on real speeds recorded on the NSR. Voyage data from the Northern Sea Route Administration (NSRA), the Centre for High North Logistics (CHNL), and ARCTIS website were analysed initially to determine the speed through ice water during the summer/autumn navigation season. Of the transit years provided by these sources, speeds are reported only in 2012 and 2013 (ARCTIS 2021a; NSRA 2016; CHNL 2021a). Speed data concerning 2011 were compiled from various sources to complement the data from NSRA, CHNL and ARCTIS. In addition, AIS data were collected from Bloomberg to analyse the actual speeds of these voyages during the 2011-2019 summer/autumn seasons (Bloomberg 2021).

Speeds obtained from Bloomberg were finally used in the analysis, as these are deemed accurate and more detailed than those reported in the aforementioned sources. AIS data of 44 transit and destination tanker voyages conducted during the 2011-2019 summer/autumn seasons were analysed (Bloomberg 2021). The data comprise 29,964 observations of tanker speeds recorded per minute for every transit between Cape Zhelanya/Kara Strait and Cape Dezhnev from end of June (30th) to mid-November (17th). The average speed on ice is calculated by dividing the travelled distances by the time interval between the start and end points of each voyage on the NSR. The speed per voyage ranges between 5.7 and 14.3 knots, highlighting the challenging conditions in the Arctic. The average speed of all voyages is found 10.1 knots during 2011-2017[22], 10.2 knots during 2018, and 10.3 knots during 2018-2019. The speed on ice found during 2018-2019 is also used as reference for the year 2020.

These average speeds are close to speeds used by Wergeland (1992) and Mulherin (1996) in their studies, that is, 11.25 knots on average during the summer/autumn season. Moreover, studies, which modelled ship speed through NSR, based on ship speed – sea ice dependency,

[22] There have not been any tanker voyages between 2015 and 2017 in the range of MR-LR3 tanker sizes. Therefore, the speed for these years is assumed the same as in 2011-2014. Detailed speed statistics through ice per navigation zone and month are provided and used in the analysis in Chapter 6.

report values which are close to the real speeds recorded through ice. An average speed of 10 knots on the NSR (Kitagawa 2001), with a minimum of 7.5 knots (von Bock und Polach et al. 2015) for LR2 tankers, and a maximum of 13-14.5 knots during summer/autumn for ships of LR1/Panamax size (Kitagawa 2001; Faury and Cariou 2016).

4.4 Analysis

4.4.1 Examining the periods 2011–2014 and 2015–2017

4.4.1.1 Optimal ship speed and fuel prices

The periods 2011-2014 and 2015-2017 are analysed in this section. The relationship between RFR and ship speed is illustrated in Figure 4.3 by using the results of a LR2 tanker voyage on the Yeosu-Rotterdam pair as an example, since this trade reflects large annual long-haul oil product volumes between the Far East and Europe (IEA 2020c). Numerical results for other tanker sizes and OD pairs are reported in Appendix Q. The left-hand side of Figure 4.3 refers to the SCR and the right-hand side to the NSR. The vertical axis represents the minimum RFR in US$/t as a function of optimal ship speed in knots (horizontal axis), with the solid curves in the graphs reflecting the period 2011-2014 and the square dotted curves the period of 2015-2017. The figure shows that when HSFO/MGO fuel prices dropped from 600/900 US$/t in 2011-2014 to 260/450 US$/t in 2015-2017[23], the minimum RFR for a single voyage decreased from 20.2 and 17.9 US$/t to 16 and 15.7 US$/t for the SCR and NSR, respectively. The change in the SCR-NSR RFR differential from high to low fuel oil price levels is illustrated by a shift of the RFR curves downwards to the left. The RFR differential was 2.3 US$/t during 2011-2014, whereas it narrowed to 0.3 US$/t during 2015-2017, which shows that the shorter NSR is favoured at high fuel prices and discounted icebreaking fees.

[23] The analysis is based on average annual fuel prices in Rotterdam and Singapore (Clarksons 2021). It is assumed that HSFO is used for the period 2011-2014 in both ECAs and non-ECAs legs, and that MGO is used for the period 2015-2020 in ECAs legs, following the implementation of the 0.1% sulphur limit for fuels within ECAs (IMO 2021).

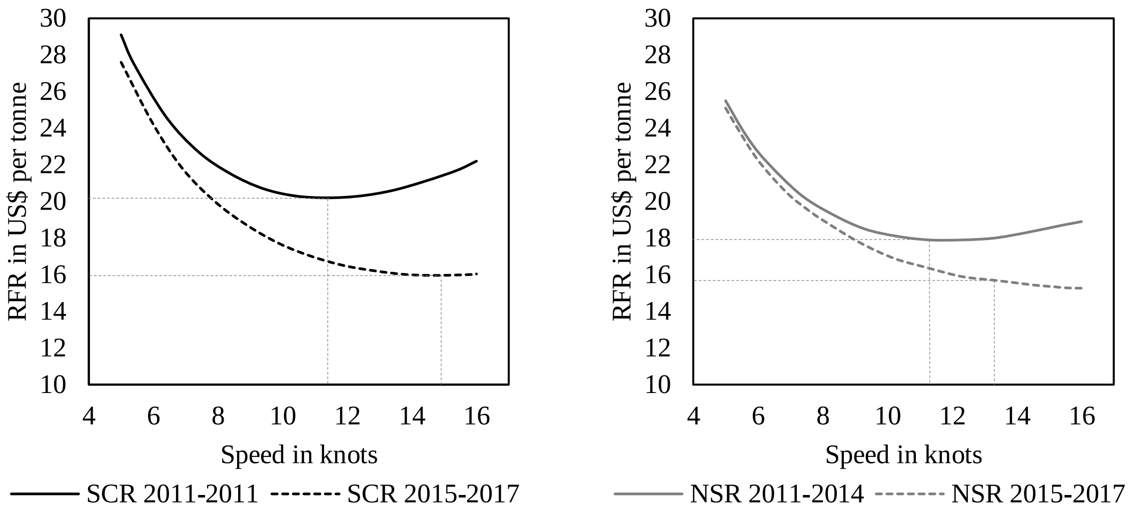


Figure 4.3. Relationship between optimal speed and minimum RFR for LR2 tanker on the Yeosu-Rotterdam pair at high (2011-2014) and low (2015-2017) fuel prices.

The optimal speed gives the minimum RFR for each route, which is different than when a ship operates at the design speed. The U-shaped RFR curves demonstrate the trade-off between fixed and variable costs, with any departure from optimal speeds being cost-wise inefficient. When the speed is lower than the optimal one, fuel costs decrease non-linearly whereas capital and operating costs increase due to the additional days per voyage, and vice versa. The optimal speed increased from 11.4 knots and 11.3 knots in 2011-2014 to 14.9 knots and 13.3 knots in 2015-2017 on the SCR and NSR, respectively. This confirms that speed optimisation and slow steaming practices can be mainly adopted at a high fuel price environment, whereas optimal speeds are close to design speed or even higher when fuel prices are very low. Should ballast voyages be included in the analysis, it would have been observed that laden speeds tend to be lower than ballast speeds. More specifically, optimal laden speeds are lower by 1.4 knots (SCR: 2011-2014) - 1.8 knots (SCR: 2015-2017), and 1.0 knots (NSR: 2011-2014) - 1.1 knots (NSR: 2015-2017) than the respective optimal ballast speeds due to the higher resistance and fuel consumption when a ship is laden. The lower optimal speeds on NSR than those on SCR is the result of the lower speed through ice, which is assumed fixed at 10.1 knots, regardless of fuel price levels.

4.4.1.2 Ship size, fuel prices, and distance between 2011 and 2017

The relationship between the minimum RFR and ship size across all OD pairs is depicted in Figure 4.4, with numerical results reported in Appendix Q. Using the NSR as a basis of comparison, the Yeosu-Rotterdam pair is considered as a long-haul, whereas the Vitino-Daesan pair a short-haul. The Mongstad-Mizushima pair is found in between these two OD pairs and is considered as a medium-haul. Distance savings increase gradually for the NSR when moving from the long to the short-haul between Northwest Europe/Baltic/Arctic to Northeast Asia. The results are based on the optimal speed, which minimises the RFR at a given OD pair and tanker size. As in Figure 4.3, there is a distinction between 2011-2014 and 2015-2017 with a high and low fuel oil price environment reflected in solid and square dotted RFR curves for each route, respectively. According to an oil product tanker shipowning company with extensive experience on the NSR, operators consider the costs of repairs when assessing alternative routes to take into account the risk of severe ice damages to the hull of a ship (Tanker Company 2018; Tanker Company 2020). To distinguish between cases where costs for repairs are included, results are shown separately in Figure 4.4. On the right-hand side, results for the SCR are kept constant, whereas those of the NSR are adjusted accordingly.

Several observations can be made concerning the relationship between the minimum RFR and ship size as well as the influence of geography on route competitiveness. First, the results show that there is always an advantage of using large tankers across every OD pair and route alternative, for these give a lower RFR than small tankers, all else being equal. Second, the economies of scale derived from large tankers in absolute terms decline when moving towards the shortest OD pair for a given route alternative. This means that scale economies are larger for the NSR on the Yeosu-Rotterdam pair but smaller on the Vitino-Daesan pair, whereas the opposite holds true for the SCR. Figure 4.5 shows this relationship with the long-haul RFR curve for each route alternative being steeper than the short-haul RFR curve. Not only do costs fall with the increase in tanker size, but also this decline is bigger in absolute terms at higher fuel prices for a given OD pair and route alternative. Figure 4.6 shows this relationship, where RFR curves at low fuel prices for both the SCR and NSR are not as steep as they are at high fuel price levels. Third, the RFR differential between SCR and NSR widens when moving from the long to the short-haul both with and without repairs. The SCR-RFR is gradually increased, whereas the NSR-RFR is decreased across all ship sizes. It should be noted that STS operations costs, when loading cargo near the port of Vitino, reduce the benefits derived from using LR3 tankers on the Vitino-Daesan pair for both the SCR and NSR. This is illustrated in Figures 4.5

and 4.6, where the respective LR3 RFR curves for the Vitino-Daesan pair are flatter compared to the LR3 RFR curves of the other two OD pairs. As a result, the LR3 NSR RFR is higher than the LR2 NSR RFR on the Vitino-Daesan pair. Further, the LR3 NSR RFR on the Vitino-Daesan pair is higher than the LR3 NSR RFR on the Mongstad-Mizushima pair.

The lowest RFR for the SCR was achieved by using a LR3 tanker on the Yeosu-Rotterdam pair at 13.7 US$/t. The lowest RFR for the NSR was achieved by using a LR3 tanker on the Mongstad-Mizushima pair at 13.5 US$/t, whereas this would have been 15.2 US$/t if repairs were included. These RFR rates refer to low fuel price levels (2015-2017), whereas they were higher by 3.6 US$/t and 1.8 US$/t at high fuel prices (2011-2014) for the SCR and NSR, respectively. Figure 4.4 shows that the NSR was more competitive than the SCR across all OD pairs at high fuel prices (2011-2014) and discounted icebreaking fees. However, the SCR-NSR RFR differential was very low or negative on the Yeosu-Rotterdam pair, that is, between 0.8 US$/t for an MR tanker and -0.6 US$/t for a LR3 tanker, at low fuel prices and official icebreaking fees. The RFR differentials on the Mongstad-Mizushima pair ranged from 3.8 US$/t (MR) to 3.1 US$/t (LR1) to 2 US$/t (LR2) and 0.9 US$/t (LR3) at low fuel prices and official icebreaking fees. The official icebreaking fees were relatively low during 2015-2017 owing to the depreciation of the Russian rouble in 2015, but still higher than the discounted ones. When including ice damage repairs in the model, the RFR differential on the Yeosu-Rotterdam pair was negative at both low and high fuel price levels across all tanker sizes. It also narrowed significantly for LR2 tankers at 1.9 US$/t and for LR3 tankers at 1.1 US$/t at high fuel prices or became negative for all tanker sizes except LR1 tanker at low fuel prices on the Mongstad-Mizushima pair. On the other hand, the RFR differential on the Vitino-Daesan pair was less impacted across all tanker sizes when including repair costs regardless of the fuel price levels. However, the RFR differential narrowed significantly for LR3 tankers at low fuel prices, which is largely attributed to the STS transfer operation costs for a LR3 tanker near the port of Vitino.

The RFR differential on the Yeosu-Rotterdam pair would have been lower if MGO fuel was used in ECAs prior to 2015. The reason is that the NSR ECAs leg is longer than the SCR ECAs leg against the Yeosu-Rotterdam pair. On the other hand, the RFR differential on the Mongstad-Mizushima pair would have been higher due to a significantly shorter ECAs leg for the NSR compared to that for the SCR.

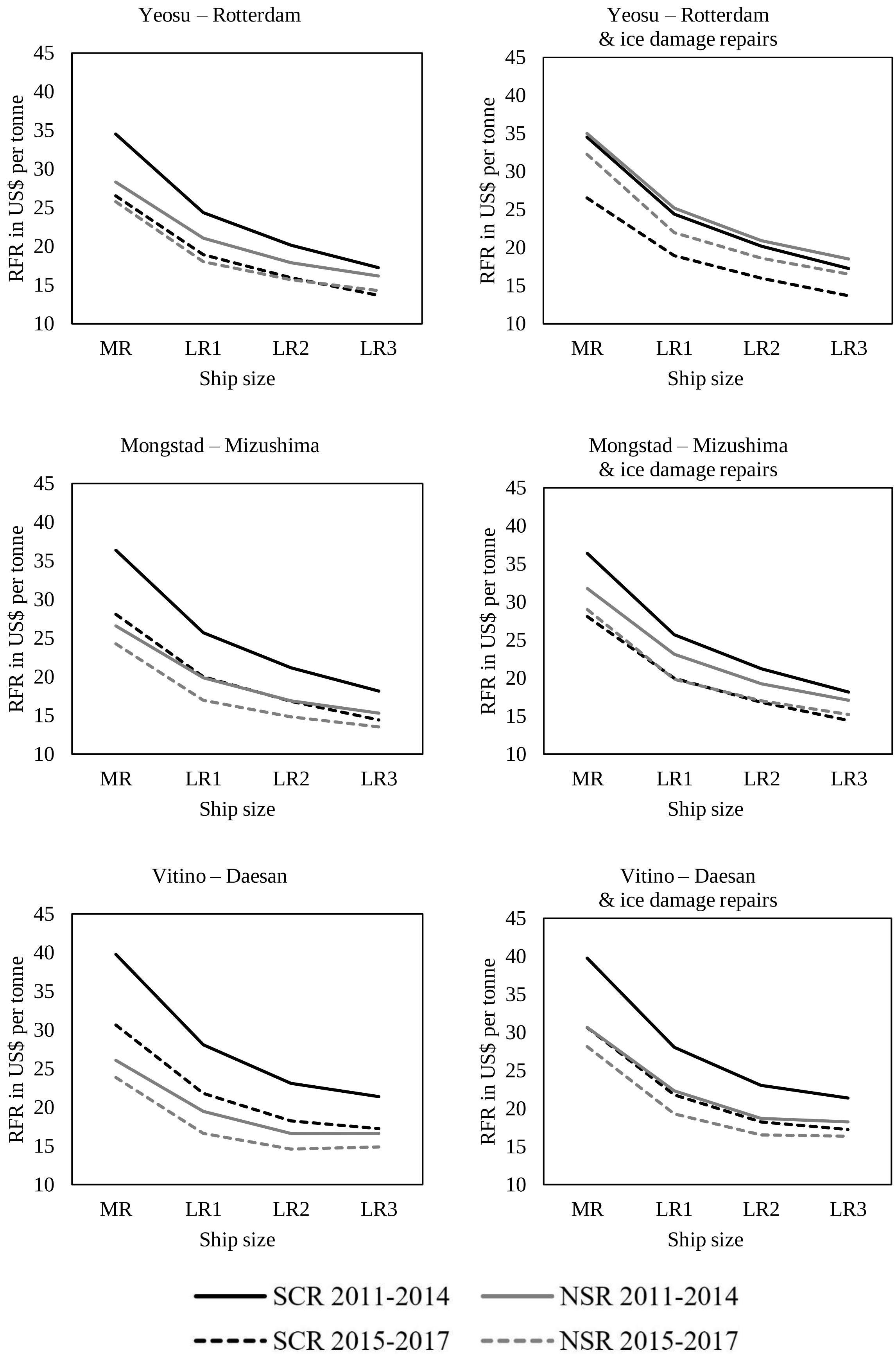


Figure 4.4. Relationship between ship size and minimum RFR for a given OD pair at high (2011-2014) and low (2015-2017) fuel prices, with and without ice damage repairs.

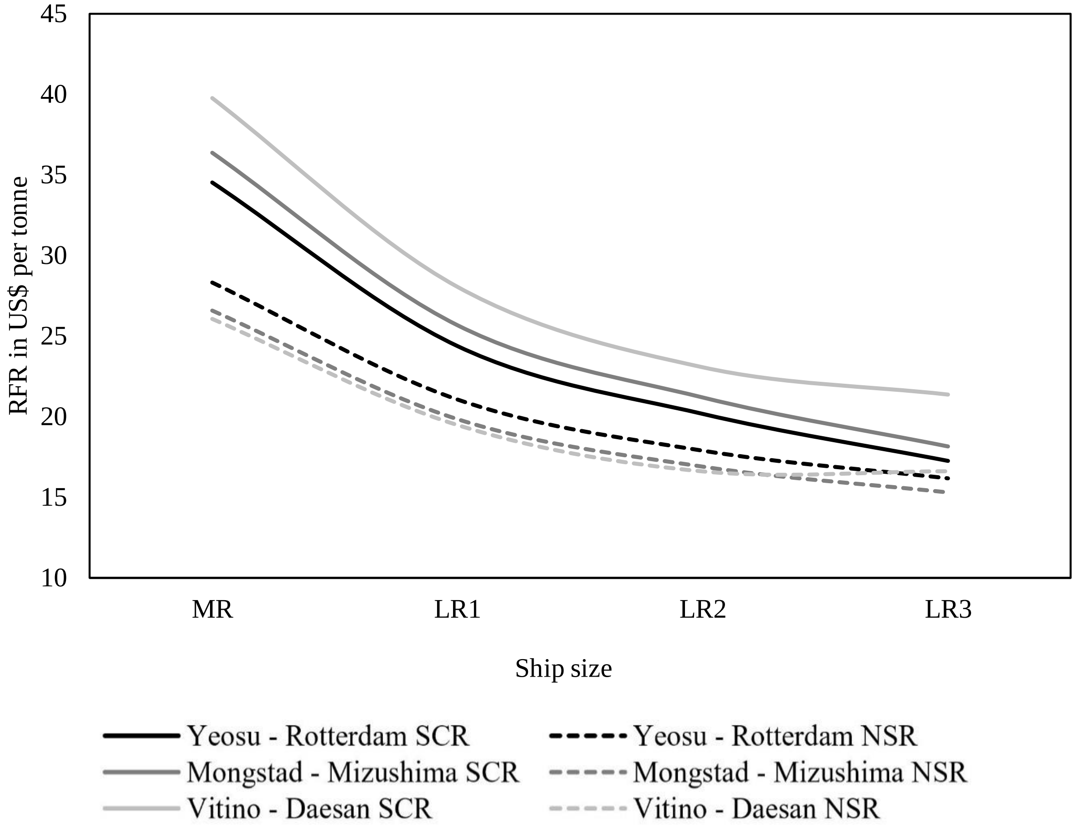


Figure 4.5. Relationship between ship size and minimum RFR for a given distance at high (2011-2014) fuel prices.

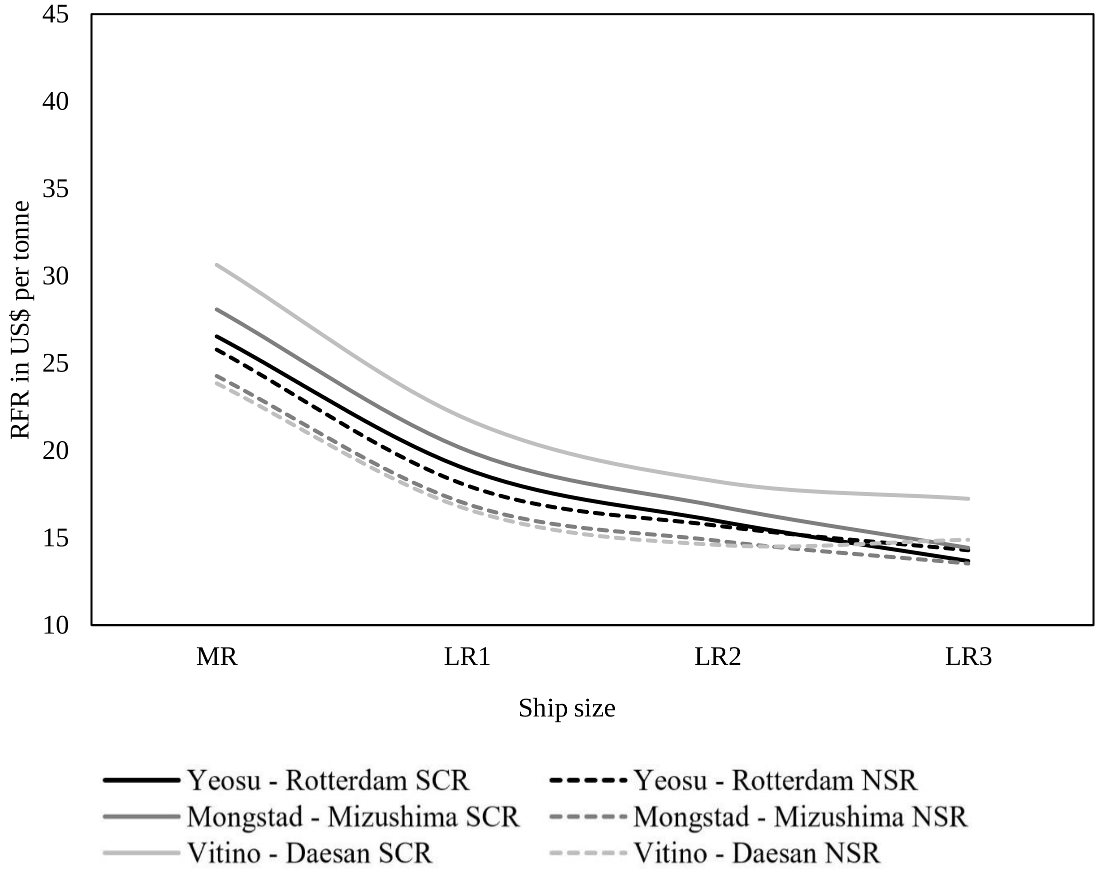


Figure 4.6. Relationship between ship size and minimum RFR for a given distance at low (2015-2017) fuel prices.

It should be mentioned that if the high-latitude route north of the New Siberian Islands is not accessible, then the Sannikov Strait sets the upper boundary with regards to ship size or dwt utilisation. The draught restriction of 13 metres means that the SCR becomes more competitive for a given OD pair when using tankers larger than an MR size, but this also depends on cargo size and dwt utilisation. Yet, this effect is dependent on the OD pair distance and fuel price levels. For example, the use of LR1 (LR2) tankers on the NSR is cheaper compared to the use of LR2 (LR3) tankers on the SCR against the Mongstad-Mizushima pair at high fuel prices. The competitiveness of the NSR increases further against the Vitino-Daesan pair, with LR1 tankers on the NSR being more competitive than even LR3 tankers on the SCR, either at high or low fuel price levels. Moreover, using an MR tanker on the NSR offers lower transport costs than a LR1 tanker on the SCR at high fuel price levels. On the other hand, there are no benefits when using smaller tankers on the NSR compared to larger tankers on the SCR against the Yeosu-Rotterdam pair, regardless of fuel prices, as well as against the Mongstad-Mizushima pair at low fuel prices.

Figure 4.7 shows results when comparing the NSR competitiveness against all OD pairs under three different periods and icebreaking fees regimes. The period 2011-2013 is shown with and without discounted fees.[24] Official icebreaking fees during that period refer to tariff rates introduced in 2011. The year 2014 is also included to show how the competitiveness of the NSR could have been impacted by the adoption of the latest official fees that year. The adoption of official fees based on tariff rates in 2011-2013 could have rendered the NSR uncompetitive even against the Vitino-Daesan pair and without including ice damage repairs in the analysis. The exception is the use of MR tankers without including repairs costs. The use of the official tariff rates adopted in 2014 could have reduced the SCR-NSR RFR differential significantly across all OD pairs, although the NSR could have retained its competitiveness against the medium and short-hauls in most cases. Yet, the RFR differentials could have been too narrow or even negative on the Vitino-Daesan pair and could have become negative on the Mongstad-Mizushima pair when including ice damage repair costs in the analysis.

[24] The average fuel price levels of 2011-2014 are assumed for this scenario since fuel prices in 2011-2013 were very close to fuel prices during 2014.

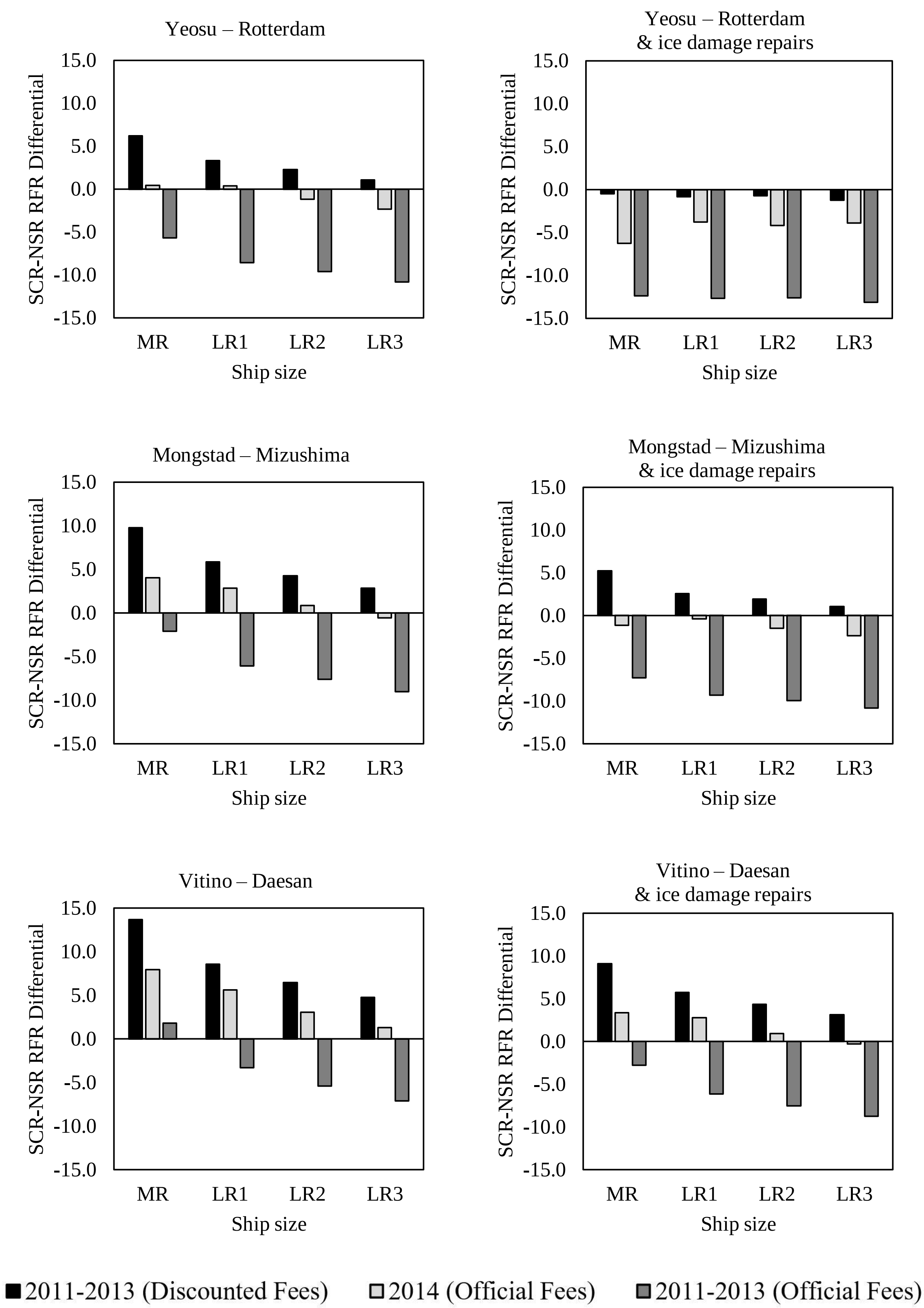


Figure 4.7. Comparison of results under three icebreaking tariff regimes and periods.

4.4.2 Modelling the years 2018, 2019, and 2020

In this section, the NSR is compared to the SCR for the years 2018, 2019, and 2020. The use of HSFO, with MGO within ECAs, is assumed for the years 2018 and 2019, whereas the use of VLSFO, with MGO within ECAs, is assumed for 2020, following the implementation of the IMO 2020 sulphur limit policy. Following the steep decline of HSFO/MGO prices (260/450 US$/t) between 2015 and 2017, HSFO prices rose at 400 US$/t in 2018 and fell at 380 US$/t in 2019, and 260 US$/t during 2020. Similarly, MGO prices rose at 630 US$/t in 2018, fell at 580 US$/t in 2019, and 380 US$/t in 2020. Yet, the USD/RUB exchange rate increased from 58.7 in 2017 to 65.8 in 2018, slightly declined at 64.4 in 2019, and increased at 75.06 in 2020. The combination of fuel price levels and currency exchange rates largely explain the cost difference between the NSR and SCR during 2018-2020, since operating costs did not vary significantly, and the loans for tankers built in 2007 were supposed to be paid in 2017.

Figure 4.8 illustrates results for 2018, 2019, and 2020. The NSR was more competitive than SCR across most OD pairs and tanker sizes in 2020, followed by 2018, and 2019, respectively. When including ice damage repairs in the model, the SCR-NSR RFR is found marginally competitive on the Vitino-Daesan pair across all years, but negative on the other two OD pairs. Although HSFO/MGO prices fell successively from 400/630 US$/t in 2018, to 380/580 in 2019, and 350 (VLSFO) / (MGO) 380 US$/t in 2020, the NSR was more competitive in 2020 than in 2018 and 2019. The main reason is that an increased USD/RUB exchange rate during 2020 resulted in reduced icebreaking fees, whereas the Suez Canal Tolls were increased somewhat from 2019 to 2020. This effect more than offset the negative impact that lower fuel price levels in 2020 than in 2018 and 2019 could have had for the competitiveness of the NSR. Similarly, the NSR was more competitive in 2018 than in 2019 owing to slightly higher USD/RUB currency exchange rate and fuel prices. On the one hand, fuel prices were not substantially low during 2018-2020, when considering annual averages. On the other hand, the steep drop of oil price levels during 2020 resulted in lower icebreaking fees levels, given the inverse relationship between oil prices and the Russian Rouble.

However, the RFR differentials were not sufficiently high to cover potential ice damage repairs, especially for the Yeosu-Rotterdam pair, which is considered an important OD pair for clean oil product trade routes, such as jet fuel/kerosene and gasoil/diesel between Asia and Europe. Besides, other factors, such as low spot commodity prices and high commodity futures prices, favoured the delay of arrivals at the destination ports, as well as longer voyages via the Cape of Good Hope route, as it is shown in Chapter 5. It should also be mentioned that diversions via the Cape route occur even for voyages between Mongstad and Japan when commodity price levels are low and there is oversupply of crude oil and oil products in the global markets. This situation also applies to the period between 2015 and 2017 amongst others. The SCR-NSR RFR differentials ranged between 0.8 US$/t (MR) / -0.7 US$/t (LR3) in 2018, to 0.4 US$/t (MR) / -0.9 US$/t (LR3) in 2019, to 1.4 US$/t (MR) / -0.1 US$/t (LR3) in 2020 on the Yeosu-Rotterdam pair.

The differentials ranged between 2.7 US$/t (MR) / 0.1 US$/t (LR3) in 2018, to 2.2 US$/t (MR) / -0.1 US$/t (LR3) in 2019, to 3.0 US$/t (MR) / 0.6 US$/t (LR3) in 2020 on the Mongstad-Mizushima pair. As regards the SCR-NSR RFR differentials on the Vitino-Daesan pair, these ranged between 4.6 US$/t (MR) / 0.9 US$/t (LR3) in 2018, to 4.1 US$/t (MR) / 0.6 US$/t (LR3) in 2019, to 4.9 US$/t (MR) / 1.4 US$/t (LR3) in 2020. The differentials for the long and medium-haul are found negative when ice damage repairs are included in the analysis, except for the short-haul, where the NSR is found marginally competitive for MR, LR1, and LR2 tankers but not for LR3 tankers in 2018 and 2019.

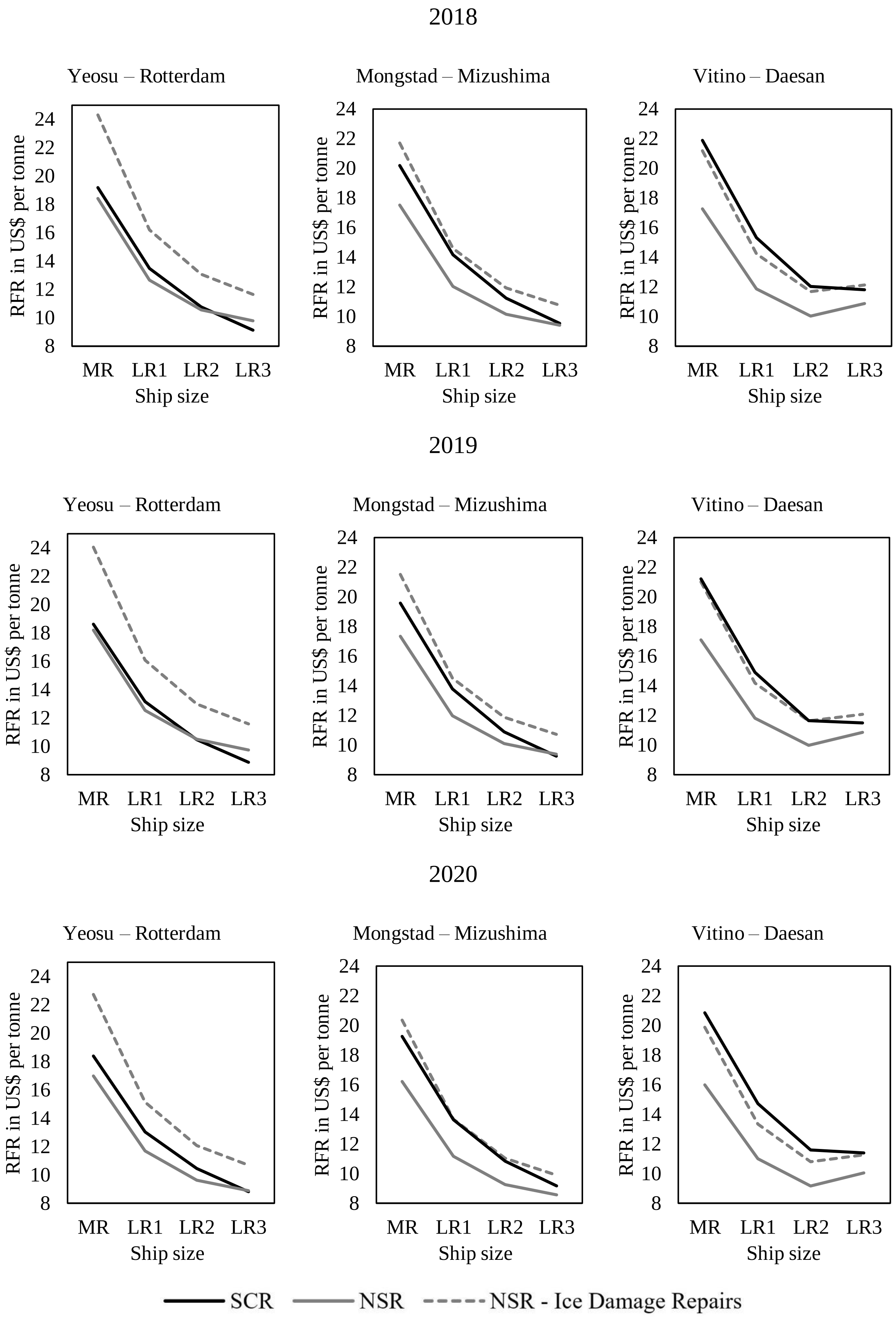


Figure 4.8. Relationship between ship size and minimum RFR for a given OD pair during with and without ice damage repairs for 2018, 2019, and 2020.

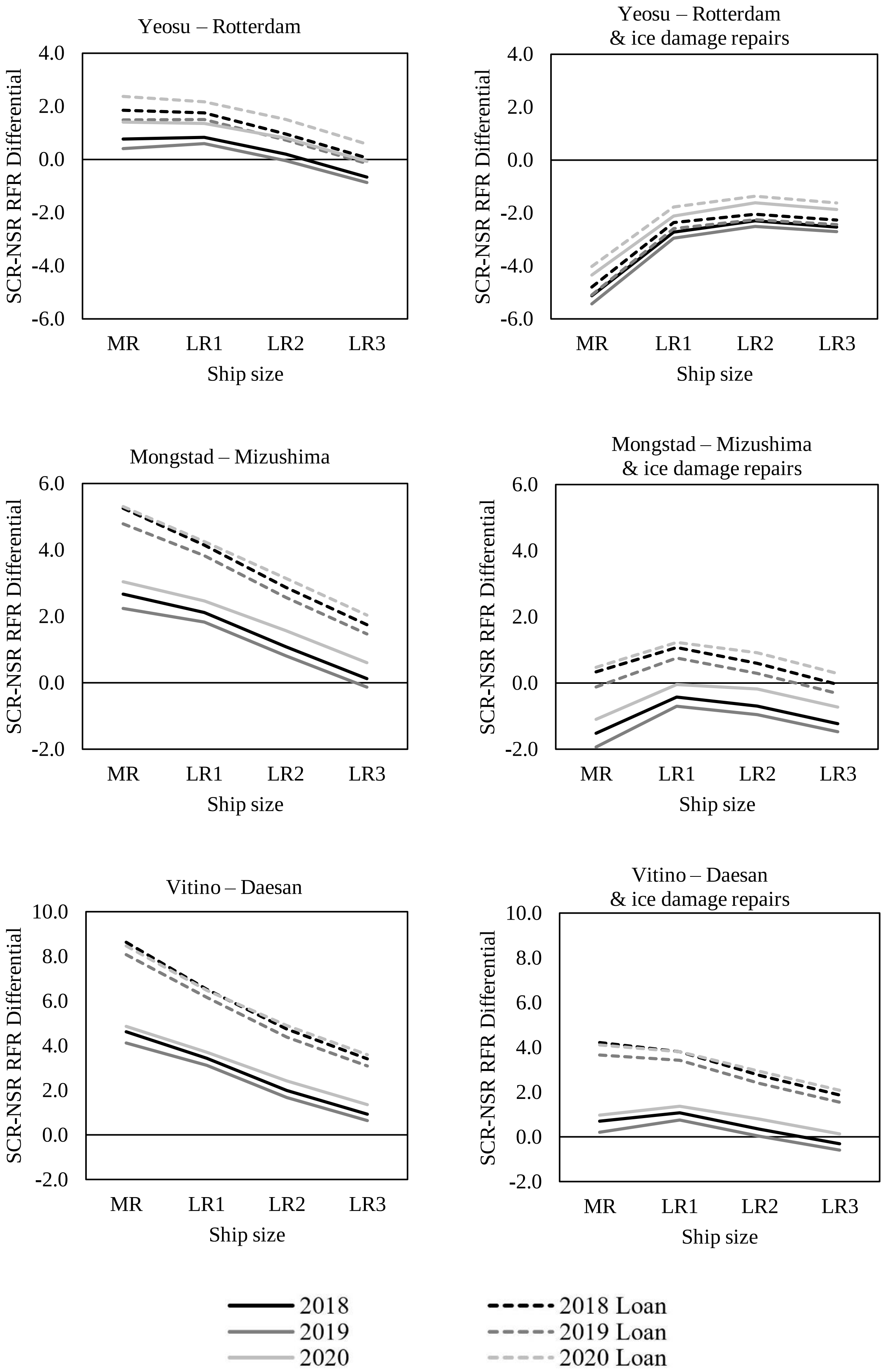


Figure 4.9.Comparison of results with and without capital costs for 2018, 2019, and 2020.

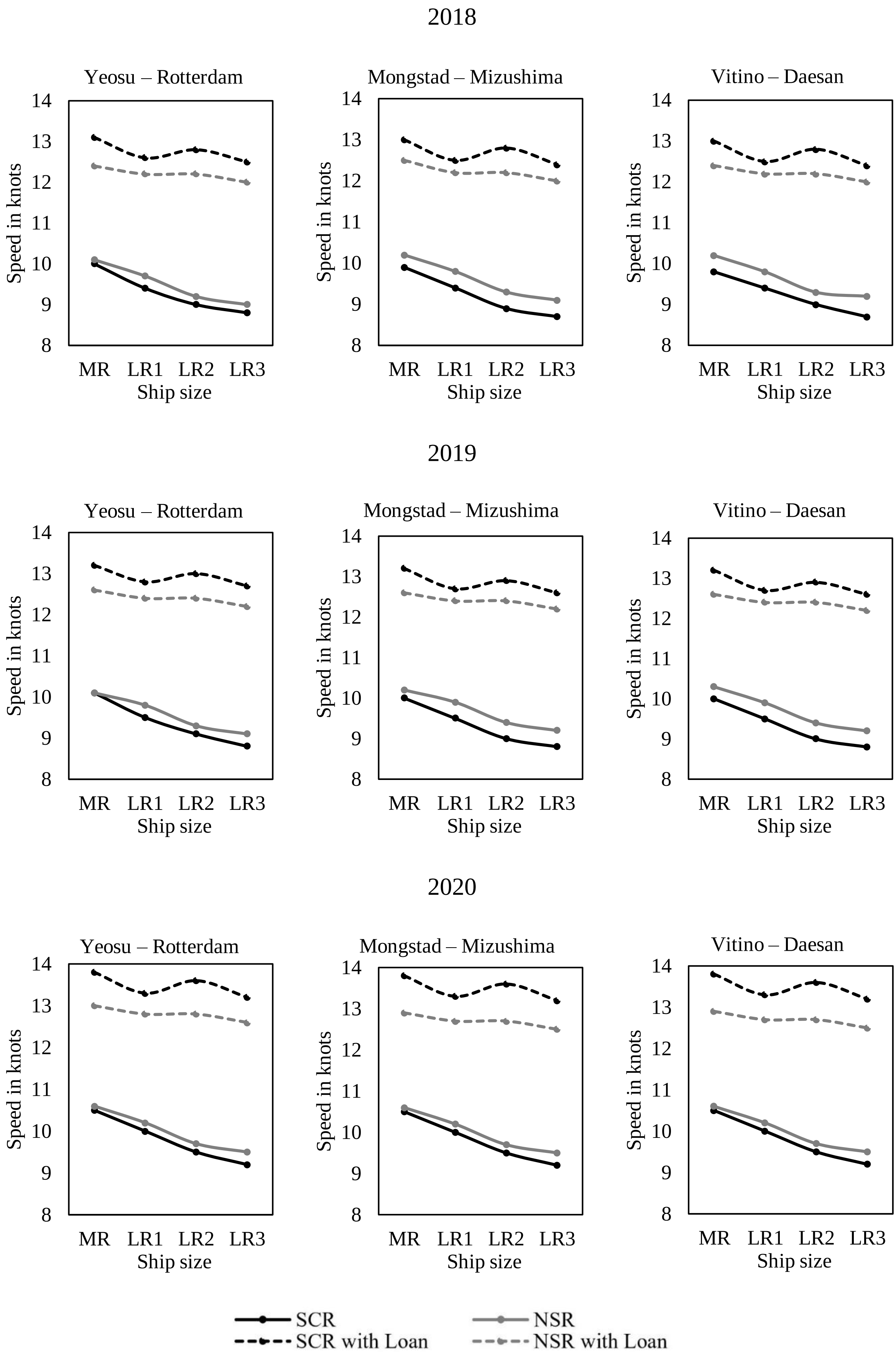


Figure 4.10. Optimal speeds for SCR and NSR, with and without capital costs for 2018, 2019, and 2020.

Figure 4.9 shows the SCR-NSR RFR differentials during 2018-2020 in solid curves, whilst the differentials in square dotted curves reflect the same period under the assumption that capital costs were still incurring for all tankers. Figure 4.10 shows the respective optimal speeds for tankers with and without capital costs during 2018-2020. These two figures help explain how a major cost element, in this case capital costs, affects the SCR-NSR RFR differential and respective optimal speeds. The results show that the competitiveness of the NSR significantly increases when including capital costs with all RFR differentials getting higher across all OD pairs and years under consideration. Thus, an increase in costs makes a shorter route more competitive than a longer route. Further, the shorter the OD pair, the higher the SCR-NSR RFR differential. Moreover, all optimal speeds are higher when including capital costs in the analysis, either for the SCR or the NSR. The economic explanation of these two results is that a tanker will need to increase the frequency of voyages or to operate through shorter routes and increase its operating speed in order to increase earnings at a given period of time to cover the capital costs now added in total costs. Mathematically, this is reflected in the optimal speed functions, where the nominator is higher when capital costs are included in the analysis.

A noteworthy finding is that the optimal NSR speed is higher than the optimal SCR speed when capital costs are not considered in the analysis, as is the case for the period 2018-2020. This is explained by the fact that the speed on ice influences more the average voyage speed than the optimal speed on open water, which is lower than the speed on ice when capital costs are not included in the analysis. Conversely, the optimal NSR speed is lower than the optimal SCR speed when capital costs are considered in the analysis, as is the case for the periods 2011-2014 and 2015-2017. This is explained by the fact that the speed on ice influences more the average voyage speed than the optimal speed on open water, which is higher than the speed on ice when capital costs are included in the analysis. All speeds and numerical results are reported in Appendix Q.

Tables 4.14 and 4.15 present a breakdown of costs for the Yeosu-Rotterdam pair as an example during 2011-2014 and 2015-2017, respectively. Tables 4.16, 4.17, and 4.18 present cost breakdowns for the years 2018, 2019, and 2020, respectively. A cost and time breakdown and results for all OD pairs, as well as for ballast voyages between an unloading port and a repair yard across all years and scenarios are reported in Appendix Q. Scale economies exist in every cost factor by using larger ships except for transit fees of LR2 tankers in either the SCR or NSR. This is due to the relatively increased SCNT and Gross Tonnage (GT) values based on the LR2 tanker characteristics chosen for the analysis, as these refer to only one LR2 tanker[25]. When it comes to the period 2011-2014, capital cost is the most important cost factor for LR1-LR3 tankers on the SCR, and for MR-LR2 tankers on the NSR. Operating costs come first for MR tankers, second for LR1 tankers, third for LR2 and LR3 tankers on the SCR. Operating costs come second for MR tankers, third for LR1 tankers, and fourth for LR2 and LR3 tankers on the NSR. Fuel cost is the third cost factor for MR and LR1 tankers and second for LR2 and LR3 tankers on the SCR, whereas it is the third cost factor for MR, LR2 and LR3 tankers, and fourth for LR1 tankers on the NSR. Suez Canal Tolls is the fourth cost factor across all tanker sizes on SCR, whereas icebreaking fees rank fourth for MR tankers, second for LR1 and LR2 tankers, and first for LR3 tankers on the NSR. When including ice damage repairs in the analysis, these are the third cost factor for MR tankers but are the least important factor for LR1-LR3 tankers. As a result, fuel and icebreaking fees become the fourth and fifth cost factors for MR tankers, respectively, on the NSR.

It can be seen that capital and operating costs are important for the SCR, whilst fuel cost becomes more important when moving towards larger tanker sizes. Capital cost is equally important for NSR, whereas fuel cost is less important than for SCR. However, icebreaking fees become more important when moving towards larger tanker sizes.

When it comes to the period 2015-2017, capital cost is the most important factor across all tanker sizes on SCR, and for MR and LR1 tankers on NSR. Operating costs come second for MR tankers, third for LR1 tankers, and fourth for LR2 and LR3 tankers. Operating costs come third across all tanker sizes on NSR. Fuel cost is the third cost factor for MR, LR2 and LR3 tankers and second for LR1 tankers on SCR, whereas it is the fourth cost factor across all tanker sizes on NSR. Suez Canal Tolls is the fourth cost factor for MR and LR1 tankers, and the second cost factor for LR2 and LR3 tankers on SCR, whereas icebreaking fees rank second for MR and LR1 tankers, and first for LR2 and LR3 tankers on NSR. When including ice damage repairs in the analysis, these are the fourth cost factor for MR, LR1, and LR2 tankers, and fifth for LR3 tankers. As a result, fuel cost becomes the fifth cost factor for MR, LR1, and LR2 tankers on NSR.

It can be seen that the ranking is similar for the period 2015-2017, with fuel costs becoming less important for both routes owing to low fuel price levels. Capital cost is the most important

[25] Only one ice class IA LR2 tanker used the NSR during 2011-2018, the M/T *Propontis* of 117,055 dwt. The average SCNT and GT for LR2 tankers of similar dwt are generally lower than those of the M/T Propontis, and therefore would provide a lower transit fee in US$ per tonne.

factor across all tanker sizes for SCR, fuel cost becomes less important, whereas Suez Canal Tolls become more important, especially for LR2 and LR3 tankers on SCR. Capital cost is equally important for NSR, fuel cost is less important than for SCR, whereas icebreaking fees become even more important across all tanker sizes than in 2011-2014.

When it comes to the years 2018, 2019, and 2020, operating costs come first, followed by Suez Canal Tolls and fuel cost across all tanker sizes on the SCR. The exception is LR2 and LR3 tankers in 2020, where Suez Canal Tolls come first, followed by operating and fuel costs. The reason for the higher Suez Canal Tolls is that tariffs increased in 2020. As regards NSR, operating cost comes first, transit fees come second, and fuel cost comes third for MR and LR1 tankers, whereas transit fees come first, followed by operating costs, and fuel costs, for LR2 and LR3 tankers, respectively. When including ice damage repairs in the analysis, these come third across all tanker sizes and years, fuel costs come fourth, whereas operating cost and transit fees retain their ranking order across all tanker sizes and years.

The prevalence of transit fees on the NSR, as well as the increased rate at which the SCR-NSR RFR differentials diminish when moving towards larger tanker sizes reflect the fact that icebreaking fees increase proportionally more than Suez Canal Tolls when moving from LR2 to LR3 tanker size. Similar results are obtained for other OD pairs, with differences in cost factor ranking being attributed to different OD distances.

Table 4.14. Total cost analysis for Yeosu – Rotterdam pair in US$ per tonne during 2011-2014.

Tanker Size	Speed (knots)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	RFR	Repairs	RFR incl. repairs
					SCR			
MR	11.6	9.2	5.3	10.2	9.8	34.5		
LR1	11.2	6.4	4.1	6.6	7.3	24.4		
LR2	11.4	5.1	4.3	4.5	6.4	20.2		
LR3	11.1	4.5	3.4	3.7	5.7	17.3		
					NSR			
MR	11.5	6.3	5.4	8.0	8.6	28.3	6.7	35.0
LR1	11.3	4.5	5.2	5.1	6.3	21.1	4.1	25.2
LR2	11.3	3.6	5.2	3.5	5.6	17.9	3.0	20.9
LR3	11.1	3.3	5.1	2.8	5.0	16.2	2.3	18.5

*Transit fees refer to Suez Canal Tolls or icebreaking fees and relevant costs.

Table 4.15. Total cost analysis for Yeosu – Rotterdam pair in US$ per tonne during 2015-2017.

Tanker Size	Speed (knots)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	RFR	Repairs	RFR incl. repairs
				SCR				
MR	15.1	6.9	5.1	7.0	7.5	26.5		
LR1	14.6	4.8	4.0	4.5	5.6	18.9		
LR2	14.9	3.8	4.3	3.0	4.9	16.0		
LR3	14.5	3.4	3.4	2.5	4.4	13.7		
				NSR				
MR	13.6	4.4	7.2	6.9	7.3	25.8	6.5	32.3
LR1	13.3	3.1	5.2	4.3	5.3	18.0	4.0	22.0
LR2	13.3	2.5	5.5	2.9	4.8	15.7	2.9	18.6
LR3	13.1	2.2	5.4	2.4	4.2	14.3	2.2	16.5

*Transit fees refer to Suez Canal Tolls or icebreaking fees and relevant costs.

Table 4.16. Total cost analysis for Yeosu – Rotterdam pair in US$ per tonne during 2018.

Tanker Size	Speed (knots)	Fuel Cost	Transit Fees*	Operating cost	RFR	Repairs	RFR incl. repairs
				SCR			
MR	10.0	4.6	5.1	9.5	19.2		
LR1	9.4	3.1	4.0	6.4	13.5		
LR2	9.0	2.1	4.2	4.4	10.8		
LR3	8.8	1.9	3.4	3.9	9.1		
				NSR			
MR	10.1	3.2	6.8	8.4	18.4	5.9	24.3
LR1	9.7	2.3	5.0	5.4	12.7	3.6	16.2
LR2	9.2	1.6	5.2	3.8	10.6	2.5	13.1
LR3	9.0	1.5	5.1	3.2	9.8	1.9	11.7

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Table 4.17. Total cost analysis for Yeosu – Rotterdam pair in US$ per tonne during 2019.

Tanker Size	Speed (knots)	Fuel Cost	Transit Fees*	Operating costs	RFR	Repairs	RFR incl. repairs
					SCR		
MR	10.1	4.4	5.0	9.2	18.6		
LR1	9.5	3.0	3.9	6.2	13.2		
LR2	9.1	2.1	4.2	4.2	10.5		
LR3	8.8	1.8	3.3	3.7	8.9		
					NSR		
MR	10.1	3.1	6.9	8.2	18.2	5.9	24.1
LR1	9.8	2.2	5.1	5.3	12.6	3.5	16.1
LR2	9.3	1.6	5.3	3.6	10.5	2.5	13.0
LR3	9.1	1.4	5.2	3.1	9.7	1.8	11.6

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Table 4.18. Total cost analysis for Yeosu – Rotterdam pair in US$ per tonne during 2020.

Tanker Size	Speed (knots)	Fuel Cost	Transit Fees*	Operating costs	RFR	Repairs	RFR incl. repairs
					SCR		
MR	10.5	4.3	5.1	8.9	18.4		
LR1	10.0	2.9	4.0	6.1	13.0		
LR2	9.5	2.0	4.3	4.1	10.4		
LR3	9.2	1.8	3.4	3.6	8.8		
					NSR		
MR	10.6	3.0	6.0	8.0	17.0	5.7	22.7
LR1	10.2	2.1	4.4	5.2	11.7	3.5	15.1
LR2	9.7	1.5	4.6	3.6	9.6	2.4	12.1
LR3	9.5	1.4	4.5	3.0	8.9	1.8	10.7

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

4.5 Discussion and concluding remarks

This modelling case examines the use of the NSR based on historic destination and transit voyages to explain its emergence since the 2010s. The factors considered are distance, fuel prices, average ship speed through ice on NSR, icebreaking fees, ice damage repairs, ship size, varying capital and operating costs, and fuel types.

The NSR is compared to the SCR for single oil product tanker voyages between Europe, the Russian Arctic, and Northeast Asia at the tactical/operational level during the summer/autumn season. The choice of OD pairs reflects historic voyages through the NSR, based on representative ports, distance savings, and tankers that were involved in the transport of major oil products during 2011-2020. Four oil product tanker sizes are considered to assess the impact of ship size on RFR and route choice.

A required freight rate (RFR) model is developed based on speed optimisation to assess the minimum cost per tonne from the shipowner’s perspective. The data and assumptions for capital, navigational, and voyage costs vary on an annual basis during 2011-2020, reflecting historic market conditions and respective voyage cost structure for competing routes. The relationship between optimal speed and minimum RFR is considered in the analysis. Moreover, the relationship between laden speeds and ballast speeds is established. A cost breakdown is provided to show how operating, voyage, and capital costs affect route competitiveness.

The analysis considers alternative fuel types to address current emissions reductions policies (ECAs, IMO sulphur limit).

The analysis of this chapter addresses **Research Question 1**: *Why did the NSR emerge as an alternative route for oil product tankers between Europe and Asia since the 2010s?*, **Research Question 2**: *How do cost and market factors affect the use of the NSR for oil product tankers?*, **Research Question 4**: *How do different approaches to ship speed choice and cost modelling affect the feasibility of the NSR for oil product tankers?*, and **Research Question 5**: *How do emissions regulations and alternative operational modes and fuel types affect the feasibility of the NSR compared to the traditional routes for oil product tankers?*

High fuel price levels along with a competitive icebreaking tariff policy and, to a lesser extent, high piracy insurance premiums explain the competitiveness of the NSR against the longer SCR during the period 2011-2014. The NSR was more competitive than the SCR across all OD pairs at high fuel prices and discounted icebreaking fees (2011-2014). The RFR differential on the Yeosu-Rotterdam pair was negative across all tanker sizes, whereas it narrowed significantly for LR2 and LR3 tankers on the Mongstad-Mizushima pair, when including ice damage repairs in the analysis. The RFR differential on the Vitino-Daesan pair was less impacted across all tanker sizes when including ice damage repairs. The majority of oil product tanker voyages (17 out of 32) were conducted between the Russian Arctic, Arctic Europe and Northeast Asia in 2011-2013. This is clearly reflected in the results for the Vitino-Daesan pair since it is the most competitive OD pair for the NSR. On the other hand, six voyages were conducted from Mongstad to Japan (1), and South Korea to the ARA region (5) in 2011-2013 (CHNL 2021a; Bloomberg 2021; Refinitiv Eikon 2021). Although more voyages occurred between the Far East and ARA region than between Mongstad and the Far East, this can be explained by other factors, such as differences in spot and futures commodity prices between the origin and destination regions during that period.

Crude oil prices fell by 47% between 2014 and 2015 and resulted in a decline of 49% and 42% in HSFO and MGO fuel oil prices, respectively. The official icebreaking fees declined during 2015-2017 owing to the depreciation of the Russian rouble in 2015 but were still higher than the discounted fees offered before 2014. The Yeosu-Rotterdam pair was mostly impacted by the steep drop in fuel oil prices during 2015-2017. The SCR-NSR RFR differential was low for MR, LR1, and LR2 tankers, whereas it was negative for LR3 tankers at low fuel prices and official icebreaking fees. The RFR differential on the Mongstad-Mizushima pair narrowed but was still positive, whereas the RFR differential on the Vitino-Daesan pair was less impacted across all tanker sizes at low fuel prices and official icebreaking fees. The RFR differential on the Yeosu-Rotterdam pair was negative across all tanker sizes, whilst it was also negative for all tanker sizes except LR1 on the Mongstad-Mizushima pair, when including ice damage repairs in the analysis. The RFR differential on the Vitino-Daesan pair was less impacted across all tanker sizes when including ice damage repairs. Yet, it narrowed significantly for LR3 tankers, which is largely attributed to the STS transfer operation costs for a LR3 tanker near the port of Vitino. The results are in line with NSR traffic records in 2015-2017. Oil product tanker destination and transit voyages linked only Russian ports during this period. A re-direction of condensate and naphtha flows from the Barents Sea and White Sea to the Baltic Sea (Bambulyak et al. 2015; Tanker Company 2018), and diplomatic tensions between Russia and the west had a negative impact on the use of the NSR amongst others (Reuters 2015; Platts 2016a; Gunnarsson and Moe 2021; Shapovalova et al. 2020). Moreover, oil products prices and piracy insurance premiums declined, and as a result, lead times and piracy risks were not deemed as critical as in 2011-2014.

The competitiveness of the NSR between 2018 and 2020 was largely determined by fuel price movements and most importantly by the USD/RUB exchange rates. The NSR is found competitive on the Yeosu-Rotterdam pair during 2020, but marginally competitive during 2018 and 2019, whereas it was found not competitive when ice damage repairs are included in the analysis, across all years and tanker sizes. Similarly, the NSR was relatively more competitive than the SCR on the Mongstad-Mizushima pair across all years, albeit with diminishing RFR differentials when moving towards larger tankers sizes. Yet, it was found not competitive when ice damage repairs are included in the analysis across all years and tanker sizes. The NSR was mostly competitive on the Vitino-Daesan pair, marginally competitive when including ice damage repairs across all tanker sizes and years, but uncompetitive for a LR3 tanker in 2018 and 2019. Although fuel prices were higher in 2018 and 2019 than in 2020, the NSR was found more competitive in 2020. The main reason is that an increased USD/RUB exchange rate during 2020 resulted in reduced icebreaking fees, whereas the Suez Canal Tolls were increased somewhat from 2019 to 2020. This effect more than offset the negative impact that lower fuel price levels in 2020 than in 2018 and 2019 could have had for the competitiveness of the NSR. The NSR was more competitive in 2018 than in 2019 owing to slightly higher USD/RUB currency exchanges rate and fuel prices.

Distance savings, which increase when moving from the long-haul (Yeosu-Rotterdam pair) to the short-haul (Vitino-Daesan pair) mean a wider RFR differential between the SCR and NSR, using the NSR as a basis of comparison. Larger ships achieve a lower RFR across every OD pair and route alternative, all else being equal. Not only do costs fall with the increase in tanker size, but also this decline is bigger in absolute terms at higher fuel prices for a given OD pair and route alternative. The economies of scale derived from larger tanker sizes in absolute terms decline when moving towards the shortest OD pair for a given route alternative. This means that scale economies are larger for the NSR on the Yeosu-Rotterdam pair but smaller on the Vitino-Daesan pair, whereas the opposite holds true for the SCR. The RFR differential between SCR and NSR widens when moving from the long to the short-haul both with and without ice damage repairs. Yet, STS operations costs reduce the benefits derived from using LR3 tankers on the Vitino-Daesan pair for both the SCR and NSR. As a result, the LR3 NSR RFR is higher than the LR2 NSR RFR on the Vitino-Daesan pair. Further, the LR3 NSR RFR on the Vitino-Daesan pair is higher than the LR3 NSR RFR on the Mongstad-Mizushima pair.

The relationship between distance and ship size is largely influenced by fuel price levels, with the use of smaller tanker sizes on the NSR being more competitive than the use of larger tanker sizes on the SCR when moving towards shorter OD pairs and high fuel prices. The shorter the distance, the lower the critical fuel price level a smaller tanker size becomes more competitive on the NSR than a larger tanker size on the SCR. The use of LR1 tankers on the NSR is more cost-effective compared to the use of LR2 tankers on the SCR at the Mongstad-Mizushima pair at high fuel prices, whilst the same also holds true between the use of a LR2 tanker on the NSR compared to the use of a LR3 tanker on the SCR. The Vitino-Daesan pair offers the biggest cost advantages with LR1 tankers on the NSR being more competitive than even LR3 tankers on the SCR either at high or low fuel price levels. Moreover, using an MR tanker on the NSR offers lower transport costs than a LR1 tanker on the SCR at high fuel price levels (2011-2014). It should also be mentioned that larger tanker sizes may be able to go through the Sannikov Strait, when assuming difficult ice conditions in the route north of the New Siberian Islands. This depends on cargo sizes, which for oil product trades they could be around 22% lower than the maximum ship capacity (Stopford 2009) and could enable a LR2/Aframax tanker to transit the Sannikov Strait. Yet, there are no benefits of using a smaller tanker size on the NSR compared to a larger tanker size on the SCR at the Yeosu-Rotterdam pair, regardless of fuel prices. Similarly, there are no benefits of using smaller tankers on the NSR compared to larger tanker sizes on the SCR at the Mongstad-Mizushima pair at low fuel prices.

Icebreaking fees is a crucial factor, which considerably affects the competitiveness of the NSR across all OD pairs and tanker sizes. High fuel prices are important but cannot determine the competitiveness of the NSR alone. It is shown that very high official icebreaking fees, owing to a low USD/RUB exchange rate, outweigh any benefit of using the NSR under a high fuel price environment. This is attributed to the inverse relationship between USD/RUB exchange rates and crude oil prices (Shibasaki et al. 2018). This relationship largely explains the practice of discounted fees compared to official tariff rates determined by the USD/RUB exchange rate and a maximum fee of 530 Russian roubles per tonne of liquid cargo before 2014 (ARCTIS 2021c). It should also be noted that discounted fees varied from case to case (Falck 2012). According to Tanker Company (2018), Tanker Company (2020) and Moe and Brigham (2016), regular users of the route could be granted even lower discounted fees than those assumed in this Thesis (Falck 2012; Gritsenko and Kiiski 2016). This explains the reason why certain voyages conducted from the ports of Vitino or Mongstad to ports located in countries, such as Thailand, Taiwan, Singapore and Malaysia before 2014. The tankers which were involved in these voyages were either owned or chartered by companies which conducted 25 of the 32 destination and transit product tanker voyages in 2011-2013. Moreover, the prevalence of transit fees on the NSR, as well as the increased rate at which the RFR differentials diminish when moving towards larger tanker sizes show that icebreaking fees increase proportionally more than the Suez Canal Tolls when moving from LR2 to LR3 tanker size.

Should the official icebreaking tariff rates before 2014 were considered in the model, this would have resulted in negative RFR differentials even on the Vitino-Daesan pair and without factoring in ice damage repairs. Following the introduction of the latest tariffs in 2014, these were still prohibitive during that year across all OD pairs owing to a relatively high USD/RUB exchange rate. The analysis shows that the SCR-NSR RFR differential is found either significantly narrow or negative on the Yeosu-Rotterdam pair across all tanker sizes even without including ice damage repairs. The RFR differentials are found negative across all tanker sizes when including repairs on the Mongstad-Mizushima pair, whereas they are found very narrow or even negative , when repairs are not considered. Therefore, the assumption of discounted fees is retained for the year 2014, when assessing the period 2011-2014.

The significance of icebreaking fees is also observed in the analysis of the period 2018-2020. More specifically, icebreaking fees were lower due to an increased USD/RUB rate during 2020. At the same time the Suez Canal Tolls were increased somewhat from 2019 to 2020. This combined effect more than offset the negative impact that lower fuel price levels in 2020 than in 2018 and 2019 could have had for the competitiveness of the NSR. Similarly, the NSR was more competitive in 2018 than in 2019 owing to slightly higher USD/RUB currency exchange rates and fuel prices. On the one hand, fuel prices were not substantially low during 2018-2020, when considering annual averages. On the other hand, the steep drop of oil price levels during 2020 resulted in lower icebreaking fees levels, given the inverse relationship between oil prices and the Russian Rouble.

The cost structure per voyage and route is significantly affected when major cost factors are included in the analysis or not. More specifically, a comparison between tankers which incur capital costs and tankers which do not incur capital costs, shows that a shorter route is significantly benefitted by the former, with increased RFR differentials across all OD pairs and tanker sizes. The shorter the OD pair, the higher the SCR-NSR RFR differential in this case as well.

Moreover, total ice damage repairs costs for a certain voyage, when these are factored in the analysis, comprise repairs costs and the costs of the voyage between the unloading port and the repair yard. This implies that a repair yard which is located farther than one which is located nearer to the unloading port might be chosen, depending on the influence of the two cost elements in the overall costs, and vice versa. This is evident in the choice of a repair yard in Qushan rather than in Ulsan, across almost all tanker sizes and periods, for voyages from Mizushima and Daesan to a repair yard. More specifically, Ulsan is nearer to both Mizushima and Daesan. Yet, repairs costs are higher at a repair yard in Ulsan than in Qushan. On the other hand, the impact of distance, fuel consumption, and fuel prices could imply a greater influence of voyage costs than repairs costs, especially for larger tanker sizes. This is evident on the LR2 tanker voyages in 2011-2014 and on the LR3 tanker voyages in 2011-2014 and 2015-2017 from Mizushima to a repair yard in Ulsan, which is nearer than Qushan. The same also holds true for LR3 tanker voyages in 2018, 2019, and 2020, when assuming incurring capital costs in the analysis. Distance, fuel consumption and fuel prices do not affect the preference of yard location in the case of a voyage from Daesan to a repair yard since the difference in the distance between Daesan and Qushan and Ulsan (63 n.m.) is not as longer as it is between Mongstad and Qushan and Ulsan (403 n.m. including ECAs).

Optimal speeds are determined by fixed costs, fuel prices, and payload. Optimal speeds are found 11-11.6 knots across all routes and OD pairs during 2011-2014. This shows that a high fuel price environment enables speed optimisation and slow steaming practices. Optimal speeds increased as a result of the drop in crude oil and fuel oil prices in 2015-2017 on both the SCR and NSR. They ranged between 13.1 knots and 15.1 knots, which shows that optimal speeds are close to design speed at high fuel price levels. Moreover, any departure from optimal speeds is cost-wise inefficient. When the speed is lower than the optimal one, fuel costs decrease non-linearly whereas capital and operating costs increase due to the additional days per voyage, and vice versa. When the speed is higher that the optimal one, fuel costs increase non-linearly whereas capital and operating costs decrease with less days per voyage. This trade-off between fixed and variable costs is illustrated in the U-shaped RFR curves. Optimal laden speeds are lower than optimal ballast speeds due to the higher resistance and fuel consumption when a ship is fully laden. Further, the lower optimal speeds on NSR than those on SCR is the result of the lower speed through ice, which is assumed fixed at 10.1 knots, regardless of fuel price levels. Moreover, all optimal speeds are higher when including capital costs in the analysis during 2018-2020, either for the SCR or the NSR. The reason is that a tanker will need to increase the frequency of voyages or to operate through shorter routes and increase its operating speed in order to increase earnings at a given period of time to cover the capital costs now added in total costs. Mathematically, this is reflected in the optimal speed functions, where the nominator is higher when capital costs are included in the analysis.

A noteworthy finding is that the optimal NSR speed is higher than the optimal SCR speed when capital costs are not considered in the analysis, as is the case for the period 2018-2020. This is explained by the fact that the speed on ice influences more the average voyage speed than the optimal speed on open water, which is lower than the speed on ice when capital costs are not included in the analysis. Conversely, the optimal NSR speed is lower than the optimal SCR speed when capital costs are considered in the analysis, as is the case for the periods 2011-2014 and 2015-2017. This is explained by the fact that the speed on ice influences more the average voyage speed than the optimal speed on open water, which is higher than the speed on ice when capital costs are included in the analysis.

The next chapter assesses the feasibility of the NSR compared to both the SCR and Cape of Good Hope routes. It extends the analysis of this chapter by aiming to explain route choice for oil product tanker trades between Northeast Asia and Europe, based on cost factors and market developments which favour longer or shorter routes. The analysis considers distance, fuel types and prices, icebreaking fees, commodity prices and in-transit inventory costs, and average speed through ice on NSR. A RFR model is developed based on a methodological approach which has two objectives. The cost assessment is based on both speed optimisation and real speeds to minimise the RFR for competing routes in the context of Arctic shipping.

5. The role of commodity prices, in-transit inventory costs, and alternative operational modes

The feasibility of the Northern Sea Route (NSR) is assessed against the Suez Canal (SCR) and Cape of Good Hope routes. The factors considered in the analysis are distance, fuel prices, average ship speed through ice on NSR, icebreaking fees, ice damage repairs, commodity prices and in-transit inventory costs, and fuel types and operational modes. The analysis in this chapter complements Chapter 4, by considering in-transit inventory costs, and addressing market structure and route choice in the wider context of oil product tanker flows drawing from Automatic Identification System (AIS) data of voyages between the Far East and Europe in 2011-2020. Not only is the NSR compared with SCR, but also the Cape route is included to explain route choice for oil product tanker trades between Northeast Asia and Europe, based on cost factors and market developments which favour longer or shorter routes. The cost-based analysis explains route choice depending on two distinct states of the market. First, it explains the choice of shorter routes when cargo value is important and fuel and commodity prices are high. Second, it explains the choice of longer routes when cargo value is not critical and fuel and commodity prices are low. The analysis is undertaken at the tactical/operational level for single oil product tanker voyages during the summer/autumn season.

The analysis reflects real practices of Long Range 2 (LR2) product tanker voyages carrying jet fuel/kerosene or gasoil/diesel, drawing from actual cargo movements between east and west. A required freight rate (RFR) model is developed to assess the cost per tonne from the shipowner's perspective. The methodological approach has two objectives. First, the cost assessment is based on speed optimisation, which minimises the RFR of a route alternative. Second, the cost assessment is based on real speeds, drawing from AIS data of LR2 tanker voyages between Northeast Asia and Northwest/Southwest Europe.

Alternative operational modes are considered to address current and future emission reductions policies, such as the Emission Control Areas (ECAs) policy, the IMO sulphur limit, the Initial IMO greenhouse gas (GHG) Strategy, and a future ban on the use of heavy fuels (HSFO, VLSFO) for operations in the Arctic. These modes include the use of High Sulphur Fuel Oil (HSFO) with scrubber (HSFO-Scrubber), the use of Very Low Sulphur Fuel Oil (VLSFO), and the use of dual fuel Oil/Liquefied Natural Gas (LNG) set-ups based on current and future technologies of LNG tank capacity (LNG-VLSFO). More specifically, two technologies are considered for the LNG-VLSFO mode in the analysis, depending on the LNG tank capacity.

The use of Marine Gasoil (MGO) is assumed within the Arctic under the HSFO-Scrubber and VLSFO modes following a future prohibition on the use of heavy fuel oils in the Arctic. Both primary and secondary data are employed in the analysis regarding cost, market, and navigational factors.

5.1 Introduction

A large number of oil product tankers ranging from 47,000 to 162,000 dwt tonnes conducted transit and destination voyages on the NSR between 2011 (31%) and 2014 (33%) (NSRA 2016; CHNL 2021a; Bloomberg 2021; Refinitiv Eikon 2021). These tankers transported jet fuel/kerosene, gasoil/diesel, condensate, naphtha, and fuel oil between the Russian Arctic, Europe, and Asia. (NSRA 2016; CHNL 2021a).

High commodity and fuel prices, a rising value of cargo on board and low oil products futures prices along with a competitive icebreaking tariff policy and Russia's ambitions to promote the use of the NSR resulted in an increased number of exploratory destination and transit oil product tanker voyages, especially between 2012 and 2013 (Platts 2011; IEA 2012; IEA 2013; Gritsenko and Kiiski 2016; NSRA 2016; CHNL 2021a, Bloomberg 2021; Refinitiv Eikon 2021).

A rapid decline in tanker destination and transit voyages linking the Atlantic with the Pacific Ocean via the NSR since 2014 is attributed to geopolitical factors, low oil prices, shifts in petroleum flows from the White and Barents Seas to the Baltic Sea, lower piracy insurance premiums for Suez Canal transits, and changes in icebreaking tariff policy amongst others (Reuters 2015; Platts 2016b; Bambulyak et al. 2015; Tanker Company 2018; Shapovalova et al. 2020). Moreover, the longer route via the Cape of Good Hope was used, especially during 2015-2017 and 2020 owing to oil oversupply and high commodity futures prices that favoured the delay of arrivals at the destination (IEA 2015; IEA 2017).

Although there are a growing number of studies assessing tanker economics from various angles and factors, the impact of commodity prices and cargo value has not been addressed[26]. Moreover, the use of the Cape of Good Hope route for oil product tankers has not been considered in the literature. Furthermore, the choice of sea routes in the wider context of oil products trades has not been considered. Although the use of LNG as an alternative fuel is included in recent studies concerning liner shipping (Ding et al. 2020, Xu and Yang 2020), the

[26] The time value of cargo in the context of general cargo and liner shipping is considered in Wergeland (1992) and Wang et al. (2016).

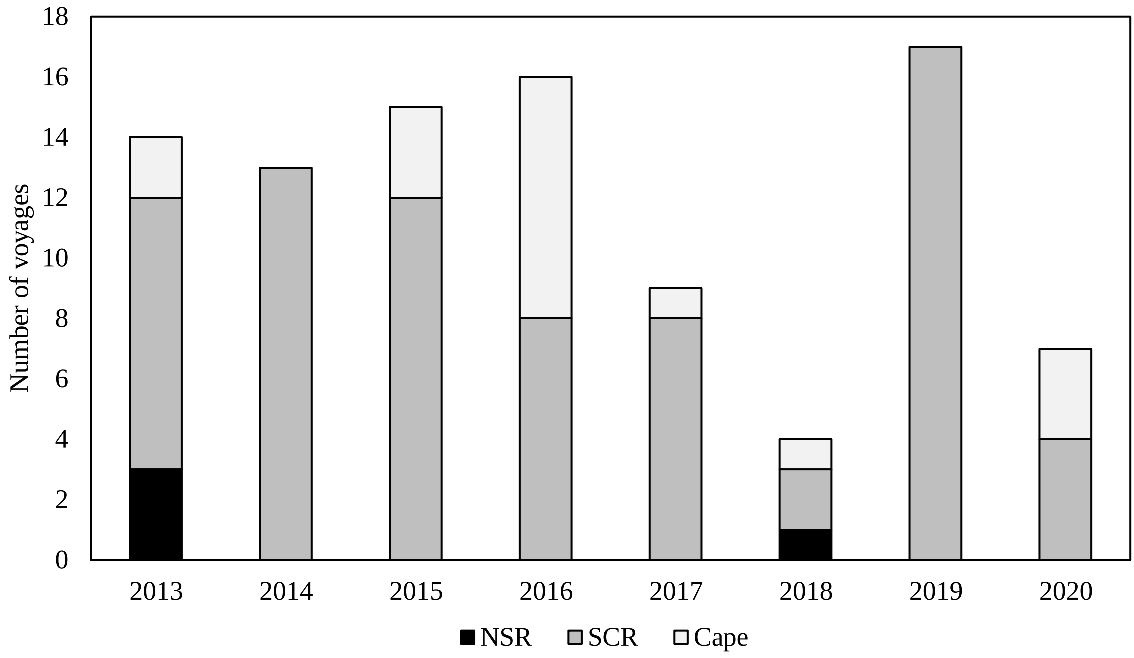
literature on tankers has so far focused on alternative oil-based fuels only (Keltoo and Woo 2020).

The analysis aims to assess the feasibility of the NSR for middle distillate flows between Northeast Asia and Northwest/Southwest Europe at the tactical/operational level during the summer/autumn season. The term middle distillates refers to refined oil products such as jet fuel, kerosene, gasoil and diesel (McKinsey 2021). The analysis considers the use of the NSR in the wider context of route choice, comparing it with the Suez Canal and the Cape of Good Hope routes, and drawing from historic middle distillate flows between Northeast Asia and Northwest/Southwest Europe through all the aforementioned routes using AIS data. A RFR analysis is established to assess the break-even point of competing routes from the shipowner's point of view. In doing so, both optimal speeds with respect to cost and market factors and real speeds are considered. The economic analysis considers the time value of cargo on board based on various commodity price levels, fuel prices as well as alternative operational modes and fuel types including Oil/LNG dual-fuel engine set-ups.

5.2 Market conditions and route choice

Figure 5.1 shows the number of voyages conducted by LR2 tankers carrying jet fuel/kerosene or gasoil/diesel from Northeast Asia to Northwest/Southwest Europe between 2013 and 2020. The NSR was used by LR2 tankers for five voyages in 2013 and one voyage in 2018[27]. Although most tankers used the Suez Canal route, it is noteworthy that the Cape of Good Hope route was used extensively during 2015-2016, in 2020 and, to a lesser extent, in 2013, 2017, and 2018. Route choice for energy commodities involving long-haul voyages between the Atlantic and the Pacific Ocean is largely determined by the prevailing commodity prices and freight rates. For tankers operating in the spot market and chartered by various traders, it is primarily the difference in spot and futures commodity prices between the origin and destination that can affect route choice either in the short, medium or long-term.

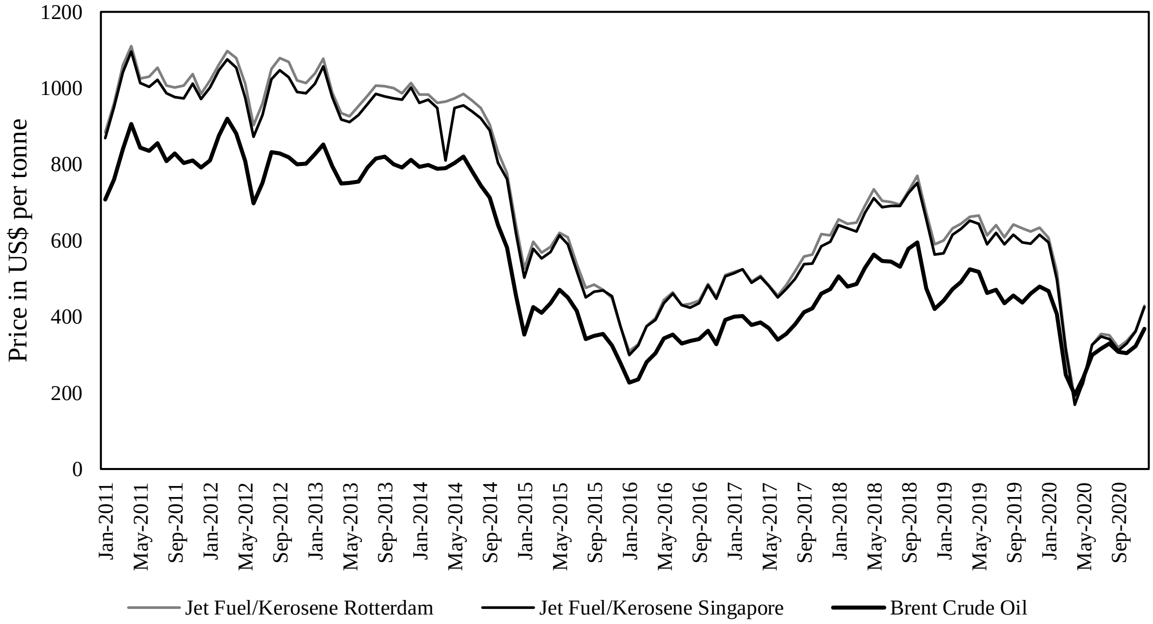
[27] Another two LR2 laden voyages were conducted in 2013, but these were naphtha cargoes from Europe to the Far East (NSRA 2016; CHNL 2021a).



Sources: Author, based on Refinitiv Eikon (2021), Bloomberg (2021).

Figure 5.1. Number of voyages per route alternative between 2013 and 2020.

Figures 5.2 and 5.3 illustrate jet fuel/kerosene and gasoil/diesel monthly prices in the major oil hubs of Rotterdam and Singapore, along with monthly Brent crude oil prices, between 2011 and 2020. All oil products prices correlate with Brent crude oil price, and all oil products prices tended to be higher in Rotterdam than in Singapore, especially during 2011-2014 and between the second half of 2017 and early 2020 (Gjølberg and Johnsen 1999; Lindstad and Eskeland 2015). In contrast, oil products prices converged between the second half of 2014 and the first half of 2017, as well as during 2020. This illustrates the typical arbitrage of jet fuel/kerosene and gasoil/diesel prices between east and west, where the Northwest/Southwest European region is a large importer of middle distillates from Asia.



Sources: OPEC (2021), Clarksons (2021).

Figure 5.2. Monthly Jet fuel/kerosene prices in Singapore and Rotterdam, and monthly Brent crude oil price between 2011 and 2020.

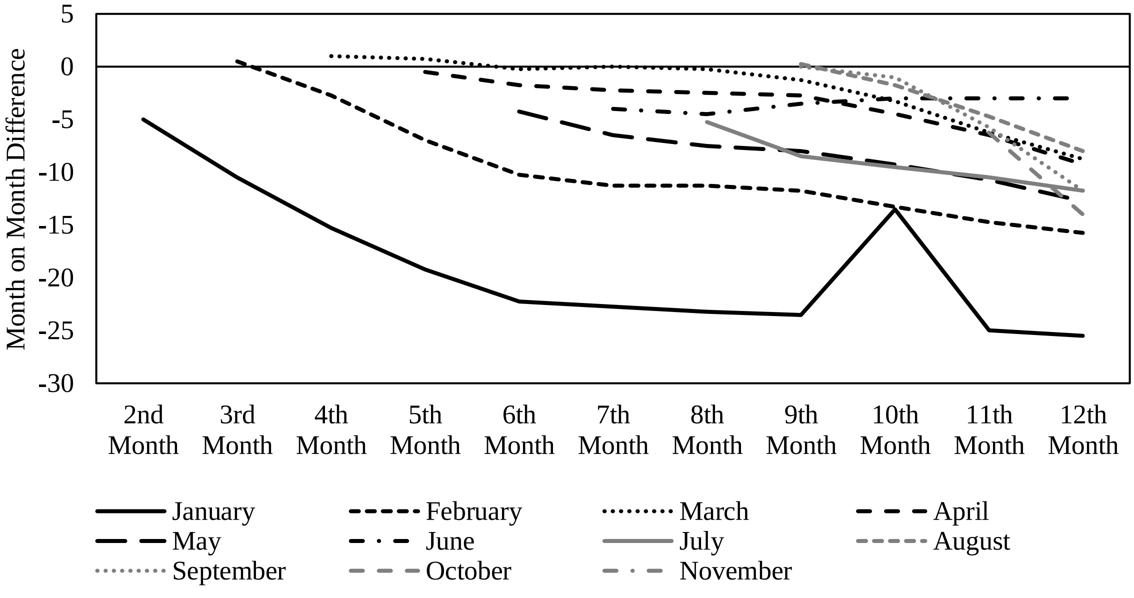
Sources: OPEC (2021), Clarksons (2021).

Figure 5.3. Monthly Gasoil/diesel prices in Singapore and Rotterdam, and monthly Brent crude oil price between 2011 and 2020.

Figures 5.4, 5.5, 5.6, and 5.7 show futures curves of the Intercontinental Exchange (ICE) Gasoil Futures Contract, which is traded on the Intercontinental Exchange (ICE) and used as a price reference for distillates in Europe by hedgers, arbitrageurs and speculators alike (Tamvakis 2015; ICE 2021d). Figures 5.4 to 5.7 include the years 2012 and 2013, where the NSR was used by oil product tankers, as well as the years 2016 and 2020, where the Cape route was used extensively as an alternative to the Suez Canal route. Starting from January, the curves show for every year the future price of the contract in each successive month (1st day of the month) ahead until December. Figures 5.4, 5.5, and 5.7 illustrate the sustained backwardation in futures prices[28] during 2012, most of 2013, and early 2020 (Platts 2011; IEA 2012; IEA 2013).

A combination of declining futures prices, high oil products prices, and therefore a rising value of cargo on board, as well as high marine fuel prices and competitive icebreaking fees, all prompted certain traders and shipowners to test the NSR as an alternative to other traditional routes to deliver the cargoes from Asia to Europe as quickly as possible in 2012 and 2013 (GCaptain 2013).

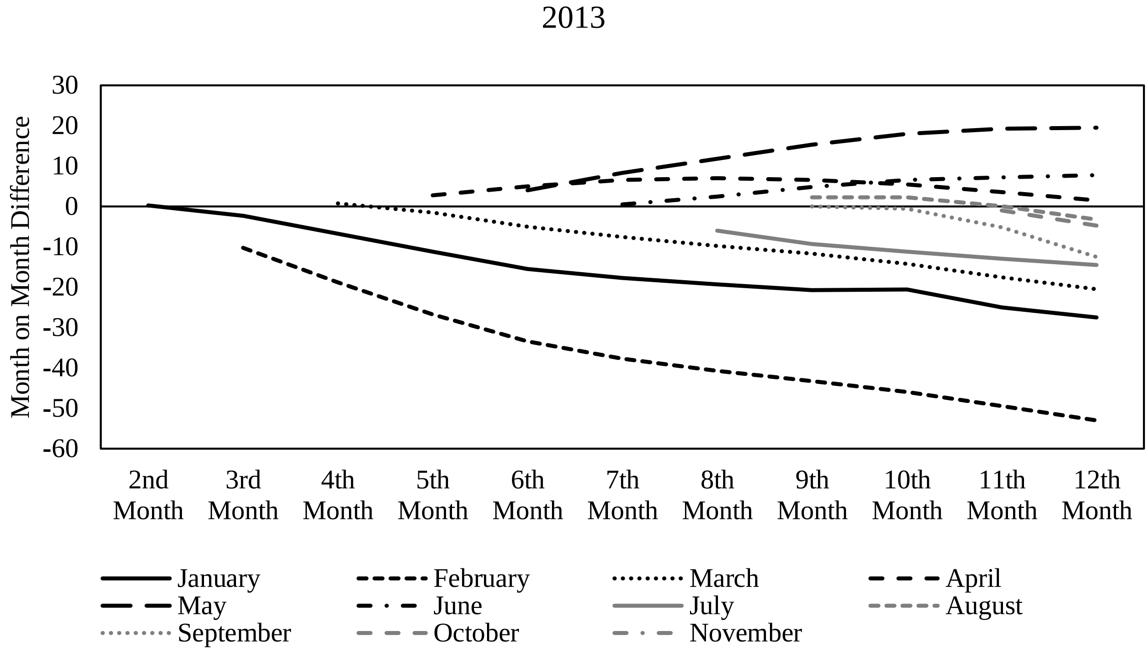
2012



Source: Author, based on data from Bloomberg (2021).

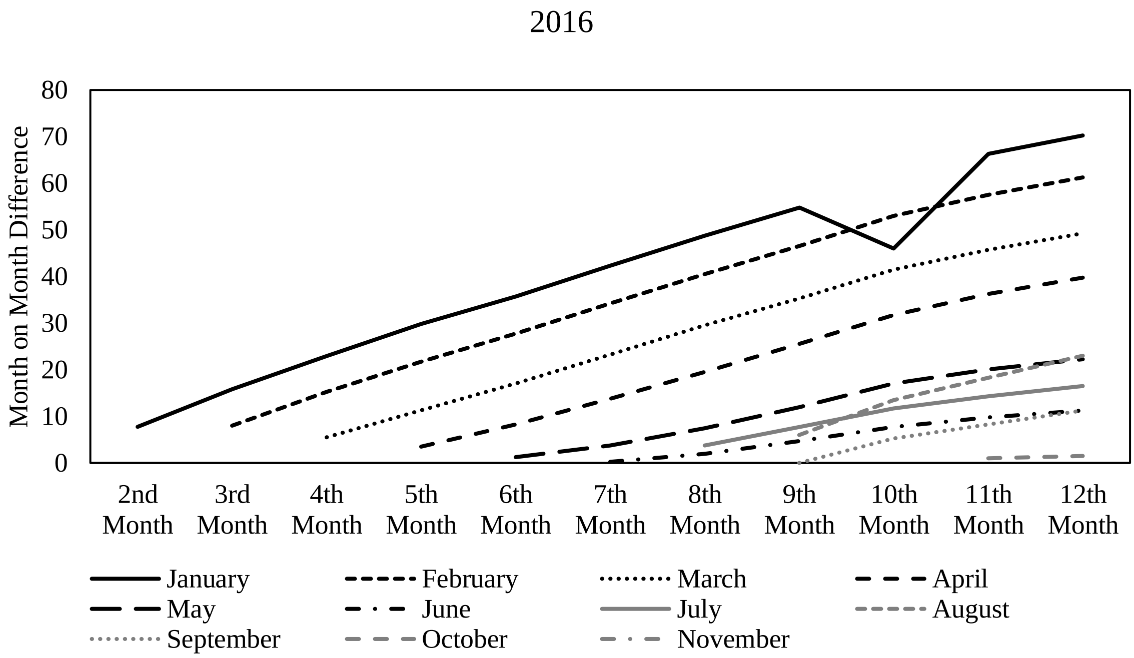
Figure 5.4. Historic ICE Low Sulphur Gasoil Futures Curves in 2012.

[28] Backwardation occurs when the price of a commodity trading in the futures market is lower than the spot price (Tamvakis 2015., pp. 193-232).



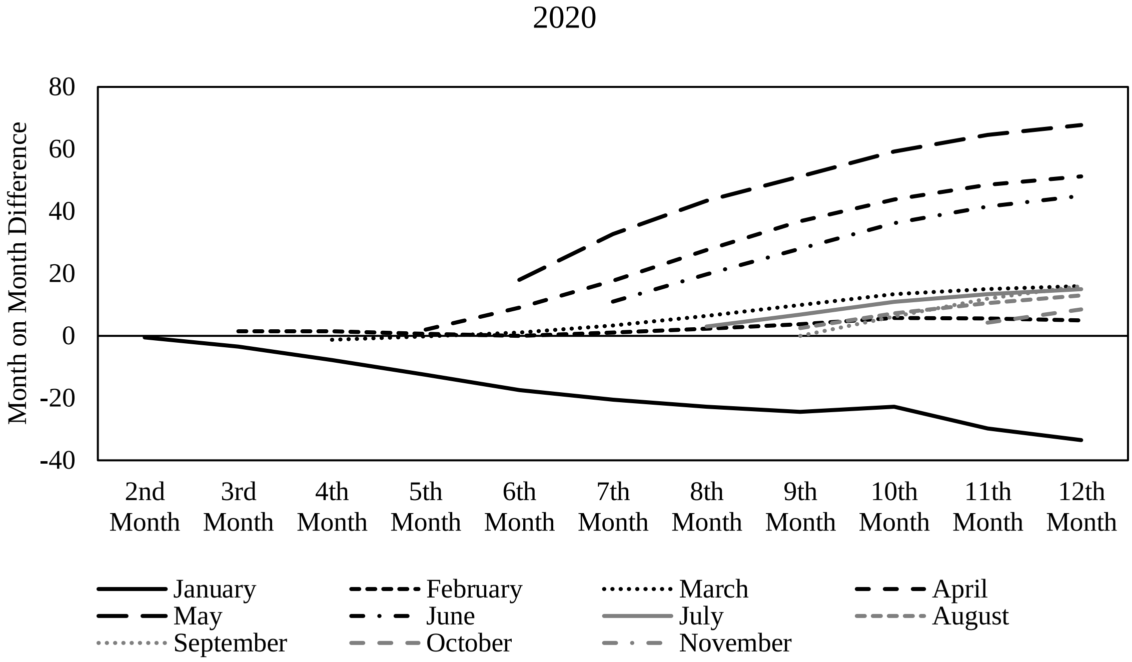
Source: Author, based on data from Bloomberg (2021).

Figure 5.5. Historic ICE Low Sulphur Gasoil Futures Curves in 2013.



Source: Author, based on data from Bloomberg (2021).

Figure 5.6. Historic ICE Low Sulphur Gasoil Futures Curves in 2016.



Source: Author, based on data from Bloomberg (2021).

Figure 5.7. Historic ICE Low Sulphur Gasoil Futures Curves in 2020.

The drop in crude oil and oil products prices during 2015 led to oversupply and high inventories in major hubs (IEA 2016). Thus, the exploration of the NSR for short transits became less significant as oil products prices converged between Asia and Europe, and the cargo value on board was lower in 2015 than in 2011-2014. Although icebreaking fees declined due to the depreciation of the Russian rouble in 2015, they were still more expensive than the discounted fees offered before 2013 (Tanker Company 2018; Tanker Company 2019; analysis in Chapter 4). Moreover, sanctions, low fuel prices and the factoring of potential ice damage repairs in costs, all negatively impacted the further use of the NSR for exploratory destination and transit voyages (Reuters 2015; Platts 2016a; Tanker Company 2018).

Not only did the steep drop in crude oil and oil products prices impact the use of the NSR, but also this resulted in increased floating storage and/or several voyages via the Cape of Good Hope instead of using the Suez Canal route between 2015 and 2017 as a result of a contango structure[29] in the oil futures markets (Figures 5.2; Figure 5.3; Figure 5.6; Figure 5.7; IEA 2015; Platts 2015; Platts 2016b; IEA 2017). Similarly, several oil product tankers used the Cape route for voyages between Asia and Europe owing to the Covid-19 pandemic and certain geopolitical events which resulted in very low fuel and commodity prices and oil oversupply in the market

[29] Contango occurs when the future price of a commodity is higher than the spot price i.e. the opposite of backwardation (Tamvakis 2015., pp. 193-232).

during 2020 (IEA 2020a; 2020b; Platts 2020; Argus 2020; Lloyd's List 2020a). A steep contango price curve in both 2015-2017 and during 2020 (Figure 5.6; Figure 5.7), meant that the structure of the market favoured the delay of cargo arrivals at the destination ports as opposed to the period 2011-2014.

5.3 Modelling

5.3.1 Modelling approach

A RFR model for competing maritime routes which determines the cost per tonne in US$ from the shipowner's perspective is developed, considering two modelling approaches. First, speed optimisation is employed to minimise the RFR for a given route alternative. Second, constant speeds are used in the cost model as opposed to theoretical optimal speeds, drawing from AIS speed data between 2014 and 2020 from LR2 tanker voyages between Northeast Asia and Northwest/Southwest Europe. On the one hand, the cost per tonne reaches its minimum when speed is optimised with respect to cost and market factors subject to engine technical boundaries. On the other hand, real ship speeds tend to depart from optimal points determined by market factors owing to organisational and technical constraints, ship, and voyage specific variables as well as weather factors amongst others (Adland et al. 2017; Adland and Jia 2018).

5.3.2 Cost assessment and optimal speeds

The minimum cost per tonne is the long-run equilibrium point between supply and demand, where revenue equals cost (Alderton 1981). Classical maritime economic theory holds that the (theoretical) optimum speed which minimises the cost per tonne is not affected by short-term freight rate volatility, port time or delays, and therefore is more appropriate for long-term planning than one which aims to maximise profit (Alderton 1981; Evans and Marlow 1990). A cost-based route comparison aims to establish the break-even point for a route and includes fixed and variable cost factors, that is, operating and capital costs for different ship types and technologies, fuel costs, transit fees, and other voyage-related costs.

Moreover, the RFR model considers the time value of cargo on board in order to minimise both the costs of transport, per se, and the in-transit inventory of the cargo. The optimal speed that minimises these costs by including both the value of ship and cargo is referred as the *least-cost inventory speed* (Alderton 1981). Goss et al. (1982) refer to the opportunity cost of cargo in-transit, which can be quantified by using a relevant interest rate and the value of cargo. The inclusion of in-transit inventory is more important in liner shipping, where manufactured or semi-manufactured cargoes have considerably higher values than dry bulk cargo, especially when large stocks of bulk cargoes are stored at ports (Alderton 1981; Notteboom 2006; Psaraftis and Kontovas 2014). However, in-transit inventory is also important in the case of oil transport and long-haul voyages (Psaraftis and Kontovas 2014; ICS 2014; Lindstad and Eskeland 2015) and for certain states of the market (Alderton 1981).

More specifically, the cargo value on board is included in the model to show quantitatively how RFR differentials, laden and ballast optimal speeds between alternative routes are impacted with varying commodity prices, and what are the implications for route choice of middle distillates between Northeast Asia and Northwest/Southwest Europe. Although the inclusion of in-transit inventory cost typically applies to a charterer's problem, it is included in the RFR model since it reflects the optimal speed and minimum cost of the service that shipowners offer to the users of their ships (Alderton 1981). According to Psaraftis and Kontovas (2014), the inclusion of in-transit inventory in a shipowner's problem is important, since a ship will be preferred by a charterer provided that their cargo will be delivered at the right time depending on market conditions, commodity prices and opportunity costs.

The RFR model incorporates alternative fuel types and technologies to consider various operational modes for competing sea routes. Three main operational modes are considered depending on the type of marine engine. As regards oil-powered engines, the use of HSFO with scrubber (HSFO-Scrubber), and the use of VLSFO with MGO within Emission Control Areas (ECAs) are considered (IMO 2021). For dual-fuel powered engines, the use of LNG and pilot MGO (gas mode), and VLSFO (oil mode) are considered. Moreover, the use of MGO within the boundaries of the NSR is considered for both the HSFO and VLSFO modes under the case of a ban of heavy fuel oil fuels in the Arctic (IMO 2020). Moreover, two options for dual-fuel gas-oil powered ships are included, that is, Oil/LNG engines with LNG tank capacities of 1,700 m^3 and 3,600 m^3 respectively, reflecting current and future technological developments.

The fuel consumption is a function of speed, fuel type, operational mode and payload (Barrass 2004; MAN Diesel and Turbo 2013a; Psaraftis and Kontovas 2013; Psaraftis and Kontovas 2014; MAN Energy Solutions 2020). Both laden and ballast voyages are considered for each route alternative.

The fuel consumption function of a ship with oil-powered engine using either of the oil-based fuels (HSFO, VLSFO, MGO) can be expressed as:

$$F_{FO}(S^{*},\nabla) = F_{FO\ d} \cdot \left(\frac{S^{*}_{FO\ L,B}}{S_d}\right)^{a} \cdot \left(\frac{P+L}{\nabla}\right)^{2/3} \quad (1)$$

The exponent a depends on the actual speed (Adland et al. 2020) and is approximated at three (3) in this study (Psaraftis and Kontovas 2014).

A dual-fuel diesel engine is capable to operate either on gas (LNG) or oil (VLSFO, HSFO, MGO) modes, where each fuel can be used depending on operational choices, market conditions and environmental considerations. The use of LNG also depends on tank capacity constraints that dictate the maximum range of the tanker, beyond which the engine is switched to oil mode. When the engine operates at gas mode, it also uses an oil-based fuel, since LNG requires an ignition source to start the combustion process (MAN Energy Solutions 2020; DNV 2021a). Since LNG is also assumed to be used within ECAs, the pilot fuel oil is assumed to be MGO for compliance with the ECAs regulations (MAN Energy Solutions 2020).

The fuel consumption functions of a ship with a dual-fuel diesel engine that operates on LNG-VLSFO mode can be expressed as:

$$F_{DF\ LNG}(S^{*},\nabla) = F_{DF\ LNG\ d} \cdot \left(\frac{S^{*}_{DF\ LNG\ L,B}}{S_d}\right)^{a} \cdot \left(\frac{P+L}{\nabla}\right)^{2/3}, \text{ for the LNG consumption,} \quad (2)$$

and

$$F_{DF\ Pilot}(S^{*},\nabla) = F_{DF\ Pilot\ d} \cdot \left(\frac{S^{*}_{DF\ LNG\ L,B}}{S_d}\right)^{a} \cdot \left(\frac{P+L}{\nabla}\right)^{2/3}, \text{ for the pilot fuel oil consumption} \quad (3)$$

It can be seen that in the case of pilot fuel oil consumption, the function (Equation 3) follows the same exponential relationship between speed and fuel consumption as in the other fuels (Equations 1, 2, 4). This is explained by the fact that pilot fuel oil consumption is proportional to the engine speed, which in turn is nearly proportional to the ship speed. This means that the pilot fuel oil consumption varies nearly linearly with ship speed (MAN Energy Solutions 2020).

The fuel consumption function when the dual-fuel diesel engine operates on oil mode can be expressed as:

$$F_{DF\ FO}(S^{*},\nabla) = F_{DF\ FO\ d} \cdot \left(\frac{S^{*}_{DF\ FO\ L,B}}{S_d}\right)^{a} \cdot \left(\frac{P+L}{\nabla}\right)^{2/3} \quad (4)$$

The objective is to minimise the total RFR per voyage of a route alternative (either RFR_{NSR} or RFR_{SCR} or RFR_{Cape}):

$$min \sum RFR \tag{5}$$

where $\sum RFR$ denotes the sum of the RFR for all legs of a voyage in either of the three routes.

The $\sum RFR$ of each voyage is a function of fuel consumption at a certain speed (either optimal or constant), distance, total cost inputs and cargo carrying capacity of a tanker for each leg.

Equation (6) presents the RFR function on either HSFO-scrubber or VLSFO modes:

$$RFR = \frac{1}{W} \cdot \left[\left(\frac{D_{SCR,NSR,Cape}}{S^*_{FO\ L,B} \cdot 24}\right) \cdot \left(\left(F_{FO}\left(S^*_{FO\ L,B}\right) \cdot P_{FO}\right) + (C_o + C_c + g \cdot C_s) + q \cdot (W \cdot P_C \cdot \frac{r}{365})\right) + C_{TI}\right] \tag{6}$$

whereas Equation (7) presents the RFR function on the LNG-VLSFO mode, where LNG and pilot MGO (gas mode) are included along with VLSFO (oil mode):

$$RFR = \frac{1}{W} \cdot \left[\left(\frac{D_{SCR,NSR,Cape}}{(S^*_{DF\ LNG\ L,B} + S^*_{DF\ FO\ L,B}) \cdot 24}\right) \cdot \left(b \cdot \left(F_{DF\ LNG}\left(S^*_{DF\ LNG\ L,B}\right) \cdot P_{LNG} + F_{DF\ Pilot}\left(S^*_{DF\ LNG\ L,B}\right) \cdot P_{FO}\right) + c \cdot \left(F_{DF\ FO}\left(S^*_{DF\ FO\ L,B}\right) \cdot P_{FO}\right) + (C_o + C_c) + q \cdot (W \cdot P_C \cdot \frac{r}{365})\right) + C_{TI}\right] \tag{7}$$

Equations (8) and (9) present the RFR for a ballast voyage between the unloading port in Northwest/Southwest Europe and the repair yard when ice damage repairs are factored in the model. This RFR includes only fuel, operating and capital costs.

Equation (8) refers to RFR for oil-based modes (HSFO-Scrubber, VLSFO, MGO). Similar to the RFR for a Northeast Asia to Northwest/Southwest Europe voyage, MGO is used along with VLSFO on the VLSFO mode depending on the ECAs mileage, whereas HSFO is scrubbed on the HSFO-scrubber mode.

$$k \cdot RFR = \frac{1}{W} \cdot \left[\left(\frac{D_B}{S^*_{FO\ B} \cdot 24}\right) \cdot \left((F_{FO}(S^*_{FO\ B}) \cdot P_{FO}) + (C_o + C_c + g \cdot C_s)\right) + C_R\right] \tag{8}$$

Equation (9) refers to RFR for the LNG-VLSFO mode, using LNG and MGO pilot fuel between the unloading port and the repair yard, including within ECAs and non-ECAs legs. LNG and pilot MGO are used in this voyage since the fuel consumption requirements satisfy the voyage length and LNG is cheaper than VLSFO, based on the assumed marine fuel prices.

$$n \cdot RFR = \frac{1}{W} \cdot \left[\left(\frac{D_B}{S^*_{DF\ LNG\ B} \cdot 24}\right) \cdot \left((F_{DF\ LNG}(S^*_{DF\ LNG\ B}) \cdot P_{LNG} + F_{DF\ Pilot}(S^*_{DF\ LNG\ B}) \cdot P_{FO}) + (C_o + C_c)\right) + C_R\right] \quad (9)$$

subject to

$$\underline{S} \leq S^* \leq \overline{S} \quad (10)$$

and

$$b, c, g, q, k, n \in \{0,1\} \quad (11)$$

Table 5.1 reports the parameters and variables used in Equations (1) – (30).

Table 5.1. Parameters and variables used in the model.

Parameters:	**Description**
P	weight of cargo, fresh water, fuel, lubricating oil, stores, water ballast, crew and effects, and baggage and passengers in metric tonnes (m.t.)
W	average weight of cargo in m.t.
$\sum_{i=1}^{n} D_{SCR}$	total SCR distance in nautical miles (n.m.)
$\sum_{i=1}^{n} D_{NSR}$	total NSR distance in n.m.
$\sum_{i=1}^{n} D_{Cape}$	total Cape of Good Hope distance in n.m.
$D_{1,SCR}, \dots, D_{n,SCR}$	SCR distance legs in n.m.
$D_{1,NSR}, \dots, D_{n,NSR}$	NSR distance legs in n.m.
$D_{1,Cape}, \dots, D_{n,Cape}$	Cape of Good Hope distance legs in n.m.
D_B	distance for ballast voyage from an unloading port to a repair yard in n.m.
P_{FO}, P_{LNG}	fuel price in US$ per tonne for fuel oils (HSFO, VLSFO, MGO), and LNG, respectively
P_C, r	commodity price in US$ per tonne (here oil products), and interest rate
C_R	cost of ice damage repairs in US$
C_o, C_c	operating costs in US$ per day, capital costs in US$ per day
C_{TI}	transit costs (canal tolls or icebreaking fees) and insurance premiums in US$
C_s	capital costs of exhaust cleaning systems (scrubber) in US$ per day
S_d	design speed in knots
$\overline{S}$	upper speed in knots
$\underline{S}$	lower speed in knots
$F_{FO\ d}$	fuel consumption for oil-based fuels (HSFO, VLSFO, MGO) at design speed in tonnes per day
$F_{DF\ LNG\ d}, F_{DF\ Pilot\ d}$	fuel consumption for LNG and Pilot MGO at design speed in tonnes per day
$F_{DF\ FO\ d}$	fuel consumption for dual-fuel engine when operating on oil-mode (VLSFO) at design speed in tonnes per day
L	lightweight of a product tanker in tonnes
∇	displacement of a product tanker in tonnes

Table 5.1. Parameters and variables used in the model (continued).

Variables	**Description**
$S^*_{FO\ L,B}$	laden, ballast optimal speeds for oil powered (HSFO, VLSFO, MGO) engine in knots
$S^*_{DF\ LNG\ L,B}$	laden, ballast optimal speeds for dual-fuel engine (LNG) in knots
$S^*_{DF\ FO\ L,B}$	laden, ballast optimal speed for dual-fuel engine (oil-mode – VLSFO, MGO) in knots
$S^*_{FO\ B}, S^*_{DF\ LNG\ B}$	optimal speeds for a ballast voyage to a repair yard in knots for oil powered (HSFO, VLSFO, MGO) and dual-fuel (LNG) engine, respectively
b, c, g, q, k, n	binary variables, equal to 1 when dual-fuel LNG mode, dual-fuel fuel oil mode, scrubber, in-transit inventory, and ballast voyages for repairs (oil only, dual-fuel) are considered respectively, and 0 otherwise
$\sum_{i=1}^{n} T_{SCR}$	total SCR transit time in days
$\sum_{i=1}^{n} T_{NSR}$	total NSR transit time in days
$\sum_{i=1}^{n} T_{Cape}$	total Cape of Good Hope transit time in days
$T_{1,SCR}, \dots, T_{n,SCR}$	SCR transit time for each leg in days
$T_{1,NSR}, \dots, T_{n,NSR}$	NSR transit time for each leg in days
$T_{1,Cape}, \dots, T_{n,Cape}$	Cape of Good Hope transit time for each leg in days
T_B	transit time for a ballast voyage from an unloading port to a repair yard in days
$RFR_{SCR}, RFR_{NSR}, RFR_{Cape}$	required freight rate for the SCR, NSR, and Cape routes in US$ per tonne
ΔRFR	RFR differential

The number 24 denotes the hours per day, which is used in Equations (6) – (9) to obtain voyage time in days. The term $\frac{1}{W}$ transforms RFR to RFR in US$ per tonne, whilst the terms $\left(\frac{D_{SCR,NSR,Cape}}{S^*_{FO\ L,B} \cdot 24}\right)$, $\left(\frac{D_{SCR,NSR,Cape}}{(S^*_{DF\ LNG\ L,B} + S^*_{DF\ FO\ L,B}) \cdot 24}\right)$, $\left(\frac{D_B}{S^*_{FO\ B} \cdot 24}\right)$, $\left(\frac{D_B}{S^*_{DF\ LNG\ B} \cdot 24}\right)$ calculate the days at sea for each leg and voyage of the respective fuel type. The use of hybrid scrubbers is assumed since open-loop scrubbers may be prohibited in certain ports, waterways and/or canals in the future. The binary variable g equals 1 when the use of a hybrid scrubber is considered with the use of HSFO or $g = 0$ otherwise. The speed range is defined between 5 and 16 knots. A minimum speed of 5 knots is assumed for an ice class IA tanker as the speed below which it cannot navigate independently (MAN Diesel and Turbo 2013b; Trafi 2017a; Solakivi et al. 2018), and a maximum speed of 16 knots for all tankers, where the design speed falls between 90-95% of the maximum speed depending on ship size (Lindstad et al. 2011). The in-transit inventory cost, expressed in US$ per day, is defined by the term $W \cdot P_C \cdot \frac{r}{365}$, where the average price of a tonne of jet fuel/gasoil in US$, P_C, is multiplied by the total quantity in tonnes, W, and a relevant interest rate for oil and petroleum products, r (Alderton 1981; Goss et al. 1982; Psaraftis and Kontovas 2014; Lindstad and Eskeland 2015) equal to 10% (McQuilling 2012). The interest rate, r, is divided by 365 to convert the value of in-transit inventory cost to US$ per day. (The binary variable q equals 1 when in-transit inventory costs are included or $q = 0$ otherwise, such as in ballast voyages or in laden voyages where in-transit inventory is not considered. Port-related costs and time, as well as cargo handling are assumed the same for either route choice. Auxiliary fuel requirements are assumed to be satisfied by the use of the main engine, which depends on the ship and engine set up (Tanker Company 2019).

Repair costs, C_R, which are the result of ice damages, along with the RFR of a ballast voyage to visit a repair yard in the Baltic region, following a laden voyage between Northeast Asia and Southwest/Northwest Europe are included when $k, n = 1$ or 0 otherwise. According to Tanker Company (2018) and Tanker Company (2020), ice damages occurred in 20% of their voyages through NSR, whilst proceeding with slow speed within the NSR could reduce the risk of damages[30]. Thus, ice damage repairs are included in the sensitivity analysis to assess how the RFR is affected when these are factored in the model.

Partial differentiation of Equations (6), (7), (8), and (9) with respect to speeds $S^*_{FO\ L,B}$, $S^*_{DF\ LNG\ L,B}$, $S^*_{DF\ FO\ L,B}$, $S^*_{FO\ B}$, $S^*_{DF\ LNG\ B}$ is carried out to obtain optimal speeds. The partial derivatives are set equal to zero, that is, $\frac{\partial RFR}{\partial_{S^*_{FO\ L,B}}} = 0$, $\frac{\partial RFR}{\partial_{S^*_{DF\ LNG\ L,B}}} = 0$, $\frac{\partial RFR}{\partial_{S^*_{DF\ FO\ L,B}}} = 0$, $\frac{\partial RFR}{\partial_{S^*_{FO\ B}}} = 0$, $\frac{\partial RFR}{\partial_{S^*_{DF\ LNG\ B}}} = 0$ with all optimal speeds subject to lower limit, $\underline{S}$, and upper limit, $\overline{S}$ respectively.

[30] Other options that reduce the risk of damages could include the use of special ice coating. However, this option is considered in Chapter 6, as it is more appropriate when an ice class tanker operates on ice for a whole season (Tanker Company 2019). The number of voyages is not given in absolute value due to confidential reasons.

Equations (12), (13) and (14) refer to optimal speeds of oil-powered and dual-fuel gas/oil modes, whilst equations (15) and (16) refer to optimal speeds of ballast voyages to a repair yard following a laden voyage between Northeast Asia and Southwest/Northwest Europe for oil-powered and dual-fuel gas/oil operational modes, respectively.

$$S^*_{FO\ L,B} = \sqrt[a]{\frac{\left((C_O+C_C+g\cdot C_S)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right)\cdot S_d{}^{a}\cdot\nabla^{2/3}}{(a-1)\cdot(F_{FO\ d}\cdot P_{FO})\cdot(P+L)^{2/3}}} \tag{12}$$

$$S^*_{DF\ LNG\ L,B} = \sqrt[a]{\frac{\left((C_O+C_C)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right)\cdot S_d{}^{a}\cdot\nabla^{2/3}}{(a-1)\cdot(F_{DF\ LNG\ d}\cdot P_{LNG}+F_{DF\ Pilot\ d}\cdot P_{FO})\cdot(P+L)^{2/3}}} \tag{13}$$

$$S^*_{DF\ FO\ L,B} = \sqrt[a]{\frac{\left((C_O+C_C)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right)\cdot S_d{}^{a}\cdot\nabla^{2/3}}{(a-1)\cdot(F_{DF\ FO\ d}\cdot P_{FO})\cdot(P+L)^{2/3}}} \tag{14}$$

$$S^*_{FO\ B} = \sqrt[a]{\frac{(C_O+C_C+g\cdot C_S)\cdot S_d{}^{a}\cdot\nabla^{2/3}}{(a-1)\cdot(F_{FO\ d}\cdot P_{FO})\cdot(P+L)^{2/3}}} \tag{15}$$

$$S^*_{DF\ LNG\ B} = \sqrt[a]{\frac{(C_O+C_C)\cdot S_d{}^{a}\cdot\nabla^{2/3}}{(a-1)\cdot(F_{DF\ LNG\ d}\cdot P_{LNG}+F_{DF\ Pilot\ d}\cdot P_{FO})\cdot(P+L)^{2/3}}} \tag{16}$$

Appendix R presents the calculations for equations (12) – (16). Equations (6) – (9) are solved by substituting the optimal speeds obtained from Equations (12) – (16) to give the minimum RFR for each leg of a certain OD pair.

These optimal speeds depend on operating and capital costs, in-transit inventory costs, fuel prices, and payload. Optimal laden speeds tend to be higher than ballast speeds because in-transit inventory costs are included to consider the charterer's value of time when the cargo is in-transit (Psaraftis and Kontovas 2014; Lindstad and Eskeland 2015). The difference between these speeds reflects real practices (Lindstad and Eskeland 2015), although these could be attributed to charterparty obligations than to in-transit inventory costs per se (Psaraftis and Kontovas 2013). Moreover, speeds through ice are assumed to not vary with respect to cost and market factors due to the influence of sea ice on ship speed, and therefore could be determined based on recorded speeds of tanker voyages through NSR (for assumptions on the average speed through ice: Section '5.4.5 Speed through ice on the NSR').

The total distance and time of each individual leg for a route alternative depends on ECAs zones, fuel types/technologies, fuel tank capacity and range, and commodity and fuel prices. They can be expressed as:

$$\sum_{i=1}^{n} D_{NSR} = D_{1,NSR} + \ldots + D_{n,NSR} \quad (17)$$

$$\sum_{i=1}^{n} T_{NSR} = T_{1,NSR} + \ldots + T_{n,NSR} \quad (18)$$

$$\sum_{i=1}^{n} D_{SCR} = D_{1,SCR} + \ldots + D_{n,SCR} \quad (19)$$

$$\sum_{i=1}^{n} T_{SCR} = T_{1,SCR} + \ldots + T_{n,SCR} \quad (20)$$

$$\sum_{i=1}^{n} D_{Cape} = D_{1,Cape} + \ldots + D_{n,Cape} \quad (21)$$

$$\sum_{i=1}^{n} T_{Cape} = T_{1,Cape} + \ldots + T_{n,Cape} \quad (22)$$

The optimal speed for either operational mode per voyage for a route alternative is defined as:

$$S^{*}_{FO\ L,B}, S^{*}_{DF\ LNG\ L,B}, S^{*}_{DF\ FO\ L,B} = \frac{\sum_{i=1}^{n} D_{NSR}}{\sum_{i=1}^{n} T_{NSR} \cdot 24} \quad (23)$$

$$S^{*}_{FO\ L,B}, S^{*}_{DF\ LNG\ L,B}, S^{*}_{DF\ FO\ L,B} = \frac{\sum_{i=1}^{n} D_{SCR}}{\sum_{i=1}^{n} T_{SCR} \cdot 24} \quad (24)$$

$$S^{*}_{FO\ L,B}, S^{*}_{DF\ LNG\ L,B}, S^{*}_{DF\ FO\ L,B} = \frac{\sum_{i=1}^{n} D_{Cape}}{\sum_{i=1}^{n} T_{Cape} \cdot 24} \quad (25)$$

Whereas the optimal speeds concerning ballast voyages from an unloading port to a repair yard are defined as:

$$S^{*}_{FO\ B} = \frac{D_B}{T_B \cdot 24} \quad (26)$$

$$S^{*}_{DF\ LNG\ B} = \frac{D_B}{T_B \cdot 24} \quad (27)$$

The RFR differentials between NSR, SCR and Cape routes are defined as:

$$\Delta RFR = RFR_{SCR} - RFR_{NSR} \quad (28)$$

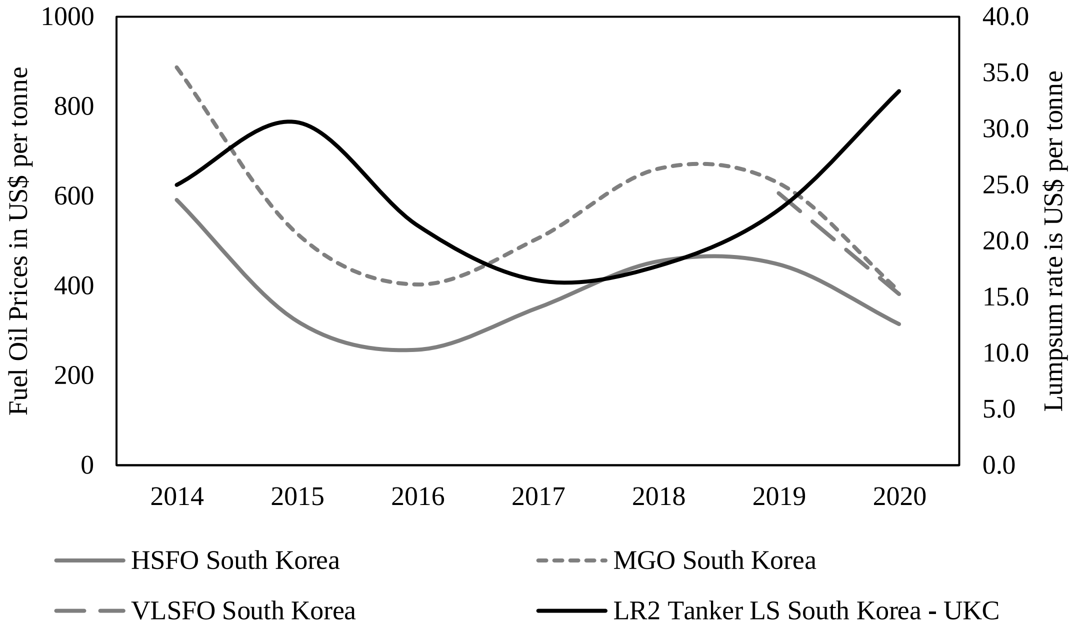
$$\Delta RFR = RFR_{Cape} - RFR_{NSR} \quad (29)$$

$$\Delta RFR = RFR_{SCR} - RFR_{Cape} \quad (30)$$

This speed optimisation approach is in line with Fagerholt et al. (2015), and Fagerholt and Psaraftis (2015), where distinct voyage legs and respective optimal speeds can be defined owing to different fuel types, technologies and prices, and environmental policies. Equations (17) – (25) also refer to non-optimal voyage speeds, and respective distances and times when assuming constant speeds for each route alternative (for real speeds and assumptions on constant speeds: Section '5.3.3 Cost assessment and real speeds').

5.3.3 Cost assessment and real speeds

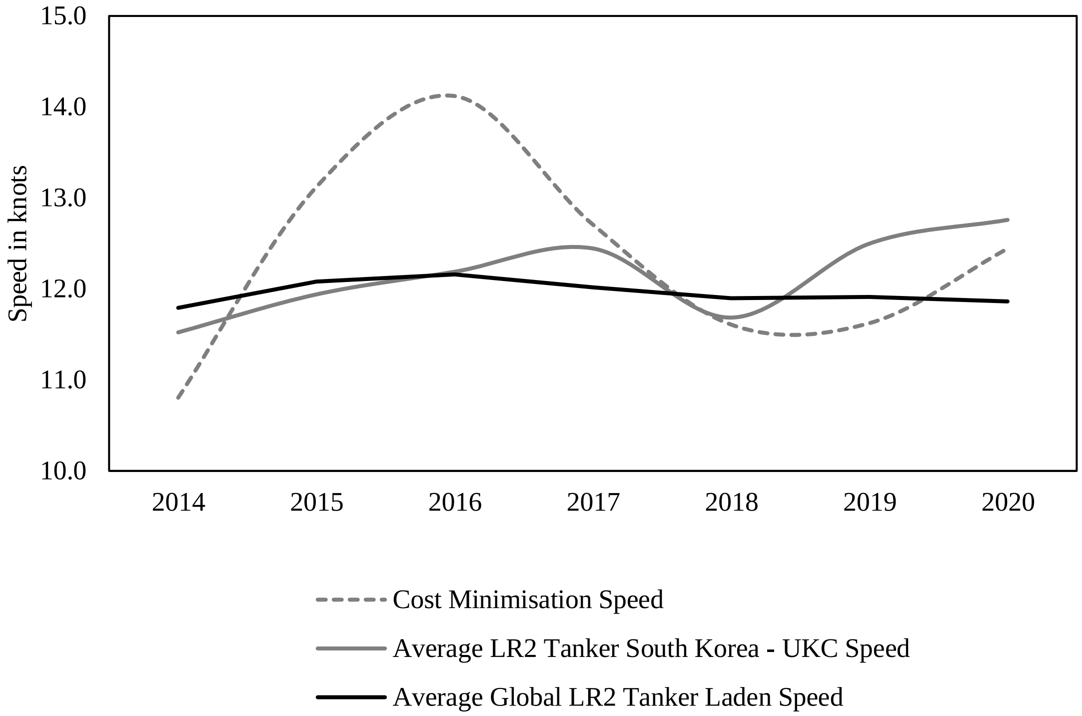
Ship speed affects both costs and revenue and is one of the factors that determine the total supply of ships globally. Speed optimisation is used to either maximise profits or minimise costs, depending on the optimiser (either shipowner or charterer or industrial carrier) and the logistical context (Alderton 1981; Evans and Marlow 1990; Psaraftis and Kontovas 2014). Figure 5.8 illustrates lumpsum (LS) rates, expressed in US$ per tonne, for middle distillate cargoes of 90,000 tonnes carried on LR2 tankers via the Suez Canal, along with marine fuel prices between 2014 and 2020, for voyages between South Korea and UKC (U.K./Continent range i.e. Southwest/Northwest Europe). LS rates rose from 2014 to 2015, fell between 2016 and 2017, and increased between 2018 and 2020. Fuel oil prices dropped during 2015-2016 in tandem with the decline in crude oil prices, whereas they rose between 2017 and 2019, to decline again during 2020. Figure 5.9 depicts the annual average voyage speed for voyages between South Korea and UKC based on AIS data, along with the theoretical cost minimisation speed from the shipowner's perspective, without accounting for in-transit inventory. This optimal speed is calculated based on historic fuel oil prices and costs during 2014-2020. The global average laden LR2 tanker speeds for the same period are also included in Figure 5.9. Data for LS rates and speeds on the South Korea – UKC LR2 tanker trades are based on 81 unique voyages between 2014 and 2020, of which 29 were direct LR2 tanker voyages loaded with 90,000 tonnes of middle distillates. These were identified and tracked in Bloomberg (2021) and Refinitiv Eikon (2021). Global LR2 tanker laden speeds refer to daily speeds between 2014 and 2020, obtained from Refinitiv Eikon (2021).



Sources: Author, based on Refinitiv Eikon (2021), Bloomberg (2021), Clarksons (2021).

Figure 5.8. Lumpsum freight rates and fuel prices for South Korea - UKC oil product trades during 2014-2020.

According to classical economic theory, a combination of high freight rates and low fuel prices result in high profit maximisation speeds and vice versa. Further, low fuel prices mean high cost minimisation speeds and vice versa, all else being equal (Alderton 1981; Evans and Marlow 1990). If freight rates and fuel prices move in the same direction, the level of a profit maximisation speed will depend on the relative impact of the values of these variables on the speed equation. It can be seen that the optimal speed for LR2 tankers rose in 2015-2016, declined in 2017-2018, and increased again during 2020, in line with fuel price movements, all else being equal. Although both global and the South Korea – UKC route real average speeds vary based on freight rate and fuel price movements, they are significantly less responsive than optimal speeds, especially during 2015-2016. Actual South Korea – UKC and global LR2 tanker speeds range between 11.5 (2014) – 12.8 (2020) and 11.8 (2014) – 11.9 (2020) knots, respectively. Similar observations can be made for voyages between Japan and UKC, and for Cape voyages. The average speed between Northeast Asia and UKC is 12 knots between 2014 and 2020, and therefore this speed is chosen to assess costs versus cost minimisation optimal speeds estimated based on Section '5.3.2 Cost assessment and optimal speeds'.



Sources: Author's calculations based on data from Refinitiv Eikon (2021) and Bloomberg (2021).

Figure 5.9. Optimal and real speeds of LR2 tanker voyages between South Korea and UKC, and global real speeds during 2014-2020.

5.4 Assumptions and data

5.4.1 Origin – Destination pairs and routes

Jet fuel/kerosene and gasoil/diesel comprised on average 63% and 32% of the volume of oil products shipped from Northeast Asia to Southwest/Northwest Europe between 2011 and 2019 (IEA 2020c). The biggest importers were the Netherlands, France, the UK, and Spain, whereas the biggest exporters were South Korea and Japan. Three OD pairs are chosen to assess route choice with respect to distance between Northeast Asia and Southwest/Northwest Europe, that is, Ulsan – Bilbao, Ulsan – Rotterdam, and Chiba – Coryton[31]. These OD pairs reflect the most frequent loading and unloading ports, historic port choices for NSR voyages, as well as LNG bunkering availability (both current and future) (Bloomberg 2021; CHNL 2021a; Clarksons 2021; Refinitiv Eikon 2021; DNV 2021b). Distance savings increase for the NSR versus the SCR and Cape routes, whereas they decrease for the Cape route versus the SCR, when moving from the former to the latter OD pair. Figure 5.10 illustrates OD pairs and sea routes. Table 5.2

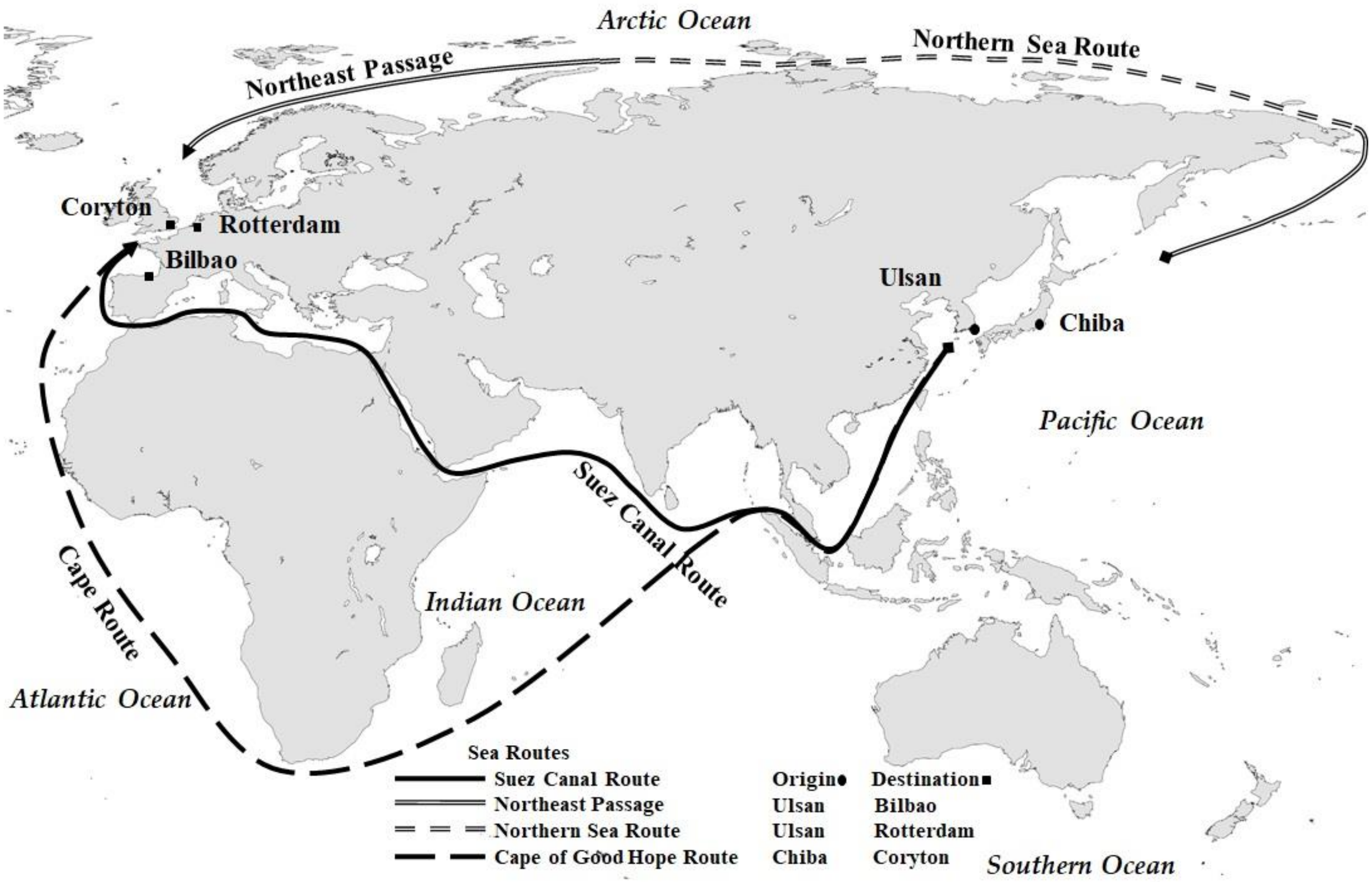
[31] Although France is the second biggest importer, a UK port is chosen as a medium-haul due to the proximity of France with the Netherlands, the first biggest importer, which is also considered in the analysis.

presents the distances for OD pairs. Distances for a ballast voyage from an unloading port to a repair yard are reported in Appendix U1. Port characteristics and LNG bunkering infrastructure are reported in Appendices S1 and S2, respectively.

Table 5.2. OD pairs and distances.

Origin – Destination (OD) Distance (n.m.)	Northern Sea Route (NSR)	Suez Canal (SCR)	Cape of Good Hope Route	Difference between NSR – SCR	Difference between NSR – Cape	Difference between SCR – Cape
Ulsan – Bilbao	7,834	10,436	13,853	-25%	-43%	-25%
Ulsan – Rotterdam	7,127	10,944	14,371	-35%	-50%	-24%
Chiba – Coryton	6,914	11,264	14,696	-39%	-53%	-23%

Source: Dataloy (2021). The distance through NSR is assumed 2,059 n.m. and refers to the deep-water high-latitude route north of the New Siberian Islands, based on the majority of historic NSR voyages (Bloomberg 2021).



Source: Author, based on Equirectangular projection (NASA 2021).

Figure 5.10. OD pairs and route alternatives.

5.4.2 Cost and navigational factors

The analysis is based on a comparison between an ordinary LR2 tanker and an ice class IA LR2 tanker, both of 115,000 dwt, with Length Overall (LOA) 250 metres, draught of 15 metres and beam of 44 metres. The fuel consumption in tonnes per day at the design speed for each engine set-up is calculated based on the Computerised Engine Application System (CEAS) provided by MAN Energy Solutions (MAN Energy Solutions 2019a; MAN Energy Solutions 2019b). Appendix T presents the calculations for the fuel consumption at the design speed based on CEAS.

A cargo of 80,000 metric tonnes of middle distillates is chosen, reflecting average jet fuel/kerosene and gasoil/diesel quantities traded between Northeast Asia and Southwest/Northwest Europe, and conforming to port characteristics and LNG bunkering infrastructure.

Table 5.3 presents costs and technical characteristics for the tankers considered in this Chapter. These refer to global average characteristics of Aframax/LR2 tankers (MAN Diesel and Turbo 2013a; MAN Diesel and Turbo 2013c; MAN Energy Solutions 2019a; MAN Energy Solutions 2019b; MAN Energy Solutions 2020; Sovcomflot 2018; TradeWinds 2020; Riviera 2020; Clarksons 2021). The ice class IA is in line with the majority of the tankers that used the NSR from 2011 to 2019 (NSRA 2016; CHNL 2021a). Sovcomflot's LNG-powered Aframax tankers which used the NSR in 2018 are of ice class IA/B. This means that they have a hull that conforms to ice class IA standards, whereas the rest of their specifications are equal to ice class IB (Sovcomflot 2018). Generally, an ice class IA ship is capable of navigating on first-year ice with a maximum thickness of 1.0 metre (MAN Diesel and Turbo 2013b; Trafi 2017a).

Table 5.3. LR2 tanker costs and technical characteristics.

	HSFO-Scrubber	VLSFO	LNG	
			LNG mode	VLSFO mode
Design Speed (knots) [a]	15	15	15	15
Maximum Speed (knots)	16	16	16	16
Fuel Consumption (tonnes/day of non-ice/ice class)[a]	46.7 / 63.2	45.6 / 61.6	36.5 / 49.6	46.7 / 63.1
MGO Consumption (tonnes/day of non-ice/ice class)[a]	–	44 / 59.4	–	–
MGO Pilot Consumption (tonnes/day of non-ice/ice class)[a]	–	–	0.91 / 0.98	–
Fuel Tank Capacity (tonnes) [a]	2,415	2,415	773	1,700
Operating Costs (US$ per day) (non-ice/ice class)[b]	7,974 / 8,406	7,974 / 8,406	7,974 / 8,406	7,974 / 8,406
Capital Costs (US$ per day) (non-ice/ice class)[c]	13,056 / 16,861	12,296 / 16,033	1,700 m^3: 12,827 / 16,562 3,600 m^3: 13,736 / 17,912	1,700 m^3: 12,827 /16,562 3,600 m^3: 13,736 / 17,912
Tonnes per Centimetre Immersion (TPC) [a]	97.2	97.2	97.2	97.2
Draught (metres) [a]	15	15	15	15
Draught when loaded (metres) [a]	12	12	12	12

Sources: [a]calculations based on Appendix T, [b]average 2011-2018 BDO (2021), [c]calculations based on Appendices O1, O2.

The LNG provides the highest energy density and therefore the lowest consumption compared to HSFO, VLSFO and MGO. However, when the dual fuel engine operates on the VLSFO mode, it consumes more than an oil-powered engine operating on the same fuel, since restrictions on its design means that it cannot be as efficient as a fuel oil-based engine at both operational modes (MAN Energy Solutions 2019a). Moreover, the HSFO option gives higher consumption than VLSFO and MGO owing to its lower energy density, as well as the use of a scrubber, which entails additional energy requirements. MGO consumption is the lowest of the oil-based fuels.

The HSFO-Scrubber mode allows the use of HSFO for a whole voyage as the scrubber (here hybrid), removes the sulphur of the fuel before it is emitted in the atmosphere. The VLSFO mode implies the use of VLSFO, with MGO used within ECAs zones. The LNG-VLSFO mode gives a dual-fuel LR2 tanker the option to use LNG for a certain distance (including within the ECAs zones and within the NSR) depending on the range and LNG tank capacity, and VLSFO for the rest of the voyage.

Two LNG-VLSFO sub-modes are considered, that is, for a tanker based on specifications similar to those of Sovcomflot's ice class IA/B Aframax tankers with LNG fuel tank capacity of 1,700 m^3, and for a tanker with LNG fuel tank capacity of 3,600 m^3, based on LR2 tanker orders from Shell and Hafnia/BW Group in 2020 (Sovcomflot 2018; TradeWinds 2020; Riviera 2020; Clarksons 2021). Different LNG tank capacities have implications on the fuel mix per voyage, costs, and route competitiveness alike (The Motorship 2018; The Motorship 2020a; The Motorship 2020b). The 1,700 m^3 tank provides a maximum range of about 7,800 nautical miles for an ordinary Oil/LNG dual-fuel LR2 tanker at the maximum speed of 16 knots, and a maximum range of 5,700 n.m. for an ice class IA dual-fuel Oil/LNG LR2 tanker at the maximum speed of 16 knots, when they are loaded with 80,000 metric tonnes of cargo, before switching to VLSFO. On the other hand, a 3,600 m^3 tank provides a range in excess of 14,696 n.m. for ordinary LR2 tankers at a speed of 16 knots, which is the longest distance assumed in this study, with about 200 tonnes of LNG remaining in the tank before switching to VLSFO.

Yet, daily LNG consumption in an optimisation setting depends on the optimal speed, which in turn depends on fixed and variable costs, payload, and displacement. Thus, the actual range can be less or equal that achieved at the maximum speed. Equally, LNG consumption through ice corresponds at speeds well below 16 knots and as a consequence it would be lower than the consumption at the maximum speed even after considering increased fuel consumption for an ice class tanker. The same also applies to cost assessment based on fixed speeds of 12 knots. Distance legs and LNG/VLSFO distance ratios per route and OD pair are reported in Appendices U1 and U2, respectively.

Increased costs for ice class tankers refer to premiums in capital, operating and voyage costs. A capital cost premium of 30.4% for a new ice class IA tanker is assumed based on Solakivi et al. (2018), and increased costs for dual fuelled Oil/LNG tankers of 4.38% and 4.50% for 1,700 m^3 and 3,600 m^3 LNG tank capacities respectively (Appendix O2; Sovcomflot 2018; Riviera 2020; TradeWinds 2020; Clarksons 2021). Increased fuel consumption is based on 30.8% higher installed power for an ice class tanker than that of a non-ice class tanker (Solakivi et al. 2018) and is obtained at the design speed for each engine set-up using CEAS calculations from MAN Energy Solutions (MAN Energy Solutions 2019a; MAN Energy Solutions 2019b).

Other additional costs for ice class tankers include a 10% premium for daily crew costs, 1,000 US$ per day for piloting, including travel expenses at US$ 5,000 per voyage, as well as US$ 50,000 for insurance and US$ 20,000 for books and charts per voyage respectively (Tanker Company 2018). Additional insurance premiums for piracy and armed guards when operating off the Gulf of Aden are approximated at US$ 10,500 per round voyage during 2018-2020 (Tanker Company 2018).

Moreover, a fixed cost of US$ 180,000 is assumed for ice damage repairs and relevant costs if these occur for any voyage from the unloading port in Southwest/Northwest Europe, after discharing a cargo, to a repair yard in Odense, Denmark (Tanker Company 2020). Moreover, additional costs are assumed for the voyage between the unloading port to a repair yard (Section '5.3.1 Modelling approach').

5.4.3 Fuel and commodity prices, and in-transit inventory costs

Residual fuel (HSFO, VLSFO) and distillate fuel (MGO) prices refer to their average values in Singapore and Rotterdam during February 2020[32]. These price levels reflect market conditions roughly one month before the combined effect of the disagreement regarding crude oil supply policy amongst major oil producers and the negative impact of the Covid-19 pandemic on demand for commodities globally. Equally, the LNG price refers to an average of the spot LNG price in Asia and the Title Transfer Facility (TTF) gas price in the Netherlands in February 2020, including distribution costs. Similarly, jet fuel/kerosene and gasoil/diesel spot prices refer to February 2020 averages in Singapore. Table 5.4 presents the assumptions on fuel and commodity prices used in the analysis.

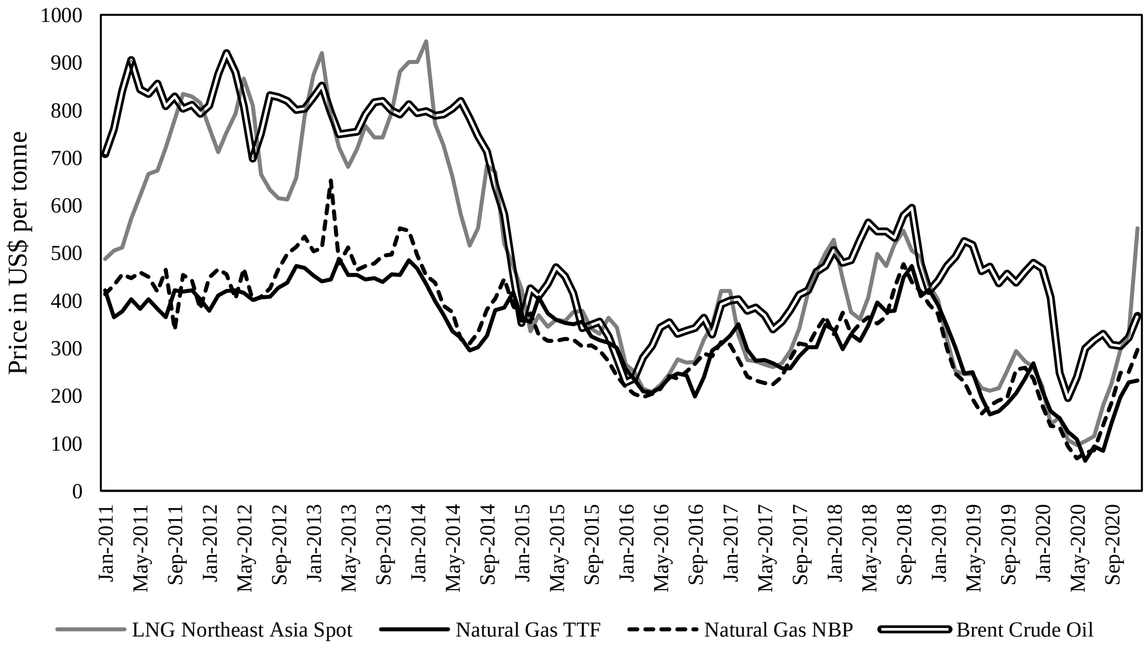
Table 5.4. Fuel and commodity prices used in the analysis.*

Fuel/Commodity Price in US$/t	HSFO[a]	VLSFO[a]	MGO[a]	LNG[b]	Jet Fuel/Kerosene – Gasoil/Diesel[c]
Low	150	240	250	150	245
Base Case	300	480	500	250	494
High	450	720	750	350	743

Source: [a]Clarksons (2021), [b]LNG TTF price (Capital IQ 2021), spot LNG Asia price (Refinitiv Eikon 2021), distribution costs in Asia (SEA LNG 2020), distribution costs in Rotterdam (MAN Energy Solutions 2018; DNV 2021c), [c]OPEC (2021). *Values are rounded to the nearest 10.

[32] Fuel oil and LNG prices in Rotterdam are considered as proxies since Rotterdam is a major oil hub in the region. The LNG TTF price is used as a proxy for LNG prices in Europe due to the fact that this is the most liquid price benchmark in the region, followed by the UK NBP gas price (Heather 2020).

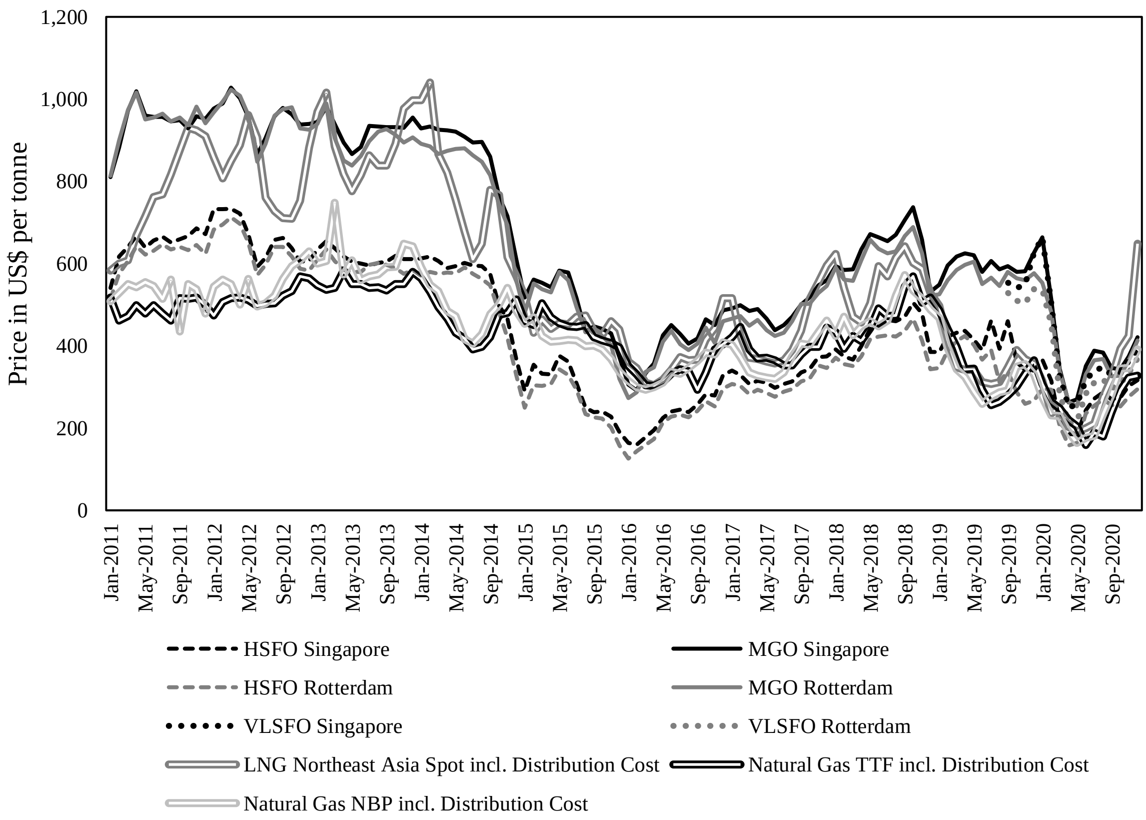
Oil-based fuel and commodity price levels at the low and high fuel/commodity price scenarios are assumed at +/- 50% of those at the base case scenarios, reflecting differences between two distinct periods i.e. average prices during 2011-2014 and average prices during 2015-2017 (Gjølberg and Johnsen 1999; Lindstad and Eskeland 2015; Clarksons 2021; OPEC 2021). LNG fuel prices are assumed at +/- 40% owing to a combination of the less responsive Dutch TTF and UK National Balancing Point (NBP) gas prices to oil price movements, the convergence between spot LNG prices in Asia and crude oil prices during those periods, as well as a mix of oil-linked and gas-on-gas competitive pricing regimes in Spain[33]. Yet, LNG spot prices in Asia decoupled from crude oil prices during 2019 (Fulwood 2019), whereas TTF gas and LNG Asian spot prices were coupled with crude oil prices during 2020 (Refinitiv Eikon 2021; Capital IQ 2021; Clarksons; 2021). Figures 5.11 and 5.12 show graphically the relationship between fuel oil, crude oil, LNG and natural gas prices. Jet Fuel/Kerosene and Gasoil/Diesel prices are illustrated in Figures 5.2 and 5.3, respectively.



Sources: Refinitiv Eikon (2021), Clarksons (2021), Capital IQ (2021).

Figure 5.11. Monthly Crude Oil, LNG and Natural Gas prices between 2011 and 2020.

[33] A similar relationship between the Dutch and UK gas price indices and crude oil prices exists, as both TTF and NBP prices are highly correlated (Clarksons 2021; BP 2020). On the other hand, gas prices in the Mediterranean, including Spain, are a mix of 53% competitive gas-on-gas pricing and 47% oil-linked pricing as of 2019 (IGU 2020).



Sources: Author, based on Refinitiv Eikon (2021), Clarksons (2021), Capital IQ (2021).

Figure 5.12. Monthly Fuel Oil prices and LNG Fuel and Natural Gas prices between 2011 and 2020.

5.4.4 Transit fees and icebreaking assistance

Suez Canal Tolls depend on the type of ship, routeing direction (northbound, southbound), the Suez Canal Net Tonnage (SCNT) of a ship, its draught and beam, laden or ballast condition, and are determined by the special drawing rights (SDR) exchange rates. The Suez Canal tariff rates and average USD per SDR rates during July-November 2019 are used to calculate the Suez Canal Tolls (IMF 2021a; Leth Agencies 2021a)[34]. Additional costs, such as tugs, mooring, pilotage, and disbursements were calculated by using an online calculator from Leth agencies (Leth Agencies 2021b).

According to the latest rules of the Northern Sea Route Administration (NSRA), icebreaking assistance depends on the prevailing ice and climatic conditions (Gritsenko and Kiiski 2016). Unescorted voyages may occur when sea ice and climatic conditions are favourable. This is evident in the voyage records of the 2011-2020 summer/autumn navigation seasons (CHNL

[34] The average SDR rates in July-November are used for an equal comparison with the NSR summer/autumn season.

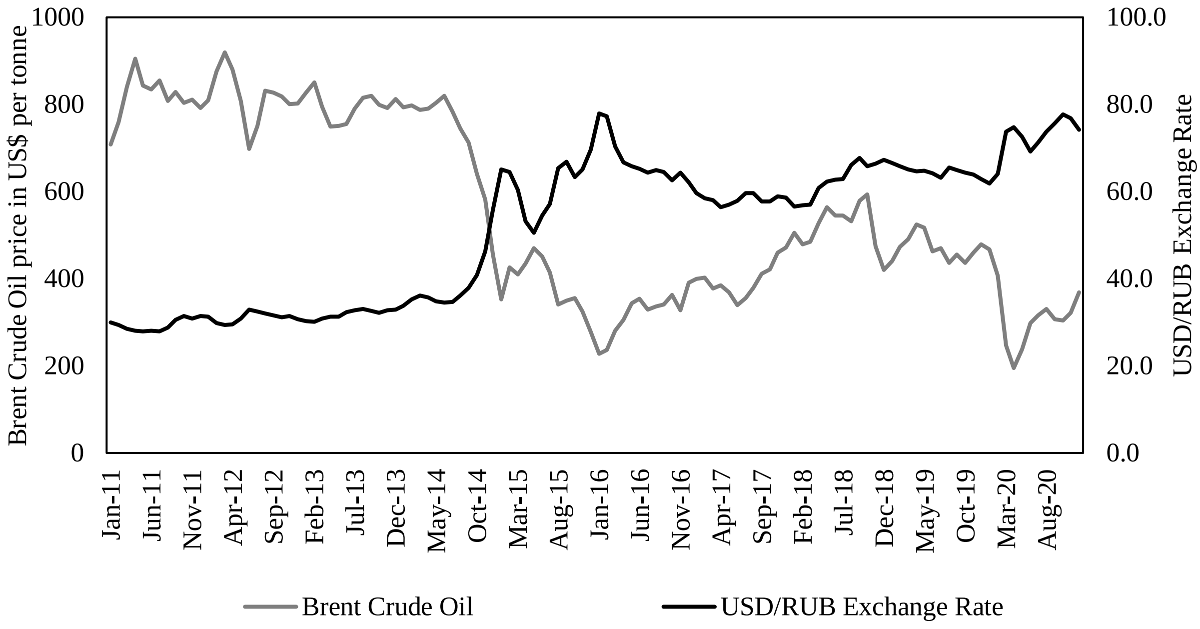
2021a). However, there are limited data regarding icebreaking assistance operations in general. Notwithstanding the long-term trend of sea ice decline in the Arctic (Parkinson and Comiso 2013; Lindsay and Schweiger 2015), the high inter-month and inter-annual variability of sea ice conditions (Stephenson et al. 2014) along with insurers' policies may deem icebreaking assistance necessary across all navigation zones (Sarrabezoles et al. 2016; Fedi et al. 2018; Fedi et al. 2020). Thus, icebreaking assistance is assumed for all navigation zones across the NSR at the base case scenario. Icebreaking fees depend on the ice class of a ship, gross tonnage, number of escorting zones and period of navigation (summer/autumn: July-November, winter/spring: December-June), and are determined by the US Dollar – Russian Rouble (USD/RUB) currency exchange rates (NSRA 2014; Bank of Russia 2021). The NSRA icebreaking fees and Suez Canal Tolls are presented in Table 5.5. Appendix P presents the assumptions and calculations for transit fees.

Table 5.5. NSRA icebreaking fees and Suez Canal Tolls for LR2 tankers.

Transit Fees in USD	Low USD/RUB rate	Base Case USD/RUB rate	High USD/RUB rate	Discounted rate (US$/t)
USD/RUB Rate	33.28	64.41	73.7	5
NSRA Tariff Rate	446.8	446.8	446.8	446.8
NSR Fees	849,238	438,793	383,506	400,000
SCR Fees (Northbound)	321,539	321,539	321,539	321,539

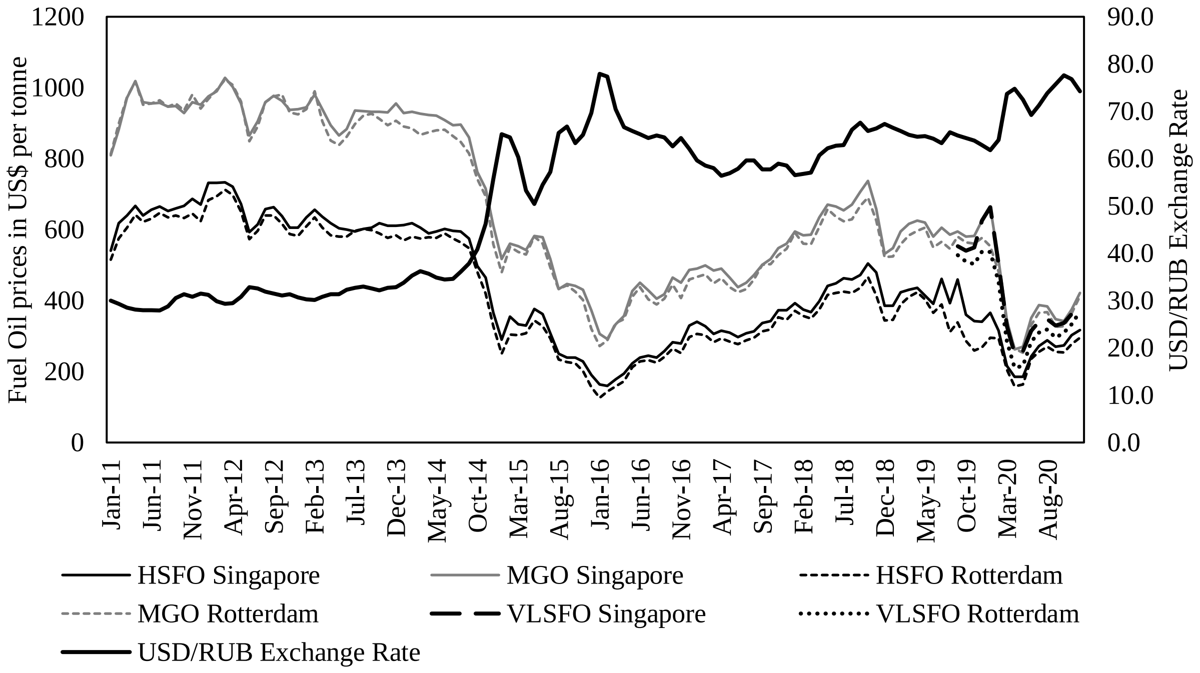
Sources: Calculations based on Appendix P.

The USD/RUB exchange rate is assumed to be high at low crude oil prices and vice versa, indicating an inverse relationship between them (Beckmann and Czudaj 2013; Yang et al. 2017; Shibasaki et al. 2018; Chuffart and Hooper 2019). More specifically, a rate of 33.28 is assumed at high fuel/commodity prices, reflecting market conditions between 2011 and 2014, a high rate of 73.7 at low fuel/commodity prices, reflecting conditions during March-May 2020, where oil and gas prices were at historic lows, and a rate of 64.41 at base case scenario, reflecting market conditions before 2020 i.e. 2015-2019 (Bank of Russia 2021). Figures 5.13 and 5.14 illustrate the inverse relationship between USD/RUB exchange rates and Brent crude oil and fuel oil prices. Discounted fees are included in the analysis, reflecting the practice of negotiated icebreaking fees, that is, 5 US$ per tonne of cargo for laden voyages (Falck 2012; Gritsenko and Kiiski 2016; Moe and Brigham 2016; Tanker Company 2018), as well as independent navigation i.e. operating within NSR without icebreaking assistance.



Sources: Bank of Russia (2021), Clarksons (2021).

Figure 5.13. Monthly Brent crude oil price and USD/RUB exchange rates between 2011 and 2020.



Sources: Bank of Russia (2021), Clarksons (2021).

Figure 5.14. Monthly fuel oil prices and USD/RUB exchange rates between 2011 and 2020.

5.4.5 Speed through ice on the NSR

There exists high uncertainty regarding the operating speed on ice, which is largely determined by sea ice thickness, sea ice concentration, ice ridges, ice floes and icebergs amongst others (Löptien and Axell 2014; Aksenov et al. 2017). Ship speed through ice depends on navigation season, month and zone, as well as on the ice class of a ship (Stephenson et al. 2014; Faury and Cariou 2016; Faury et al. 2020; Cheaitou et al. 2020; Cariou et al. 2021). This means that speed through ice may not be optimised with respect to cost and market factors as on open water, and therefore it has to be approximated based on either physical factors, such as ice thickness, or on real speeds recorded on the NSR. Ship speed on ice is considered based on the analysis of AIS data of 44 destination and transit tanker voyages conducted during the 2011-2019 summer/autumn seasons (Bloomberg 2021; Chapter 4, Section '4.3.2.5 Speed through ice on the NSR'). The average speed on ice is calculated by dividing the travelled distances by the time interval between the start and end points of each voyage on the NSR. The average speed of all voyages is found 10.3 knots during 2011-2019. This speed is used as the ship speed through ice in the analysis, reflecting average conditions on the NSR during the summer/autumn season.

5.5 Analysis

5.5.1 Optimal laden and ballast speeds, fuel and commodity prices, and in-transit inventory

Figure 5.15 illustrates the relationship between optimal speed and minimum RFR across all route alternatives and fuel and commodity price levels. Results are shown for the Ulsan Rotterdam pair at the VLSFO mode as an example, given that this is currently the most widely used marine fuel globally. The vertical axis represents the minimum RFR in US$ per tonne as a function of optimal speed in knots, which is shown in the horizontal axis. Black dotted curves show minimum RFR at optimal laden speeds, whereas grey solid curves show minimum RFR at optimal ballast speeds. Black solid curves reflect minimum RFR at optimal laden speeds when in-transit inventory costs are included in the analysis. The figure shows that optimal laden speeds are always lower than optimal ballast speeds across all fuel prices and route alternatives. The reason is that when a ship is loaded with cargo, fuel consumption and resistance are higher than when it operates in ballast. As a result, the minimum RFR is higher when a ship is laden than when it is not, owing to higher fuel, operating and capital costs.

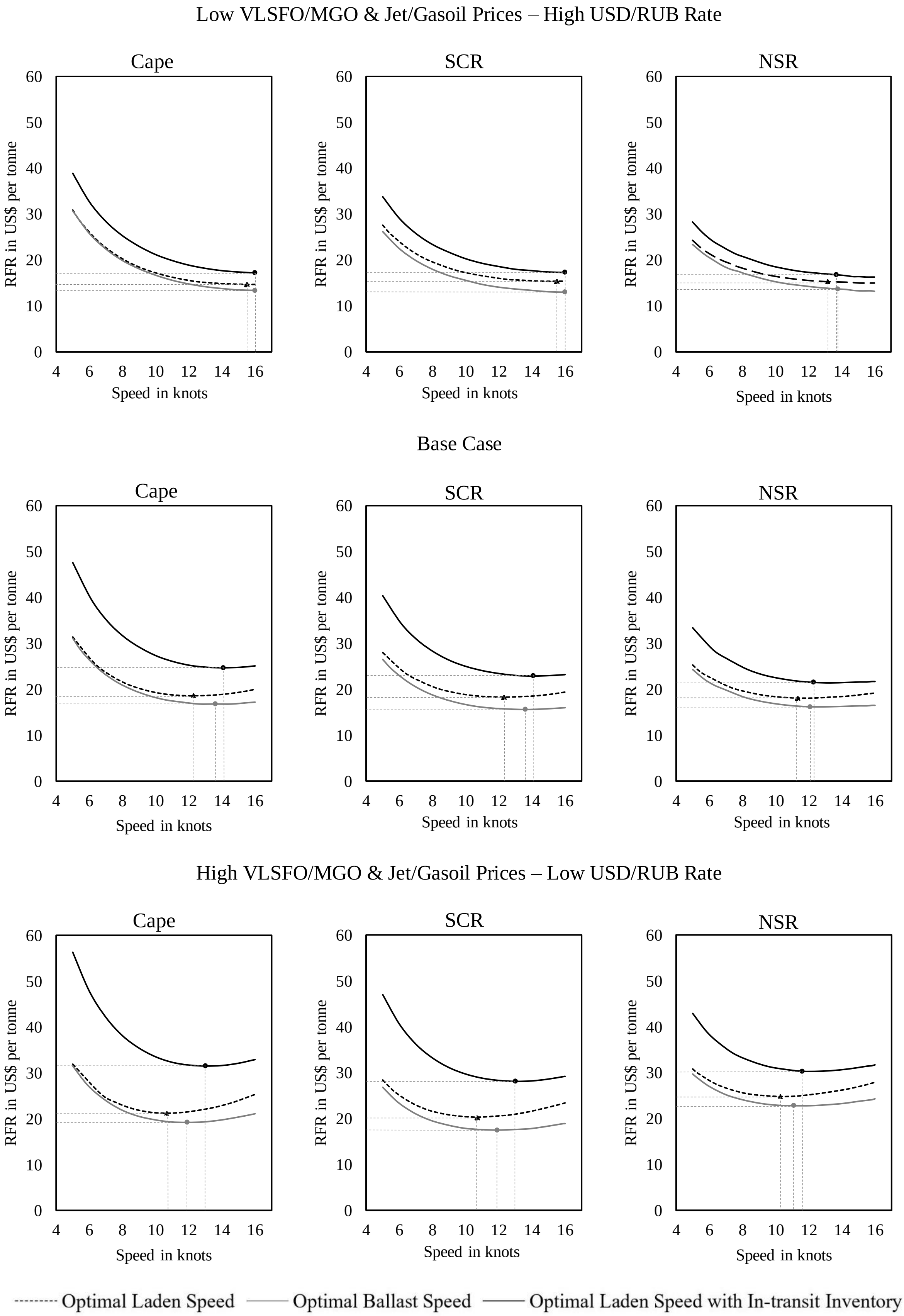


Figure 5.15. Relationship between LR2 tanker optimal laden and ballast speed, with and without in-transit inventory cost for Ulsan-Rotterdam pair at VLSFO mode, all route alternatives, and scenarios.

The higher the fuel prices, the higher the minimum RFR at the optimal laden speed than at the ballast speed since the impact of higher fuel prices at the decrease of optimal speed and the increase in fuel costs is more pronounced when a ship is laden than when it is not. Thus, fixed costs are higher at a lower optimal laden speed than at a lower optimal ballast speed, whereas the difference in fuel costs depends on the speed differential at each fuel price level.

When including in-transit inventory costs in the model, optimal laden speeds become higher than optimal ballast speeds across all fuel and commodity prices, and route alternatives. This indicates that optimal laden speeds are more sensitive to the value of cargo than to fuel prices, depending on the interest rate, the price of the commodity and its price relationship with fuel prices. Not only are minimum RFR rates at laden speeds, including in-transit inventory, higher than those at ballast speeds but also they are higher than minimum RFR rates at laden speeds without in-transit inventory. Both fuel and fixed costs are higher at optimal laden than ballast speeds when moving towards high fuel and commodity price levels. On the one hand, a growing value of cargo on board influences fixed costs more than the lower operating and capital costs per fuel and commodity price level. On the other hand, fuel costs are higher due to both an increased speed differential and increased fuel consumption when a ship is loaded with cargo.

Laden speeds on both SCR and Cape routes are 15.5 knots, 12.3 knots, and 10.7 knots, whereas ballast speeds are 16 knots, 13.6 knots, and 11.9 knots, at low, base case, and high fuel prices, respectively. Laden speeds on the NSR are 13.2 knots, 11.3 knots, and 10.3 knots, whereas ballast speeds are 13.8 knots, 12.1 knots, and 11.1 knots at low, base case, and high fuel prices, respectively. When in-transit inventory costs are considered, laden speeds on both SCR and Cape routes become 16 knots, 14.1 knots, and 13 knots, at low, base case and high fuel/commodity prices, respectively. Laden speeds on the NSR become 13.7 knots, 12.3 knots, and 11.6 knots, at low, base case, and high fuel/commodity prices, respectively. Similar relationships between optimal ballast and laden/laden with inventory speeds are expected for other fuel types and operational modes. The SCR-NSR RFR and Cape-NSR RFR differentials range from 0.1 US$/t / -0.5 US$/t to 0.2 US$/t / 0.5 US$/t to -4.5 US$/t / -3.6 US$/t at low, base case and high fuel price scenarios, whereas they become 0.5 US$/t / 0.5 US$/t, 1.4 US$/t / 3.2 US$/t, and -2.2 US$/t / 1.1 US$/t at each scenario respectively when in-transit inventory is included. Similarly, the SCR-Cape RFR differential ranges from 0.6 US$/t (0 US$/t) to -0.3 US$/t (-1.7 US$/t) to -0.9 US$/t (-3.4 US$/t) at low, base case and high fuel price scenarios without and with in-transit inventory costs, respectively. As a result, when in-transit inventory costs are included in the model, shorter route alternatives are always benefitted, depending on commodity and fuel prices. On the other hand, the lower the fuel and commodity prices, the more competitive a longer route becomes and vice versa. Moreover, when the value of cargo is not considered in the analysis, this further increases the competitiveness of a longer route when moving towards low fuel and commodity prices. For example, the minimum RFR on the Cape route is on par with that on the SCR, whilst the NSR is more competitive than the Cape route by 0.5 US$/t at the low fuel and commodity price scenario. However, if in-transit inventory costs are not included in the model, the Cape route becomes more competitive than SCR and NSR by 0.6 US$/t and 0.5 US$/t, respectively. Similar observations can be made between the SCR and NSR, where the RFR differential is reduced from 0.5 US$/t to 0.1 US$/t when in-transit inventory is not included at the low fuel/commodity price scenario. This effect can have implications for route choice and transport costs, also depending on the structure of the market (either contango or backwardation between the origin and destination ports), and therefore the value of transit time, and the difference between total landed costs and revenue when the cargo reaches its destination.

5.5.2 Optimal ship speed and alternative operational modes

Figure 5.16 depicts the relationship between optimal laden speed, including in-transit inventory costs, and minimum RFR across all routes and alternative operational modes using the Ulsan-Rotterdam pair at the base case fuel/commodity price scenario as an example. Similar to Figure 5.15, the minimum RFR in US$/t is shown in the vertical axis as a function of optimal speed in knots, which is shown in the horizontal axis. Black solid curves show the minimum RFR at the HSFO-Scrubber mode and black dashed curves show the minimum RFR at the VLSFO mode. Grey solid curves show the minimum RFR at the dual-fuel LNG-VLSFO option with a tank capacity of 1,700 m^3, whereas grey dotted curves illustrate the minimum RFR at the dual-fuel LNG-VLSFO option with a tank capacity of 3,600 m^3.

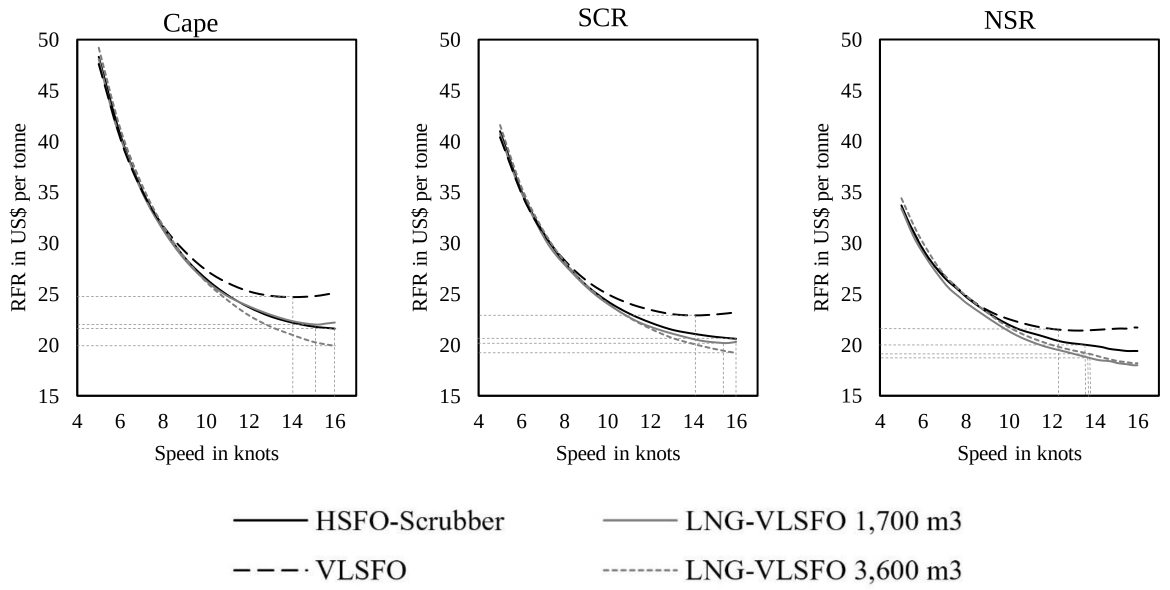


Figure 5.16. LR2 tanker minimum RFR at optimal speed for Ulsan-Rotterdam pair at all route alternatives and operational modes under Base Case Scenario.

Figure 5.16 shows that the lowest costs are found at the LNG-VLSFO mode for each route alternative. The lowest RFR for SCR and Cape routes is found at the sub-option of 3,600 m^3, whereas the lowest NSR RFR is found at the sub-option of 1,700 m^3. This difference for the NSR can be explained by the fact that capital costs of the sub-mode of 3,600 m^3 are higher than those of the 1,700 m^3 sub-mode. On the one hand, the use of a tank capacity of 3,600 m^3 at the SCR and Cape routes allows the use of the low-cost LNG only, for the whole voyage, compared to the other fuel alternatives, based on prices as of February 2020. Thus, voyage costs outweigh the increase in capital costs. On the other hand, the range under which the shorter NSR can be benefitted from LNG is already high at the sub-mode of 1,700 m^3, and therefore the increase in capital costs is more pronounced on this route than on SCR and Cape routes[35]. The HSFO-Scrubber option comes third for the SCR and NSR. However, the HSFO-Scrubber comes second for the Cape route, followed by the 1,700 m^3 sub-mode, since the minimum Cape RFR is disadvantaged by the large proportion of VLSFO at this LNG-VLSFO sub-mode. The VLSFO option is the most expensive for each route alternative. Similar observations can be made for the rest OD pairs, where the ranking of each operational mode varies with respect to distance, fuel and commodity price levels, as well as optimal speed levels and/or real speed levels.

[35] The distance leg under which VLSFO is used on the NSR at the 1,700 m^3 sub-mode is 188 n.m., compared to 6,571 n.m. and 3,144 n.m. on the Cape and SCR routes, respectively.

5.5.3 Optimal and real ship speeds, alternative operational modes, distance, and route choice

Figures 5.17, 5.18, and 5.19 illustrate RFR rates for the Cape, SCR and NSR routes across all OD pairs, operational modes, and fuel and commodity prices, whilst numerical results are reported in Appendix V. All results refer to laden voyages, including in-transit inventory costs, and are based in two distinct speed regimes. The upper part of each of the Figures 5.17, 5.18, and 5.19 shows results when speeds are optimised with respect to costs and market factors, whereas the lower part shows results at a constant speed of 12 knots, considering actual speed choice from historic voyages between Northeast Asia and Southwest/Northwest Europe in 2014-2020 (based on Section '5.3.3 Cost assessment and real speeds'). Results for the NSR include RFR rates at discounted fees under high fuel/commodity prices to reflect a flexible marketing practice that the NSRA could adopt, similar to that during 2011-2013, when a high USD/RUB exchange rate combined with high fuel prices rendered voyages through NSR very expensive at official icebreaking fees.

First, it can be seen that Cape is always more competitive than SCR across all OD pairs at low fuel/commodity prices and optimal speeds under the HSFO-Scrubber and LNG-VLSFO 3,600 m^3 modes. It is on par with SCR on the short and medium-hauls at low fuel/commodity prices and optimal speeds under the VLSFO mode and marginally uncompetitive under the LNG-VLSFO 1,700 m^3 mode. The Cape route becomes less competitive than SCR across all OD pairs at the base case and high fuel/commodity price scenarios, and optimal speeds under all operational modes. The biggest losses are realised under the LNG-VLSFO 1,700 m^3 mode and the least losses are realised under the LNG-VLSFO 3,600 m^3 mode. The Cape route becomes uncompetitive across all OD pairs at low fuel/commodity prices and a constant speed of 12 knots under all operational modes. Moreover, it becomes more uncompetitive across all OD pairs at the base case and high fuel/commodity price scenarios under the constant speed of 12 knots than under an optimal speed regime across all operational modes. The exception is the LNG-VLSFO 1,700 m^3 sub-mode, where the LNG/VLSFO distance ratio gets higher as the use of LNG fuel is increased with lower speed. As a result, the SCR-Cape RFR differentials are reduced at the constant speed regime compared to the RFR differentials under the optimal speed regime.

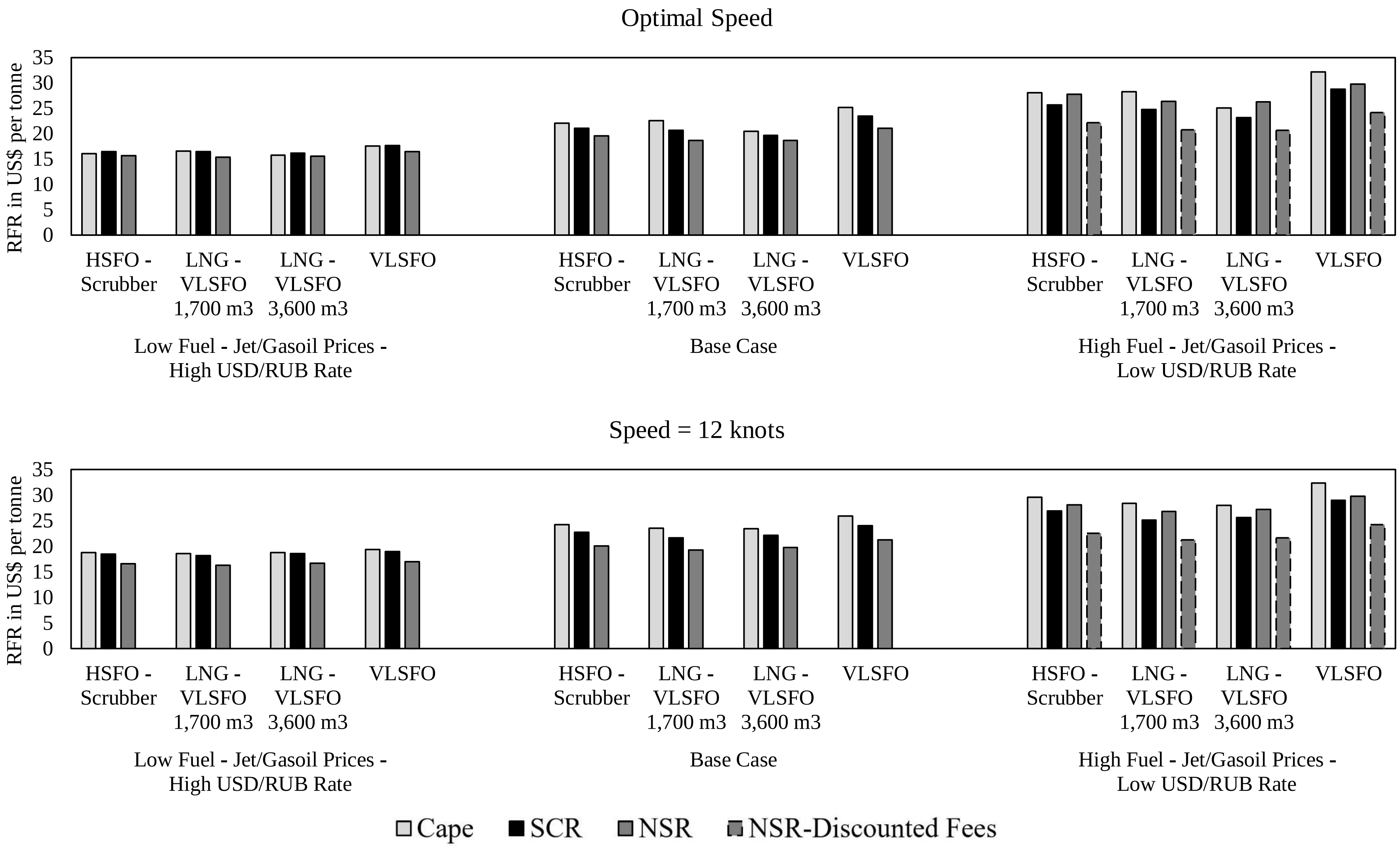


Figure 5.17. RFR comparison at two speed regimes across all route alternatives, operational modes, and scenarios for the Chiba-Coryton pair.

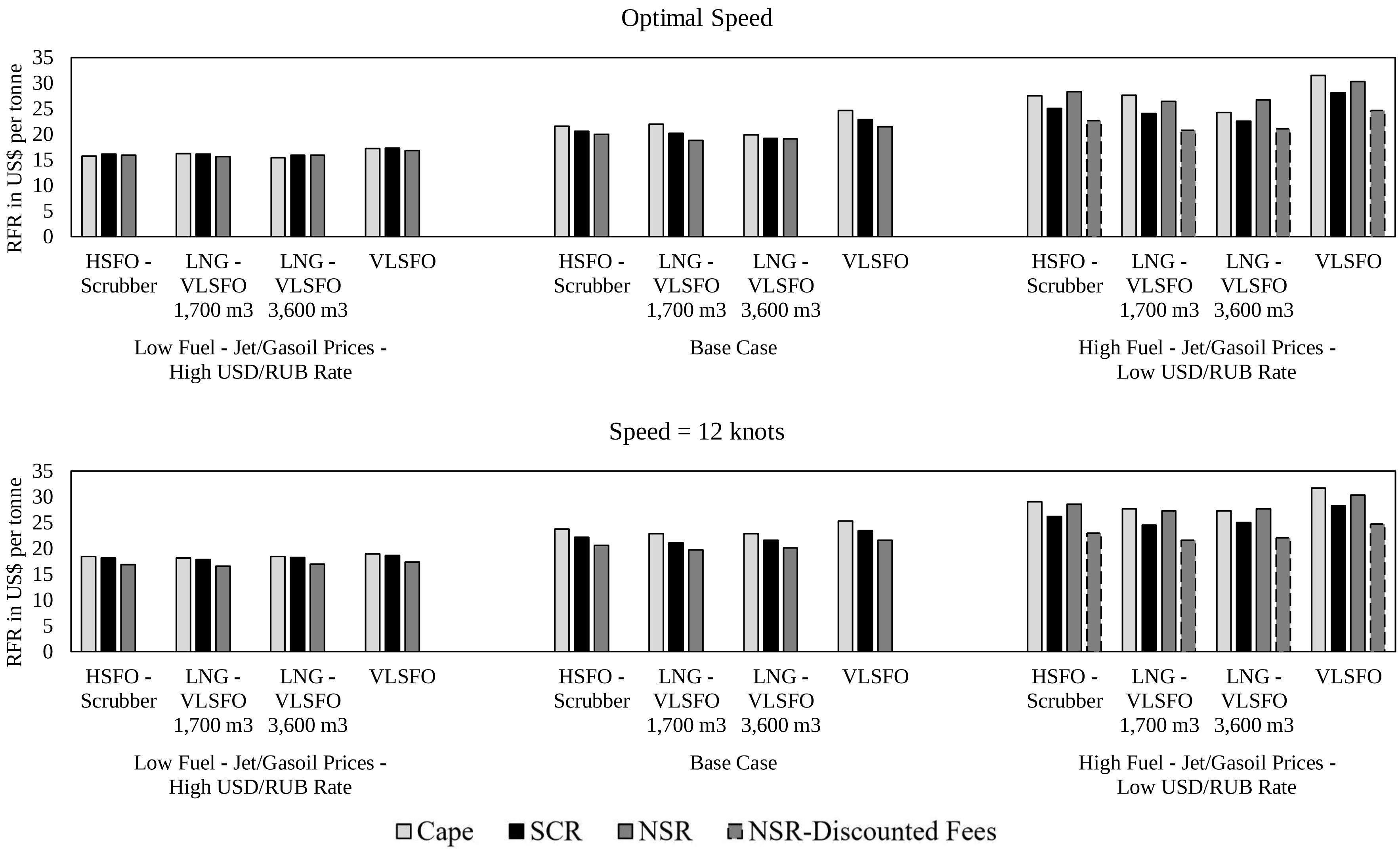


Figure 5.18. RFR comparison at two speed regimes across all route alternatives, operational modes, and scenarios for the Ulsan-Rotterdam pair.

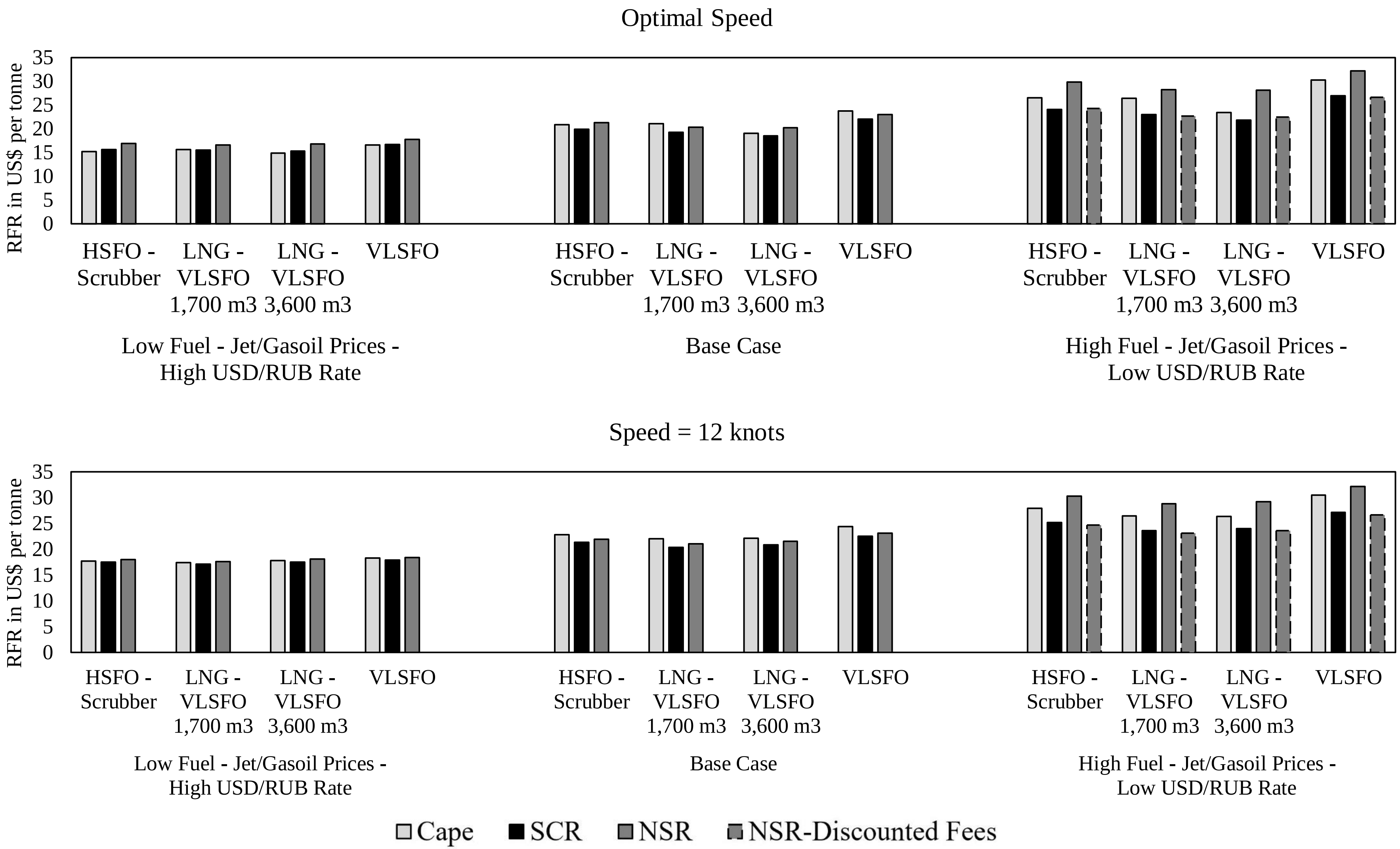


Figure 5.19. RFR comparison at two speed regimes across all route alternatives, operational modes, and scenarios for the Ulsan-Bilbao pair.

Second, the NSR is less competitive than Cape on the long-haul at low fuel/commodity prices across all operational modes, regardless of the speed regime, as well as on the medium-haul at low fuel/commodity prices and optimal speeds under the HSFO-Scrubber and LNG-VLSFO 3,600 m^3 modes. It is also less competitive than Cape on the long-haul at the base case scenario and optimal speeds under the HSFO-Scrubber and LNG-VLSFO 3,600 m^3 modes. The NSR is always more competitive than the Cape route on the short haul across all fuel/commodity prices, speed regimes and operational modes. It is also more competitive than Cape on the medium-haul across all price scenarios and speed regimes under the VLSFO and LNG-VLSFO 1,700 m^3 modes. Yet, the NSR is less competitive than Cape, especially on the long-haul, at high fuel/commodity prices, regardless of speed regime and operational modes. It is also less competitive than Cape on the medium haul at high fuel/commodity prices and both speed regimes under the HSFO-Scrubber and LNG-VLSFO 3,600 m^3 modes.

Third, the NSR is more competitive than SCR on the short and medium-hauls at low and base case fuel/commodity price scenarios and both speed regimes under all operational modes, whereas it is not competitive on the long-haul, regardless of fuel/commodity price levels and speed regimes under all operational modes. Yet, the NSR is less competitive than SCR across all OD pairs at high fuel/commodity prices and both speed regimes under all operational modes. On the one hand, the competitiveness of the NSR is reduced at low fuel prices across all OD pairs, speed regimes and operational modes. On the other hand, high icebreaking fees owing to a low USD/RUB rate reduce the potential of the NSR at high fuel/commodity prices. The NSR becomes more competitive than both SCR and Cape across all OD pairs at high fuel/commodity prices and constant speeds under all operational modes, when assuming discounted fees. Moreover, the NSR minimises its losses to the SCR on the long-haul at high fuel/commodity prices and optimal speeds under the HSFO-Scrubber and LNG-VLSFO 3,600 m^3 modes, when assuming discounted fees.

5.6 Sensitivity analysis

The results are tested against different fuel/commodity price and icebreaking fees levels, the assumption of ice damage repairs, and a future ban on the use of heavy fuels in the Arctic (either HSFO, including with the use of scrubbers, or VLSFO) (IMO 2020). Table 5.6 presents sensitivity analysis results across all routes, fuel/commodity price levels, and speed regimes, using the Ulsan-Rotterdam pair as an example. Results for the rest OD pairs, as well as cost and time breakdowns are presented in Appendix V. It can be seen that the use of MGO through ice on NSR by oil-powered tankers reduces the competitiveness of the NSR compared to both the Cape and SCR routes on the HSFO-Scrubber mode, especially when moving towards high fuel/commodity prices. The impact is similar either at optimal or constant speed regimes and both with and without icebreaking fees. This is the result of wide HSFO-MGO price differentials i.e. between 100 US$/t (low prices) and 300 US$/t (high prices) assumed in the analysis. The difference is negligible on the VLSFO mode, where the VLSFO-MGO price differential ranges between 10 US$/t (low prices) and 30 US$ (high prices), based on prices as of February 2020 as a reference. The NSR becomes uncompetitive across all scenarios and under all operational modes when including ice damage repairs in the analysis. It is only more competitive than the Cape route on the short and medium-hauls at the base case scenario under HSFO and constant speeds, under VLSFO at both speed regimes, including with the MGO option through ice on NSR, as well as under LNG-VLSFO 1,700 m^3 at both speed regimes. The competitiveness of the NSR increases under discounted fees across all scenarios, whilst it is always more competitive compared to both SCR and Cape under independent navigation, regardless of fuel/commodity price levels. The highest SCR-NSR RFR differentials and Cape-NSR RFR differentials are found at the high fuel/commodity price scenario under the assumption of independent navigation. The highest SCR-NSR and Cape-NSR RFR differentials at optimal speeds are found under the VLSFO mode, followed by the LNG-VLSFO 1,700 m^3, HSFO, and LNG-VLSFO 3,600 m^3 modes, respectively. The highest SCR-NSR RFR differentials at constant speeds are found under the VLSFO mode, followed by HSFO, LNG-VLSFO 1,700 m^3 and 3,600 m^3 modes, respectively. The highest Cape-NSR RFR differentials are the same as those at the optimal speed regime. When including ice damage repairs, the LNG-VLSFO 1,700 m^3 mode comes first, followed by VLSFO, HSFO, and LNG-VLSFO 3,600 m^3 modes for both the SCR-NSR and Cape-NSR RFR differentials at optimal speeds, respectively. Yet, the order of modes for RFR differentials at constant speeds is the same as that when ice damage repairs are not included. Similar results are obtained for the other OD pairs, with differences being attributed to different OD distances.

Table 5.6. Sensitivity Analysis for Ulsan-Rotterdam pair.*

ΔRFR	Low Fuel - Jet/Gasoil Prices – High USD/RUB rate				Base Case						High Fuel - Jet/Gasoil Prices – Low USD/RUB rate					
	Official Fees	Independent Navigation	Official Fees	Independent Navigation	Official Fees	Discounted Fees	Independent Navigation	Official Fees	Discounted Fees	Independent Navigation	Official Fees	Discounted Fees	Independent Navigation	Official Fees	Discounted Fees	Independent Navigation
	HSFO-Scrubber		MGO on NSR		HSFO-Scrubber			MGO on NSR			HSFO-Scrubber			MGO on NSR		
	Optimal Speed															
SCR-NSR	0.2	5.0	0.0	4.8	0.7	1.1	6.1	0.4	0.8	5.8	-3.2	2.4	7.4	-3.7	1.9	6.9
	(-2.7)	(2.1)	(-2.9)	(1.9)	(-2.4)	(-1.9)	(3.1)	(-2.7)	(-2.2)	(2.8)	(-6.4)	(-0.8)	(4.2)	(-6.8)	(-1.2)	(3.8)
Cape-NSR	-0.2	4.6	-0.4	4.4	1.7	2.2	7.2	1.4	1.8	6.8	-0.8	4.8	9.8	-1.3	4.4	9.4
	(-3.1)	(1.7)	(-3.3)	(1.5)	(-1.4)	(-0.9)	(4.1)	(-1.7)	(-1.2)	(3.8)	(-4.0)	(1.6)	(6.6)	(-4.4)	(1.2)	(6.2)
SCR-Cape	0.4		0.4		-1.0			-1.0			-2.4			-2.4		
	12 knots															
SCR-NSR	1.2	6.0	1.1	5.9	1.6	2.1	7.1	1.3	1.8	6.8	-2.4	3.2	8.2	-2.9	2.7	7.7
	(-1.8)	(3.0)	(-2.0)	(2.8)	(-1.5)	(-1.0)	(4.0)	(-1.8)	(-1.3)	(3.7)	(-5.6)	(0.0)	(5.0)	(-6.1)	(-0.5)	(4.5)
Cape-NSR	1.4	6.2	1.3	6.1	3.1	3.6	8.6	2.8	3.3	8.3	0.3	5.9	10.9	-0.1	5.5	10.5
	(-1.6)	(3.2)	(-1.7)	(3.1)	(0.0)	(0.5)	(5.5)	(-0.3)	(0.2)	(5.2)	(-2.9)	(2.8)	(7.8)	(-3.3)	(2.3)	(7.3)
SCR-Cape	-0.2		-0.2		-1.5			-1.5			-2.8			-2.8		
	VLSFO		MGO on NSR		VLSFO			MGO on NSR			VLSFO			MGO on NSR		
	Optimal Speed															
SCR-NSR	0.5	5.3	0.5	5.3	1.4	1.9	6.9	1.4	1.9	6.9	-2.2	3.4	8.4	-2.2	3.4	8.4
	(-2.5)	(2.3)	(-2.5)	(2.3)	(-1.7)	(-1.2)	(3.8)	(-1.7)	(-1.2)	(3.8)	(-5.5)	(0.1)	(5.1)	(-5.5)	(0.1)	(5.1)
Cape-NSR	0.5	5.3	0.5	5.3	3.2	3.7	8.7	3.2	3.7	8.7	1.1	6.7	11.7	1.1	6.7	11.7
	(-2.5)	(2.3)	(-2.5)	(2.3)	(0.0)	(0.5)	(5.5)	(0.0)	(0.5)	(5.5)	(-2.2)	(3.4)	(8.4)	(-2.2)	(3.4)	(8.4)
SCR-Cape	0.0		0.0		-1.7			-1.7			-3.4			-3.4		
	12 knots															
SCR-NSR	1.3	6.1	1.3	6.1	1.8	2.3	7.3	1.8	2.3	7.3	-2.1	3.5	8.5	-2.1	3.5	8.5
	(-1.8)	(3.0)	(-1.8)	(3.0)	(-1.4)	(-0.9)	(4.1)	(-1.4)	(-0.9)	(4.1)	(-5.4)	(0.2)	(5.2)	(-5.4)	(0.2)	(5.2)
Cape-NSR	1.6	6.4	1.6	6.4	3.7	4.2	9.2	3.7	4.2	9.2	1.3	7.0	12.0	1.3	6.9	11.9
	(-1.4)	(3.4)	(-1.4)	(3.4)	(0.5)	(1.0)	(6.0)	(0.5)	(1.0)	(6.0)	(-2.0)	(3.6)	(8.6)	(-2.0)	(3.6)	(8.6)
SCR-Cape	-0.4		-0.4		-1.9			-1.9			-3.4			-3.4		
	LNG-VLSFO at 1,700 m^3		LNG-VLSFO at 3,600 m^3		LNG-VLSFO at 1,700 m^3			LNG-VLSFO at 3,600 m^3			LNG-VLSFO at 1,700 m^3			LNG-VLSFO at 3,600 m^3		
	Optimal Speed															
SCR-NSR	0.6	5.4	0.0	4.8	1.4	1.9	6.9	0.2	0.7	5.7	-2.4	3.2	8.2	-4.1	1.5	6.5
	(-2.3)	(2.5)	(-2.9)	(1.9)	(-1.6)	(-1.1)	(3.9)	(-2.8)	(-2.3)	(2.7)	(-5.4)	(0.2)	(5.2)	(-7.1)	(-1.5)	(3.5)
Cape-NSR	0.6	5.4	-0.4	4.4	3.2	3.7	8.7	0.8	1.3	6.3	1.1	6.7	11.7	-2.4	3.2	8.2
	(-2.2)	(2.6)	(-3.3)	(1.5)	(0.3)	(0.8)	(5.8)	(-2.1)	(-1.7)	(3.3)	(-1.9)	(3.7)	(8.7)	(-5.4)	(0.2)	(5.2)
SCR-Cape	-0.1		0.4		-1.8			-0.6			-3.5			-1.7		
	12 knots															
SCR-NSR	1.1	5.9	1.1	5.9	1.4	1.9	6.9	1.4	1.9	6.9	-2.7	2.9	7.9	-2.7	2.9	7.9
	(-1.9)	(2.9)	(-1.9)	(2.9)	(-1.6)	(-1.1)	(3.9)	(-1.6)	(-1.1)	(3.9)	(-5.8)	(-0.2)	(4.8)	(-5.8)	(-0.2)	(4.8)
Cape-NSR	1.5	6.3	1.4	6.2	3.2	3.7	8.7	2.7	3.2	8.2	0.4	6.0	11.0	-0.4	5.3	10.3
	(-1.5)	(3.3)	(-1.6)	(3.2)	(0.1)	(0.6)	(5.6)	(-0.3)	(0.2)	(5.2)	(-2.7)	(3.0)	(8.0)	(-3.4)	(2.2)	(7.2)
SCR-Cape	-0.4		-0.2		-1.8			-1.3			-3.2			-2.4		

*RFR Differentials in parentheses refer to results when ice damage repairs are factored in the analysis. MGO on NSR refer to the use of MGO through ice on NSR.

5.7 Discussion and concluding remarks

This modelling case examines the use of the NSR drawing from real practices of route choice for major arbitrage trade flows between the Atlantic and the Pacific Ocean. The factors considered in the analysis are distance, fuel prices, average ship speed through ice on NSR, icebreaking fees, ice damage repairs, commodity prices and in-transit inventory costs, and fuel types and operational modes.

The analysis in this chapter complements Chapter 4, by considering in-transit inventory costs, and addressing market structure and route choice in the wider context of oil product tanker flows drawing from AIS data of voyages between the Far East and Europe in 2011-2020. The NSR is compared to the SCR and Cape of Good Hope routes for single oil product tanker voyages between Southwest Europe, Northwest Europe and Northeast Asia at the tactical/operational level during the summer/autumn season. The choice of OD pairs reflects the main oil products trades between the Far East and Europe as well as historic transit voyages conducted on the NSR during 2011-2019.

A required freight rate (RFR) model is developed to assess the cost per tonne from the shipowner’s perspective. The methodological approach has two objectives. First, the cost assessment is based on speed optimisation, which minimises the RFR of a route alternative. Second, the cost assessment is based on real speeds, drawing from Automatic Identification System (AIS) data of LR2 tanker voyages between Northeast Asia and Northwest/Southwest Europe. The relationship between optimal speed, real speed and minimum RFR is considered in the analysis. Moreover, the relationship between laden speeds and laden speeds with in-transit inventory costs and ballast speeds is established. A sensitivity analysis is conducted to control for important cost and navigational factors.

The analysis considers alternative fuel types and operational modes to address current and future emissions reductions policies (ECAs, IMO sulphur limit, Initial IMO GHG Strategy, future prohibition on the use of heavy fuels in the Arctic).

The analysis of this chapter addresses **Research Question 1**: *Why did the NSR emerge as an alternative route for oil product tankers between Europe and Asia since the 2010s?*, **Research Question 2**: *How do cost and market factors affect the use of the NSR for oil product tankers?*, **Research Question 4**: *How do different approaches to ship speed choice and cost modelling affect the feasibility of the NSR for oil product tankers?*, and **Research Question 5**: *How do* *emissions regulations and alternative operational modes and fuel types affect the feasibility of the NSR compared to the traditional routes for oil product tankers?*

The NSR was used by LR2 tankers for three voyages in 2013 and one voyage in 2018. Although most LR2 tankers used the SCR during 2013-2020, it is noteworthy that the route via the Cape of Good Hope was used extensively during 2015-2016, in 2020, and, to a lesser extent, in 2013, 2017, and 2018. Route choice for energy commodities involving long-haul voyages between the Atlantic and the Pacific Ocean is largely determined by the prevailing commodity prices and freight rates. For tankers operating in the spot market and chartered by various traders, it is primarily the difference in spot and futures commodity prices between the origin and destination that can affect route choice either in the short, medium or long-term.

A combination of declining futures prices, high spot commodity prices, and therefore a rising value of cargo on-board, as well as high marine fuel prices, and competitive icebreaking fees, all prompted certain traders and shipowners to test the NSR as an alternative to other traditional routes to deliver the cargoes from Asia to Europe as quickly as possible in 2012 and 2013.

A steep drop in crude oil and oil products prices, geopolitical developments, low marine fuel prices and the factoring of potential ice damage repairs in costs, all negatively impacted the further use of the NSR for exploratory destination and transit voyages since 2015. Moreover, rising futures prices, low spot commodity prices, and therefore a declining value of cargo on board resulted in increased floating storage and/or several voyages via the Cape of Good Hope along with voyages via the SCR during 2015-2016 and 2020.

The Cape route is more competitive than SCR at low fuel/commodity prices across all OD pairs and optimal speeds under the HSFO-Scrubber and LNG-VLSFO 3,600 m^3 modes. However, it is not competitive compared to SCR on the short and medium-hauls at low fuel/commodity prices and optimal speeds under the LNG-VLSFO 1,700 m^3 mode. Yet, the Cape RFR is on par with the SCR RFR under the VLSFO mode. Moreover, it is less competitive than SCR across all OD pairs at the base case and high fuel/commodity price scenarios, and optimal speeds under all operational modes. The LNG-VLSFO 3,600 m^3 mode gives the least losses, whereas the LNG-VLSFO 1,700 m^3 mode gives the biggest losses. Further, the Cape is less competitive than SCR across all OD pairs at low fuel/commodity prices and a constant speed under all operational modes, whilst it becomes more uncompetitive at the base case and high fuel/commodity price scenarios under the constant speed of 12 knots than under an optimal speed regime.

The NSR is more competitive than SCR on the short and medium-hauls at low and base case fuel/commodity price scenarios and both speed regimes under all operational modes, whereas it is not competitive on the long-haul, regardless of fuel/commodity price levels and speed regimes under all operational modes. Yet, the NSR is less competitive than SCR across all OD pairs at high fuel/commodity prices and both speed regimes under all operational modes.

The NSR is less competitive than Cape on the long-haul at low fuel/commodity prices and across all operational modes, regardless of the speed regime, as well as on the medium-haul at low fuel/commodity prices and optimal speeds under the HSFO-Scrubber and LNG-VLSFO 3,600 m^3 modes. It is also less competitive than the Cape route on the long-haul at the base case scenario and optimal speeds under the HSFO-Scrubber and LNG-VLSFO 3,600 m^3 modes.

However, the NSR is more competitive than Cape on the short haul across all fuel/commodity prices, speed regimes and operational modes. It is also more competitive than Cape on the medium-haul across all price scenarios and speed regimes under the VLSFO and LNG-VLSFO 1,700 m^3 modes. Yet, the NSR is less competitive than Cape, especially on the long-haul, at high fuel/commodity prices, regardless of speed regime and operational modes. It is also less competitive than Cape on the medium haul at high fuel/commodity prices and both speed regimes under the HSFO-Scrubber and LNG-VLSFO 3,600 m^3 modes.

The NSR is found more competitive than both the SCR and Cape across all OD pairs at high fuel/commodity prices and constant speeds under all operational modes, when assuming discounted fees. Moreover, the NSR minimises its losses to the SCR on the long-haul at high fuel/commodity prices and optimal speeds under the HSFO-Scrubber and LNG-VLSFO 3,600 m^3 modes, when assuming discounted fees.

Optimal laden speeds are always lower than optimal ballast speeds regardless of fuel price levels and route alternatives. The explanation is that when a ship is loaded with cargo, fuel consumption and resistance are higher than when it operates in ballast. As a result, the minimum RFR is higher when a ship is laden than when it is not, owing to higher fuel costs, operating and capital costs. The higher the fuel prices, the higher the minimum RFR at the optimal laden speed than at the ballast speed since the impact of higher fuel prices at the decrease of optimal speed and the increase in fuel costs is more pronounced when a ship is laden than when it is not. Thus, fixed costs are higher at a lower optimal laden speed than at a lower optimal ballast speed, whereas the difference in fuel costs depends on the speed differential at each fuel price level.

When considering the cargo value on board by including in-transit inventory costs in the analysis, optimal laden speeds become higher than optimal ballast speeds across all fuel and commodity prices, and route alternatives. This indicates that optimal laden speeds are more sensitive to the value of cargo than to fuel prices, depending on the interest rate, the price of the commodity and its price relationship with fuel prices. Not only are minimum RFR rates at laden speeds, including in-transit inventory, higher than those at ballast speeds but also they are higher than minimum RFR rates at laden speeds without in-transit inventory. Both fuel and fixed costs are higher at optimal laden than ballast speeds when moving towards high fuel and commodity price levels. On the one hand, a growing value of cargo on board influences fixed costs more than the lower operating and capital costs per fuel and commodity price level. On the other hand, fuel costs are higher due to both an increased speed differential and increased fuel consumption when a ship is loaded with cargo.

When comparing a shorter route with a longer route against the constant speed of 12 knots, such as, NSR versus SCR and Cape or SCR versus Cape, it is found that a shorter route is more competitive than a longer route. The reason is that transit times for a longer route increase more than those for a shorter route. On the one hand, a speed which is lower than the design or optimal speed results in higher fuel costs owing to the non-linear increase in fuel consumption. On the other hand, fixed costs increase significantly, especially in-transit inventory costs. This is the result of longer transit times since the speed of 12 knots is lower than the design or optimal speed. Yet, longer routes increase their competitiveness either at optimal or lower than optimal or fixed speeds, when in-transit inventory costs are not considered in the analysis

The level of ship speed has further implications for the competitiveness of competing routes, depending on fuel types and technologies. The competitiveness of a longer route over a shorter route, such as, SCR versus NSR or Cape versus SCR and NSR increases at constant speeds, which are lower than optimal speeds, when assuming an increase in the use of a low-priced fuel and a simultaneous decrease in the use of a high-priced fuel under a dual-fuel operational mode. Yet, this effect is also dependent on OD pair distances, fuel heating (calorific) values, and the price difference between the two fuels. This applies to the Cape route versus the SCR across all OD pairs at the base case and high fuel/commodity price scenarios of the LNG-VLSFO 1,700 m^3 mode under the constant speed regime of 12 knots. The reason is that the use of LNG fuel increases with lower speeds and results in a higher LNG/VLSFO distance ratio. As a result, the SCR-Cape RFR differentials are reduced at the constant speed regime compared to the RFR differentials under the optimal speed regime.

Generally, the competitiveness of a longer route over a shorter route, such as, SCR versus NSR or Cape versus SCR and NSR increases under low-priced fuel types/operational modes, such as, HSFO and LNG-VLSFO 3,600 m^3, low fuel and commodity prices, high LNG/VLSFO distance ratios, and vice versa. The use of the NSR is favoured under high fuel/commodity prices, discounted fees, independent navigation, and high-priced fuel types/operational modes, such as, VLSFO and LNG-VLSFO 1,700 m^3, across all OD pairs and optimal speed regimes.

The competitiveness of a longer route over a shorter route, such as, SCR versus NSR or Cape versus SCR and NSR increases when moving from shorter to longer OD pairs and vice versa, depending on operational mode, fuel prices, and speed regimes. The competitiveness of a shorter route over a longer route, such as, NSR versus SCR and Cape or SCR versus Cape, increases when in-transit inventory costs are included in the analysis, since the time value of cargo becomes the most important factor when moving from lower to higher commodity prices and from longer to shorter OD pairs.

A ban on the use of heavy fuels in the Arctic (HSFO, VLSFO) reduces the competitiveness of the NSR either at optimal or constant speed regimes, depending on the price difference between HSFO and MGO or VLSFO and MGO for each operational mode, respectively. The impact is greater on HSFO-Scrubber mode than on VLSFO mode, given the wide HSFO-MGO price differential. The NSR is uncompetitive across all OD pairs and operational modes under official icebreaking fees, when including ice damage repairs in the analysis. The NSR is only competitive against the Cape route on the short and medium hauls at the base case scenario and under the VLSFO (including with the MGO option when operating through ice water on NSR), and LNG-VLSFO 1,700 m^3 modes, mostly at optimal speeds and, to a lesser extent, at constant speeds.

The results show that Cape is more competitive than both the SCR and NSR when moving from short to long hauls and under low fuel/commodity prices. Although Cape is marginally uncompetitive under real speeds, it may still be chosen, depending on OD pair distances, operational modes and fuel prices. More specifically, if the difference between the spot commodity price at the origin and the future commodity price at the destination is high enough to compensate for the increased freight, the Cape route could still be a viable alternative. The reason is that the contango structure in the market favours the delay of arrivals so that profits could increase based on the difference between the low cargo price at the origin including transport costs, and the high cargo price at the destination (Platts 2015). Yet, regional supply and demand factors determine the actual freight rate levels, which may or may not be higher than those for voyages through other routes, such as the Suez Canal route (Platts 2015; Lloyd's List 2020a). This implies that freight rates may be higher, lower or very close to the RFR of a voyage or route alternative. This point emphasises that freight is part of the total landed price of the cargo, and route choice is not considered solely on absolute transport cost differences. Freight is important when commodity prices are high and commodity futures prices are lower than spot prices, in which case quick delivery of the cargo and shorter routes are favoured.

Although oversupply in oil markets is generally linked with a low price environment and contango structure, backwardation may not always concur with high spot commodity prices. For example, persistent contango in ICE gasoil futures prices during 2011 and for some part of 2013 occurred at historically high oil products and fuel price levels. Figure 5.1 illustrates that point, where some Cape voyages occurred even in 2013. Cape voyages also occurred in 2018, a year where oil products and fuel prices had increased following a steep drop in 2015-2017.

The results show that route competitiveness depends on operational mode and technology as much as it depends on fuel price levels. Although a low-priced LNG favours the shorter NSR at LNG-VLSFO 1,700 m^3 mode, depending on OD pair distances, a larger LNG tank capacity reduces this benefit. Yet, market factors and the adoption of more than one fuel type/technology could increase the versatility of a tanker (The Motorship 2020a).

The next chapter assesses the feasibility of the NSR compared to SCR for seasonal operations. It extends the analysis of this chapter and Chapter 4 by aiming to examine the impact of ship speed through ice on the economics of the NSR. The NSR is compared to the SCR for oil product tanker voyages between Northwest Europe, the Russian Baltic, and Northeast Asia at the strategic level (choice of oil products and routes as an expert-based scenario) during the whole summer/autumn season. The analysis considers distance, fuel types and prices, icebreaking fees, commodity prices and in-transit inventory costs, and ship speed through ice on NSR per month, navigation zone, and voyage direction. A speed optimisation model is developed that minimises the RFR for competing routes in the context of Arctic shipping.

6. The role of ship speed on ice and alternative fuel types for seasonal navigation

The feasibility of the Northern Sea Route (NSR) is assessed against the Suez Canal (SCR) for seasonal navigation operations. The factors considered are distance, fuel prices, ship speed through ice on NSR, seasonal navigation, icebreaking fees, commodity prices and in-transit inventory costs, and fuel types and operational modes. The analysis in this chapter complements Chapter 4 and Chapter 5, by developing seasonal navigation scenarios and considering real hourly Automated Identification System (AIS) speed data of historic tanker voyages conducted on NSR to determine the varying speed through ice on NSR. The analysis assesses seasonal navigation between ports located in the Baltic Sea, Northwest Europe and Northeast Asia during the summer/autumn season. The analysis is undertaken at the strategic level (choice of oil products/commodities and routes as an expert-based scenario).

The analysis assumes Long Range 2 (LR2) voyages of naphtha and jet fuel/kerosene cargo, based on major oil products trades and historic tanker voyages conducted on NSR between east and west. A required freight rate (RFR) model is developed based on speed optimisation to assess the minimum cost per tonne from the shipowner's perspective. The methodological approach considers ship speed through ice per month, navigation zone and voyage direction. AIS data are used to extract real hourly speed data of historic tanker voyages conducted on NSR to inform the analysis.

Alternative operational modes are considered to address current and future emissions reductions policies, such as the Emission Control Areas (ECAs) policy, the IMO sulphur limit, the Initial IMO greenhouse gas (GHG) Strategy, and a future ban on the use of heavy fuels (HSFO, VLSFO) for operations in the Arctic. These modes include the use of High Sulphur Fuel Oil (HSFO) with scrubber (HSFO-Scrubber), the use of Very Low Sulphur Fuel Oil (VLSFO), and the use of dual fuel Oil/Liquefied Natural Gas (LNG) set-ups based on current technologies of LNG tank capacity (LNG-VLSFO). The use of Marine Gasoil (MGO) is assumed within the Arctic under the HSFO-Scrubber and VLSFO modes following a future prohibition on the use of heavy fuel oils in the Arctic. Both primary and secondary data are employed in the analysis regarding cost, market, and navigational factors.

6.1 Introduction

Sea ice conditions and the navigation season extent largely determine the potential of the NSR to compete with the more established routes/canals such as the Suez and Panama Canals and the Cape of Good Hope route. More specifically, sea ice exhibits inter-annual variability and uneven distribution along the NSR (Stephenson et al. 2014; Yumashev et al. 2017). Therefore, ship speed on ice is determined by local sea ice conditions, which vary within the same season, across different zones and also depend on the ice class of a ship (Faury and Cariou 2016; Cariou and Faury 2020; Faury et al. 2020; Cheaitou et al. 2020; Cariou et al. 2021). Consequently, the impact of variable ship speed on ice means increased uncertainty of transit times and higher voyage and operating costs. Conversely, high speeds increase voyage frequency and therefore profitability (Wergeland 1992; Guy 2006; Lasserre 2014; Lasserre 2015), albeit at the expense of safety depending on ice conditions (Lasserre and Pelletier 2011). Moreover, the use of ice class ships implies increased capital costs and fuel consumption, depending on the ice class (Erikstad and Ehlers 2012; von Bock und Polach et al. 2015; Faury et al. 2020; Cheaitou et al. 2020).

The literature on the viability of the NSR for seasonal/annual operations is focused primarily on liner shipping, whereas only four studies reporting research on tankers investigated annual (Keltoo and Woo 2020) and/or prospective annual (Faury et al. 2020; Wang et al. 2020; Cheaitou et al. 2020) operations. Whilst the sea ice-ship speed dependency has been thoroughly investigated by employing historic sea ice thickness data to determine tanker speeds on the NSR (Faury and Cariou 2016; Cariou and Faury 2020; Faury et al. 2020; Cheaitou et al. 2020), there have not been any studies that used real data regarding ship speed on ice from actual NSR tanker transits, and therefore providing an alternative approach to the literature. Further, there have been only two studies that explored the impact of the IMO 2020 sulphur limit (Keltoo and Woo 2020; Wang et al. 2020). Although seasonal/annual planning and scheduling is more suitable to liner shipping due to the nature of this sector, seasonal/annual voyage opportunities for bulk shipping and more specifically for tankers may exist, especially for certain trade routes with established oil flows and/or frequent arbitrage opportunities.

The analysis aims to assess the seasonal feasibility of the NSR for naphtha and middle distillate flows between Northeast Asia, Northwest Europe, and the Baltic during the summer/autumn season. A RFR analysis is established to assess the break-even point of competing routes from the shipowner's point of view. The analysis considers the time value of cargo on board based on various commodity price levels, fuel prices as well as alternative operational modes and fuel types. AIS data are used to obtain real hourly speeds of tankers which operated on the NSR during the 2011-2019 summer/autumn seasons. Seasonal consecutive voyages are assumed in the analysis. The ship speed through open water is optimised with respect to cost and market factors, whereas the ship speed through ice is determined by sea ice conditions, depending on the navigation zone, month and direction (east/west) when operating through ice on the NSR.

6.2 Modelling

6.2.1 Modelling approach

A RFR minimisation model based on speed optimisation, which incorporates different fuel types and technologies is developed. The RFR or minimum cost per tonne in US$ is determined at the optimal speed where cost equal revenue, that is, the long-run equilibrium point between supply and demand (Alderton 1981).

The fuel types considered for oil-powered engines are HSFO with scrubber (HSFO-Scrubber), and VLSFO with MGO within Emission Control Areas (ECAs) (IMO 2021). As regards dual-fuel gas-oil powered engines, two modes are considered: LNG and pilot MGO (gas mode), and VLSFO (oil mode). The use of MGO is also considered for oil-powered engines following a future ban of heavy fuels in the Arctic (IMO 2020). One option for dual-fuel gas-oil powered ships is included, that is, an Oil/LNG engine with LNG tank capacity of 1,700 m^3, reflecting current technological developments.

The fuel consumption is a function of speed, fuel type, operational mode and payload (Barrass 2004; MAN Diesel and Turbo 2013a; Psaraftis and Kontovas 2013; Psaraftis and Kontovas 2014; MAN Energy Solutions 2020).

The fuel consumption function of a ship using either of the oil-based fuels (HSFO, VLSFO, MGO) can be expressed as:

$$F_{FO}(S^*, \nabla) = F_{FO\ d} \cdot \left(\frac{S_{FO}^*}{S_d}\right)^a \cdot \left(\frac{P+L}{\nabla}\right)^{2/3} \tag{1}$$

The exponent a ranges between 0.11 and 3.8 for LR2/Aframax tankers (Adland et al. 2020) and is approximated at three (3) in this study (Psaraftis and Kontovas 2013). All fuel consumption functions of this form depend on speed and payload (Psaraftis and Kontovas 2013; Psaraftis and Kontovas 2014).

A dual-fuel diesel engine is capable to operate either on gas (LNG) or oil (VLSFO, HSFO, MGO) modes. The choice of fuel type depends on operational choices, market conditions and environmental considerations. The use of LNG also depends on tank capacity constraints that dictate the maximum range of the tanker, beyond which the engine is switched to oil mode. When a dual-fuel diesel engine operates at gas mode, it also uses oil-based pilot consumption, since LNG requires an ignition source to start the combustion process (MAN Energy Solutions 2020; DNV 2021a). Since LNG is also assumed to be used within ECAs, the pilot fuel oil is assumed to be MGO for compliance with the ECAs regulations (MAN Energy Solutions 2020).

The fuel consumption functions of a ship with a dual-fuel diesel engine that operates on LNG mode can be expressed as:

$$F_{DF\,LNG}(S^*,\nabla) = F_{DF\,LNG\,d} \cdot \left(\frac{S^*_{DF\,LNG}}{S_d}\right)^a \cdot \left(\frac{P+L}{\nabla}\right)^{2/3}, \text{ for the LNG consumption,} \tag{2}$$

and

$$F_{DF\,Pilot}(S^*,\nabla) = F_{DF\,Pilot\,d} \cdot \left(\frac{S^*_{DF\,LNG}}{S_d}\right)^a \cdot \left(\frac{P+L}{\nabla}\right)^{2/3}, \text{ for the pilot fuel oil consumption,} \tag{3}$$

whereas the fuel consumption function when the dual-fuel diesel engine operates on oil mode can be expressed as:

$$F_{DF\,FO}(S^*,\nabla) = F_{DF\,FO\,d} \cdot \left(\frac{S^*_{DF\,FO}}{S_d}\right)^a \cdot \left(\frac{P+L}{\nabla}\right)^{2/3} \tag{4}$$

Equation (3) follows the same exponential relationship between speed and fuel consumption as in the other fuels (Equations 1, 2, 4). The pilot fuel oil consumption is proportional to the engine speed, which in turn is nearly proportional to the ship speed. This means that the pilot fuel oil consumption varies nearly linearly with ship speed (MAN Energy Solutions 2020).

The objective is to minimise the total RFR of all voyages for a route alternative (either RFR_{NSR} or RFR_{SCR}):

$$min \sum RFR + e \cdot C_{IC} \tag{5}$$

The objective function also minimises the RFR of single voyages when these are not summed up. The term $\sum RFR$ denotes the sum of the RFR for each leg of a voyage in either of the two routes and/or the sum of the RFR of all voyages for seasonal round voyage operations. The term $e \cdot C_{IC}$ denotes the additional costs of ice coating for ice class tankers to enhance the ship's hull and reduce the risk of ice damages. This option is considered when the strategy of the shipowner is to operate their tankers through the NSR for a whole ice season, in contrast to occasional single voyages via the NSR that do not necessitate such an investment (Tanker Company 2019).

The RFR is a function of distance, fuel consumption, optimal speed, total cost inputs and cargo carrying capacity of a tanker for each leg and voyage. Equation (6) presents the RFR function for oil-based scenarios (HSFO-Scrubber or VLSFO), whereas Equation (7) that of dual-fuel scenarios where LNG and pilot fuel oil are included. Equations (8) and (9) present the RFR for a ballast voyage between two ports that link seasonal operations of laden voyages, where only fuel, capital, and operating costs are included. Equation (8) refers to the use of either HSFO or MGO under the HSFO-Scrubber and VLSFO modes respectively, whereas Equation (9) refers to the use of LNG and pilot MGO under the LNG-VLSFO mode. It is assumed that MGO is used in ballast voyages under the VLSFO option since these voyages occur within the North Sea and Baltic Sea ECAs zones. LNG and pilot MGO are used only in this voyage as the fuel consumption requirements satisfy the voyage length and LNG is cheaper than VLSFO, based on the assumed marine fuel prices.

The number 24 denotes the hours per day, which is used in Equations (6) – (9) to obtain voyage time in days. The RFR incorporates both the value of the ship and the value of the cargo on-board, that is, the in-transit inventory cost (Alderton 1981). The in-transit inventory cost, expressed in US$ per day, is defined by the term $W \cdot P_C \cdot \frac{r}{365}$, where the price in US$/t of a tonne of naphtha or jet fuel/kerosene, P_C, is multiplied by the total quantity in tonnes, W, and a relevant interest rate for oil and petroleum products, r (Alderton 1981; Goss et al. 1982; Psaraftis and Kontovas 2014; Lindstad and Eskeland 2015) equal to 10% (McQuilling 2012). The interest rate, r, is divided by 365 to convert the value of in-transit inventory cost to US$ per day. The inclusion of in-transit inventory cost in a RFR model based on the shipowner's perspective is relevant, even if this is essentially a charterer's expense. The explanation is that a charterer will prefer a ship that delivers their cargo at the right time depending on market conditions, commodity prices and opportunity costs (Psaraftis and Kontovas 2014).

$$RFR = \frac{1}{W} \cdot \left[\left(\frac{D_{SCR,NSR}}{S^*_{FO} \cdot 24}\right) \cdot \left((F_{FO}(S^*_{FO}) \cdot P_{FO}) + (C_o + C_c + g \cdot C_s) + (W \cdot P_C \cdot \frac{r}{365})\right) + C_{TI}\right] \quad (6)$$

$$RFR = \frac{1}{W} \cdot \left[\left(\frac{D_{SCR,NSR}}{(S^*_{DF\ LNG} + S^*_{DF\ FO}) \cdot 24}\right) \cdot \left(b \cdot (F_{DF\ LNG}(S^*_{DF\ LNG}) \cdot P_{LNG} + F_{DF\ Pilot}(S^*_{DF\ LNG}) \cdot P_{FO}) + c \cdot (F_{DF\ FO}(S^*_{DF\ FO}) \cdot P_{FO}) + (C_o + C_c) + (W \cdot P_C \cdot \frac{r}{365})\right) + C_{TI}\right] \quad (7)$$

$$RFR = \frac{1}{W} \cdot \left[\left(\frac{D_B}{S^*_{FO\ B} \cdot 24} \right) \cdot \left((F_{FO}(S^*_{FO\ B}) \cdot P_{FO}) + (C_o + C_c + g \cdot C_s) \right) \right] \quad (8)$$

$$RFR = \frac{1}{W} \cdot \left[\left(\frac{D_B}{S^*_{DF\ LNG\ B} \cdot 24} \right) \cdot \left((F_{DF\ LNG}(S^*_{DF\ LNG\ B}) \cdot P_{LNG} + F_{DF\ Pilot}(S^*_{DF\ LNG\ B}) \cdot P_{FO}) + (C_o + C_c) \right) \right] \quad (9)$$

subject to

$$\underline{S} \leq S^* \leq \overline{S} \quad (10)$$

and

$$b, c, e, g \in \{0,1\} \quad (11)$$

Table 6.1 reports the parameters and variables used in Equations (1) – (27).

Table 6.1. Parameters and variables used in the model.

Parameters:	**Description**
P	weight of cargo, fresh water, fuel, lubricating oil, stores, water ballast, crew and effects, and baggage and passengers in metric tonnes (m.t.)
W	average weight of cargo in m.t.
$\sum_{i=1}^{n} D_{SCR}$	total SCR distance in nautical miles (n.m.)
$\sum_{i=1}^{n} D_{NSR}$	total NSR distance in n.m.
D_B	distance for ballast voyage between Rotterdam and Ust-Luga ports in n.m.
D_{ICE}	total distance through ice on NSR in n.m.
$D_{1,SCR}, \dots, D_{n,SCR}$	SCR distance legs in n.m.
$D_{1,NSR}, \dots D_{ICE} \dots, D_{n,NSR}$	NSR distance legs in n.m.
$d_1, \dots, d_6$	NSR distance legs through ice in n.m.
P_{FO}, P_{LNG}	fuel price in US$ per tonne for fuel oils (HSFO, VLSFO, MGO), and LNG, respectively
P_C, r	commodity price in US$ per tonne (here oil products), and interest rate
C_{IC}	cost of ice coating for seasonal operations scenarios in US$
C_o, C_c	operating costs in US$ per day, capital costs in US$ per day
C_{TI}	transit costs (canal tolls or icebreaking fees) and insurance premiums in US$
C_s	capital costs of exhaust cleaning systems (scrubber) in US$ per day
S_d	design speed in knots
$\overline{S}$	upper speed in knots
$\underline{S}$	lower speed in knots
$F_{FO\ d}$	fuel consumption for oil-based fuels (HSFO, VLSFO, MGO) at design speed in tonnes per day
$F_{DF\ LNG\ d}, F_{DF\ Pilot\ d}$	fuel consumption for LNG and Pilot MGO at design speed in tonnes per day
$F_{DF\ FO\ d}$	fuel consumption for dual-fuel engine when operating on oil-mode (VLSFO) at design speed in tonnes per day
L	lightweight of a product tanker in tonnes
∇	displacement of a product tanker in tonnes

Table 6.1. Parameters and variables used in the model (continued).

Variables	Description
S^*_{FO}	optimal laden speed for oil powered (HSFO, VLSFO, MGO) engine in knots
$S^*_{DF\ LNG}$	optimal laden speed for dual-fuel engine (LNG) in knots
$S^*_{DF\ FO}$	optimal laden speed for dual-fuel engine (oil-mode – VLSFO, MGO) in knots
$S^*_{FO\ B}, S^*_{DF\ LNG\ B}$	optimal speeds for a ballast voyage in knots for oil powered (HSFO, VLSFO, MGO) and dual-fuel (LNG) engine, respectively
b, c, e, g	binary variables, equal to 1 when dual-fuel LNG mode, dual-fuel fuel oil mode, ice coating cost, and scrubber are considered respectively, and 0 otherwise
$\sum_{i=1}^{n} T_{SCR}$	total SCR transit time in days
$\sum_{i=1}^{n} T_{NSR}$	total NSR transit time in days
T_{ICE}	total transit time through ice on NSR in days
$T_{1,SCR}, \dots, T_{n,SCR}$	SCR transit time for each leg in days
$T_{1,NSR}, \dots T_{ICE} \dots, T_{n,NSR}$	NSR transit time for each leg in days
T_B	transit time for a ballast voyage (leg) between Rotterdam and Ust-Luga ports in days
$t_1, \dots, t_6$	transit time for each NSR leg through ice in days
RFR_{SCR}, RFR_{NSR}	required freight rate (RFR) for the SCR and NSR routes in US$ per tonne
ΔRFR	RFR differential

The term $\frac{1}{W}$ transforms RFR to RFR in US$ per tonne, whilst the terms $\left(\frac{D_{SCR,NSR}}{S^*_{FO} \cdot 24}\right), \left(\frac{D_{SCR,NSR}}{(S^*_{DF\ LNG} + S^*_{DF\ FO}) \cdot 24}\right), \left(\frac{D_B}{S^*_{FO\ B} \cdot 24}\right), \left(\frac{D_B}{S^*_{DF\ LNG\ B} \cdot 24}\right)$ calculate the days at sea per voyage and leg for each of the fuel types/modes. The variable g denotes the use of a hybrid scrubber, where $g = 1$ for the HSFO-Scrubber mode or $g = 0$ otherwise. The minimum speed is unrestricted when icebreaking assistance is assumed, implying the possibility of blockage (Cariou et al. 2020). Yet, a minimum speed of 5 knots is assumed for an ice class IA ship as the speed below which it cannot navigate independently (MAN Diesel and Turbo 2013b; Trafi 2017a; Solakivi et al. 2018), and a maximum speed of 16 knots for all tankers, where the design speed falls between 90-95% of the maximum speed depending on ship size (Lindstad et al. 2011). The variable e equals 1 when special (ice) coating is included in the analysis for seasonal operations of consecutive round voyages or 0 otherwise. According to Tanker Company (2019), the use of ice coating depends on planning and the strategy of a shipowner. It is essential when operating on ice for a complete season as it can reduce the risk of ice damages and subsequent repairs. Thus, this cost is spread over the entire length of seasonal operations compared to single occasional voyages through ice that do not require such an investment. Additional costs such as port dues, cargo handling, and fuel cost in port are excluded from the cost analysis since these are assumed to be the same for either routeing alternative. Auxiliary fuel requirements are assumed to be satisfied by the use of the main engine, which depends on the ship and engine set up (Tanker Company 2019).

The optimal speeds are obtained by partial differentiation of Equations (6), (7), (8), and (9) with respect to speeds S^*_{FO}, $S^*_{DF\ LNG}$, $S^*_{DF\ FO}$, $S^*_{FO\ B}$, and $S^*_{DF\ LNG\ B}$, which are set equal to zero, that is, $\frac{\partial RFR}{\partial_{S^*_{FO}}} = 0$, $\frac{\partial RFR}{\partial_{S^*_{DF\ LNG}}} = 0$, $\frac{\partial RFR}{\partial_{S^*_{DF\ FO}}} = 0$, $\frac{\partial RFR}{\partial_{S^*_{FO\ B}}} = 0$, $\frac{\partial RFR}{\partial_{S^*_{DF\ LNG\ B}}} = 0$, with all optimal speeds subject to lower, $\underline{S}$, (when independent navigation is assumed), and upper limits, $\overline{S}$.

Appendix R presents the calculations for Equations (12) – (16). Equations (6) – (9) are solved by substituting the optimal speeds obtained from Equations (12) – (16) to give the minimum RFR for each leg of a certain OD.

$$S^*_{FO} = \sqrt[a]{\frac{\left(C_o+C_c+g\cdot C_S+W\cdot P_C\cdot\frac{r}{365}\right)\cdot S_d{}^a\cdot\nabla^{2/3}}{(a-1)\cdot(F_{FO\ d}\cdot P_{FO})\cdot(P+L)^{2/3}}} \tag{12}$$

$$S^*_{DF\ LNG} = \sqrt[a]{\frac{\left(C_o+C_c+W\cdot P_C\cdot\frac{r}{365}\right)\cdot S_d{}^a\cdot\nabla^{2/3}}{(a-1)\cdot(F_{DF\ LNG\ d}\cdot P_{LNG}+F_{DF\ Pilot\ d}\cdot P_{FO})\cdot(P+L)^{2/3}}} \tag{13}$$

$$S^*_{DF\ FO} = \sqrt[a]{\frac{\left(C_o+C_c+W\cdot P_C\cdot\frac{r}{365}\right)\cdot S_d{}^a\cdot\nabla^{2/3}}{(a-1)\cdot(F_{DF\ FO\ d}\cdot P_{FO})\cdot(P+L)^{2/3}}} \tag{14}$$

$$S^*_{FO\ B} = \sqrt[a]{\frac{(C_o+C_c+g\cdot C_S)\cdot S_d{}^a\cdot\nabla^{2/3}}{(a-1)\cdot(F_{FO\ d}\cdot P_{FO})\cdot(P+L)^{2/3}}} \tag{15}$$

$$S^*_{DF\ LNG\ B} = \sqrt[a]{\frac{(C_o+C_c)\cdot S_d{}^a\cdot\nabla^{2/3}}{(a-1)\cdot(F_{DF\ LNG\ d}\cdot P_{LNG}+F_{DF\ Pilot\ d}\cdot P_{FO})\cdot(P+L)^{2/3}}} \tag{16}$$

These optimal speeds depend on operating and capital costs, in-transit inventory costs, fuel prices, and payload. These optimal speeds are not affected by charterparty obligations or any other constraints (Psaraftis and Kontovas 2014; Cariou and Faury 2015). Optimal speeds obtained from Equations (12) – (14) refer to operations on open water for both SCR and NSR, whereas the speeds through the ice legs on the NSR are not necessarily optimised with respect to cost and market conditions. The reason is that speed through ice primarily depends on sea ice conditions and may not equal the optimal speed (for assumptions on the average speed through ice: Section '6.3.5 Speed on the NSR and seasonal navigation planning').

Moreover, increased capital and operating costs as well as higher fuel consumption for an ice class IA tanker affect the open water optimal speeds and costs in both open water and ice.

The total distance and time of each individual leg for either SCR or NSR depends on a certain fuel type/technology, ECAs zones, fuel tank capacity and range, and commodity and fuel prices. They can be expressed as:

$$\sum_{i=1}^{n} D_{NSR} = D_{1,NSR} + D_{ICE} + \ldots + D_{n,NSR} \tag{17}$$

$$\sum_{i=1}^{n} T_{NSR} = T_{1,NSR} + T_{ICE} + \ldots + T_{n,NSR} \tag{18}$$

$$\sum_{i=1}^{n} D_{SCR} = D_{1,SCR} + \ldots + D_{n,SCR} \tag{19}$$

$$\sum_{i=1}^{n} T_{SCR} = T_{1,SCR} + \ldots + T_{n,SCR} \tag{20}$$

The total distance and time through ice water on the NSR can be similarly defined as:

$$D_{ICE} = d_1 + d_2 + d_3 + d_4 + d_5 + d_6 \tag{21}$$

$$T_{ICE} = t_1 + t_2 + t_3 + t_4 + t_5 + t_6 \tag{22}$$

where each of the distance and time legs refer to the East Kara Sea, West Laptev Sea, East Laptev Sea, East Siberian West Sea, East Siberian East Sea, and Chukchi Sea, respectively.

Voyages for each OD pair, including distances for each leg depending on the fuel type are included in Appendix W.

The optimal speed for either fuel type/mode per voyage for a route alternative is defined as:

$$S_{FO}^{*}, S_{DF\ LNG}^{*}, S_{DF\ FO}^{*} = \frac{\sum_{i=1}^{n} D_{NSR}}{\sum_{i=1}^{n} T_{NSR} \cdot 24} \tag{23}$$

$$S^*_{FO}, S^*_{DF\ LNG}, S^*_{DF\ FO} = \frac{\sum_{i=1}^{n} D_{SCR}}{\sum_{i=1}^{n} T_{SCR} \cdot 24} \tag{24}$$

Whereas the optimal speeds concerning ballast voyages from Rotterdam to Ust-Luga are defined as:

$$S^*_{FO\ B} = \frac{D_B}{T_B \cdot 24} \tag{25}$$

$$S^*_{DF\ LNG\ B} = \frac{D_B}{T_B \cdot 24} \tag{26}$$

The RFR differential between NSR and SCR is defined as:

$$\Delta RFR = RFR_{SCR} - RFR_{NSR} \tag{27}$$

6.3 Assumptions and data

6.3.1 Origin – Destination pairs

In general, two main operational patterns of tankers can be identified. The first one consists of loading cargo in one port, discharging in another port and then operating in ballast either back to the loading port or to the next loading port, which can be located in a different geographic region. Alternatively, a tanker can load its next cargo either in the discharging port or in a port located relatively close to the discharging port, performing what is known as *triangulation*, and effectively reducing long ballast voyages. Various options of triangulated voyages exist in both the Atlantic and the Pacific Ocean for short, medium, or even longer oil product tanker voyages. In the Atlantic basin, a typical example is a front haul gasoline voyage from Northwest Europe to the U.S. Atlantic Coast, with a backhaul diesel/gasoil voyage from U.S. Gulf to Northwest Europe (Clarksons 2021). In the geographic region east of Suez, a naphtha voyage from Middle East Gulf (MEG) to South Korea or Japan is triangulated with a gasoil/diesel voyage from South Korea to Hong Kong, followed by a gasoline/diesel voyage to Singapore, which in turn is followed by either a ballast leg back to MEG or by a naphtha voyage to Japan (Clarksons 2021). It can be seen that in all cases the main aims are to reduce the time a ship spends on ballast voyages and increase earnings.

Table 6.2 presents records of seasonal tanker round voyages in either direction of the NSR between 2011 and 2019. It can be seen that some traders/operators used the NSR for round voyages in order to exploit the seasonal window during the summer/autumn navigation season. The number of seasonal round voyages between west and east varies from two to three and providing that some tankers did not perform certain voyages outside the NSR (Bloomberg

2021), they could use the NSR for up to four or five consecutive voyages during the summer/autumn navigation season, depending on the month, distances between OD pairs, ballast voyages linking loading ports, sea ice as well as market conditions and employment opportunities. For example, *Perseverance* could perform another two voyages, in August and October respectively, between July and November, whereas *Propontis* could perform four voyages between July and October, provided that its first voyage started in early July.

Table 6.2. Historic seasonal NSR tanker round voyages.

Year	Tanker	Size	Voyage	Period	Cargo	Metric tonnes
2011	Perseverance	LR1	Arctic Russia – China	June-July	Condensate	59,981
			South Korea – Netherlands	September	Jet Fuel/ Kerosene	64,400
			Arctic Russia – China	November	Condensate	61,275
2012	Stena Poseidon	LR1	South Korea – Finland	July	Jet Fuel/ Kerosene	66,416
			Arctic Russia – South Korea	September	Condensate	60,370
	Palva	LR1	Arctic Russia – South Korea	July-August	Condensate	60,310
			South Korea – Finland	September	Jet Fuel/ Kerosene	66,275
	Marika	LR1	South Korea – Finland	August-September	Jet Fuel/ Kerosene	66,552
			Arctic Russia – South Korea	October	Condensate	61,266
2013	Propontis	LR2	Norway – Japan	July-August	Naphtha	79,846
			South Korea – Netherlands	September-October	Gasoil	109,090
2014	Anichkov Bridge	MR	Far East Russia – Baltic Russia	July-August	Ballast	
			Baltic Russia – Far East Russia	September	Fuel Oil	44,175
			Far East Russia – Baltic Russia	October	Ballast	
	SCF Neva	MR	Far East Russia – Baltic Russia	August	Ballast	
			Baltic Russia – Far East Russia	September	Fuel Oil	44,050
	SCF Amur		Far East Russia – Arctic Russia	August	Ballast	
			Arctic Russia – Far East Russia	September	Fuel Oil	43,998
			Far East Russia – Arctic Russia	October	Ballast	
2019	Korolev Prospect	Afra max	Arctic Russia – China	August-September	Crude Oil	N.A.
			China – Arctic Russia	September-October	Ballast (?)	

Source: CHNL (2021a). *Crude oil and fuel oil round voyages are also included. Some tankers reported in the table may have changed names. MR: Medium Range, LR1: Long Range 1, LR2: Long Range 2.

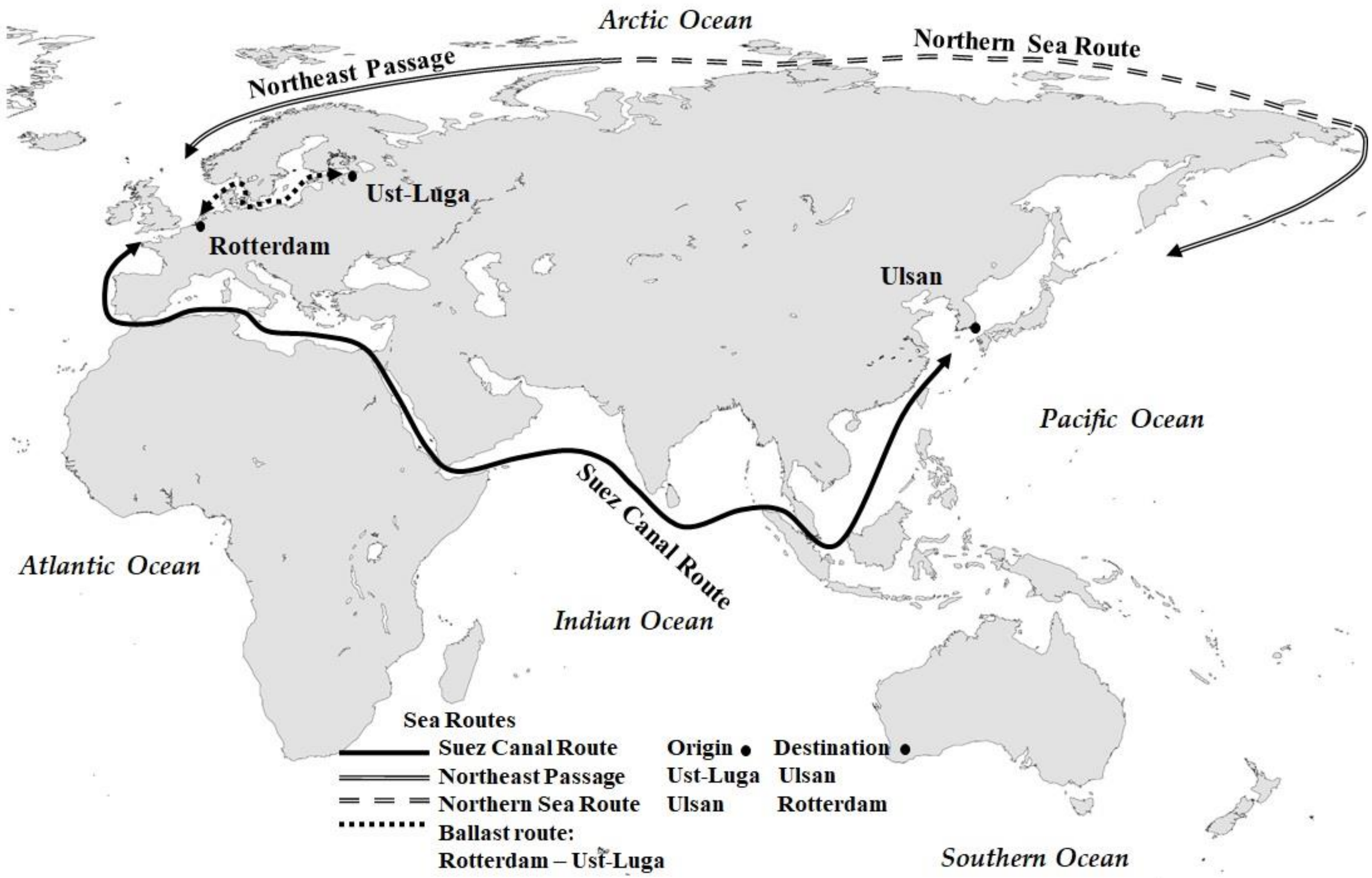
The choice of seasonal multiple voyages for oil product tankers between Northwest Europe and Northeast Asia is based on the respective oil products trade flows, tanker routeing patterns, and historic voyages through the NSR.

According to data from IEA (2019), naphtha was the largest single oil product in volume (metric tonnes), shipped from Northwest Europe and the Baltic to Northeast and Southeast

Asia, and Oceania between 2016 and 2018 (76-70%). Russia was the biggest exporter (84-87%) and South Korea (72-79%) was the biggest importer. On the other hand, jet fuel/kerosene was the dominant oil product exported from Northeast and Southeast Asia, and Oceania to Northwest Europe between 2016 and 2018 (56-65%). South Korea was the biggest exporter (65-60%) and the Netherlands was the biggest importer (57-56%) of the commodity.

These statistics reflect the typical arbitrage oil product trades between Asia, the Baltic, and the Amsterdam-Rotterdam-Antwerp (ARA) region, whilst this is also evident from the NSR seasonal single or round voyages between 2011 and 2019, where naphtha was shipped from the Baltic or Norway to the Far East and jet fuel/kerosene was transported from the Far East to the ARA region (CHNL 2021a). Besides, the re-direction of naphtha and condensate flows from the port of Vitino in the White Sea to the port of Ust-Luga in the Baltic since 2014, shifted Arctic-originated oil products to Baltic ports for exports to Asia (Bambulyak et al. 2015).

Therefore, the analysis is based on consecutive seasonal round voyages between Russia Baltic (Ust-Luga) and South Korea (Ulsan) for the front haul naphtha voyage, and between South Korea (Ulsan) and the Netherlands (Rotterdam) for the backhaul jet fuel/kerosene voyage, including a ballast leg between Rotterdam and Ust-Luga for the next front haul voyage to Ulsan. The choice of ports is based on fixtures from Clarksons (2021) for the respective commodities. Figure 6.1 illustrates OD pairs and sea routes. Port characteristics and LNG bunkering infrastructure are presented in Appendices X1 and X2, respectively.



Source: Author, based on Equirectangular projection (NASA 2021).

Figure 6.1. OD pairs and route alternatives.

6.3.2 Cost and navigational factors

The analysis is based on a comparison between an ordinary LR2 tanker and an ice class IA LR2 tanker, both of 115,000 dwt, with Length Overall (LOA) 250 metres, draught of 15 metres and beam of 44 metres. The fuel consumption in tonnes per day at the design speed for each engine set-up is calculated based on the Computerised Engine Application System (CEAS) provided by MAN Energy Solutions (MAN Energy Solutions 2019a; MAN Energy Solutions 2019b). Appendix T presents the calculations for the fuel consumption at the design speed based on CEAS.

The ship size chosen is based on typical naphtha and jet fuel/kerosene quantities for long-haul voyages of LR2 tankers between Europe and the Far East. Naphtha cargoes are typically traded in quantities of 75-90,000 metric tonnes, and jet fuel/kerosene cargoes are traded in quantities of 80-90,000 metric tonnes (Clarksons 2021). These figures are also in line with NSR voyages during 2011-2019 (Table 6.2; CHNL 2021a). The choice of cargo quantity also depends on port characteristics as well as any other logistical or physical constraints. The naphtha or jet fuel/kerosene cargo quantity is assumed 80,000 metric tonnes.

Table 6.3 presents costs and technical characteristics for the tankers considered in this Chapter. These refer to global average characteristics of Aframax/LR2 tankers as well as those of Sovcomflot’s LNG-powered ice class IA/B Aframax tankers (MAN Diesel and Turbo 2013a; MAN Diesel and Turbo 2013c; MAN Energy Solutions 2019a; MAN Energy Solutions 2019b; MAN Energy Solutions 2020; Sovcomflot 2018; Clarksons 2021). The ice class IA is in line with the majority of the tankers that used the NSR from 2011 to 2019 (NSRA 2016; CHNL 2021a). Sovcomflot’s LNG-powered Aframax tankers which used the NSR in 2018 are of ice class IA/B. This means that they have a hull that conforms to ice class IA standards, whereas the rest of their specifications are equal to ice class IB (Sovcomflot 2018). Generally, an ice class IA ship is capable of navigating on first-year ice with a maximum thickness of 1.0 metre (MAN Diesel and Turbo 2013b; Trafi 2017a).

Table 6.3. LR2 tanker costs and technical characteristics for all fuels.

	HSFO-Scrubber	VLSFO	LNG	
			LNG mode	VLSFO mode
Design Speed (knots) [a]	15	15	15	15
Maximum Speed (knots)	16	16	16	16
Fuel Consumption (tonnes/day of non-ice/ice class)[a]	46.7 / 63.2	45.6 / 61.6	36.5 / 49.6	46.7 / 63.1
MGO Consumption (tonnes/day of non-ice/ice class)[a]	–	44 / 59.4	–	–
MGO Pilot Consumption (tonnes/day of non-ice/ice class)[a]	–	–	0.91 / 0.98	–
Fuel Tank Capacity (tonnes) [a]	2,415	2,415	773	1,700
Operating Costs (US$ per day) (non-ice/ice class)[b]	7,974 / 8,406	7,974 / 8,406	7,974 / 8,406	7,974 / 8,406
Capital Costs (US$ per day) (non-ice/ice class)[c]	13,056 / 16,861	12,296 / 16,033	12,827 / 16,562	12,827 / 16,562
Tonnes per Centimetre Immersion (TPC) [a]	97.2	97.2	97.2	97.2
Draught (metres) [a]	15	15	15	15
Draught when loaded (metres)[a]	12	12	12	12

Sources: [a]calculations based on Appendix T, [b]average 2011-2018 BDO (2021), [c]calculations based on Appendices O1, O2.

The LNG provides the highest energy density and therefore the lowest consumption compared to HSFO, VLSFO and MGO. However, when the dual fuel engine operates on the VLSFO mode, it consumes more than an oil-powered engine operating on the same fuel, since restrictions on its design means that it cannot be as efficient as a fuel oil-based engine at both operational modes (MAN Energy Solutions 2019a). Moreover, the HSFO option gives higher consumption than VLSFO and MGO owing to its lower energy density, as well as the use of a scrubber, which entails additional energy requirements. MGO consumption is the lowest of the oil-based fuels.

The HSFO-Scrubber mode allows the use of HSFO for a whole voyage as the scrubber (here hybrid), removes the sulphur of the fuel before it is emitted in the atmosphere. The VLSFO mode implies the use of VLSFO, with MGO used within ECAs zones. The LNG-VLSFO mode gives a dual-fuel LR2 tanker the option to use LNG for a certain distance (including within the ECAs zones and within the NSR) depending on the range and LNG tank capacity, and VLSFO for the rest of the voyage.

One LNG-VLSFO mode is considered, that is, for a tanker based on specifications similar to those of Sovcomflot's ice class IA/B Aframax tankers with LNG fuel tank capacity of 1,700 m^3 (Sovcomflot 2018; Clarksons 2021). The LNG tank capacity has implications on the fuel mix per voyage, costs, and route competitiveness alike (The Motorship 2018; The Motorship 2020a; The Motorship 2020b). The 1,700 m^3 tank provides a maximum range of about 7,800 nautical miles for an ordinary Oil/LNG dual-fuel LR2 tanker at the maximum speed of 16 knots, and a maximum range of 5,700 n.m. for an ice class IA dual-fuel Oil/LNG LR2 tanker at the maximum speed of 16 knots, when they are loaded with 80,000 metric tonnes of cargo, before switching to VLSFO.

Yet, daily LNG consumption in an optimisation setting depends on the optimal speed, which in turn depends on fixed and variable costs, payload, and displacement. Thus, the actual range can be less or equal that achieved at the maximum speed. Equally, LNG consumption through ice corresponds at speeds well below 16 knots and as a consequence it would be lower than the consumption at the maximum speed even after considering increased fuel consumption for an ice class tanker. Thus, the actual LNG consumption for the ice class tanker before switching to oil mode ranges between 6,659 n.m. and 7,159 n.m. depending on the different speed regimes per navigation zone on the NSR. Voyages for each OD pair, including distances for each leg depending on the fuel type, as well as LNG/VLSFO distance ratios, are reported in Appendices W1 and W2, respectively.

Increased costs for ice class tankers refer to premiums in capital, operating and voyage costs. A capital cost premium of 30.4% for a new ice class IA tanker is assumed based on Solakivi et al. (2018), and increased costs for dual fuelled Oil/LNG tankers of 4.38% for a 1,700 m^3 LNG tank capacity (Table 6.3; Sovcomflot 2018; Clarksons 2021). Increased fuel consumption is based on 30.8% higher installed power for an ice class tanker than that of a non-ice class tanker (Solakivi et al. 2018) and is obtained at the design speed for each engine set-up using CEAS calculations from MAN Energy Solutions (MAN Energy Solutions 2019a; MAN Energy Solutions 2019b).

Other costs related with operations on the NSR include fixed costs of US$ 50,000 and US$ 20,000 for insurance, books and charts per voyage, as well as a 10% premium in crew costs per day, whereas piloting is estimated at 1,000 US$ per day with travel expenses at US$ 5,000 per voyage (Tanker Company 2018). Piracy insurance premiums for transits through the Gulf of Aden are estimated at 10,500 US$ currently (Tanker Company 2018).

Additional costs for ice class tankers conducting several voyages on the NSR or for the whole summer/autumn season, include ice coating in the hull for additional protection from ice, which is estimated at 75,000 US$ (Tanker Company 2019).

6.3.3 Fuel and commodity prices, and in-transit inventory costs

Residual fuel (HSFO, VLSFO) and distillate fuel (MGO) prices refer to their average values in Singapore and Rotterdam during February 2020[36]. Equally, naphtha and jet fuel/kerosene spot prices refer to February 2020 in Rotterdam and Singapore, respectively. LNG price refers to an average of the spot LNG price in Asia and the Title Transfer Facility (TTF) gas price in the Netherlands in February 2020, including distribution costs. Table 6.4 presents the assumptions on fuel and commodity prices used in the analysis.

Table 6.4. Fuel and commodity prices used in the analysis.*

Fuel/Commodity Price in US$/t	HSFO[a]	VLSFO[a]	MGO[a]	LNG[b]	Naphtha[c]	Jet Fuel/Kerosene[c]
Low	150	240	250	150	228	249
Base Case	300	480	500	250	457	498
High	450	720	750	350	685	747

Source: [a]Clarksons (2021), [b]LNG TTF price (Capital IQ 2021), spot LNG Asia price (Refinitiv Eikon 2021), distribution costs in Asia (SEA LNG 2020), distribution costs in Rotterdam (MAN Energy Solutions 2018; DNV 2021c), [c]OPEC (2021). *Values are rounded to the nearest 10.

Oil-based fuel and commodity price levels at the low and high fuel/commodity price scenarios in the sensitivity analysis are assumed at +/- 50% of those at the base case scenarios, reflecting differences between two distinct periods i.e. average prices during 2011-2014 and average prices during 2015-2017 (Gjølberg and Johnsen 1999; Lindstad and Eskeland 2015; Clarksons 2021; OPEC 2021). LNG fuel prices are assumed at +/- 40% owing to a combination of the

[36] Fuel oil and LNG prices in Rotterdam are considered as proxies since Rotterdam is a major oil hub in the region. The LNG TTF price is used as a proxy for LNG prices in Europe due to the fact that this is the most liquid price benchmark in the region, followed by the UK NBP gas price (Heather 2020).

less responsive Dutch TTF and UK National Balancing Point (NBP) gas prices to oil price movements, and the convergence between spot LNG prices in Asia and crude oil prices during those periods[37]. Yet, LNG spot prices in Asia decoupled from crude oil prices during 2019 (Fulwood 2019), whereas TTF gas and LNG Asian spot prices were coupled with crude oil prices during 2020 (Refinitiv Eikon 2021; Capital IQ 2021; Clarksons; 2021). Figures 5.11 and 5.12 in Chapter 5 show graphically the relationship between fuel oil, crude oil and LNG and natural gas prices. Naphtha prices in Rotterdam, Jet Fuel/Kerosene prices in Singapore, and crude oil prices are illustrated in Figure 6.2.

Sources: OPEC (2021), Clarksons (2021).

Figure 6.2. Monthly Naphtha prices in Rotterdam, monthly Jet Fuel/Kerosene prices in Singapore, and monthly Brent crude oil price between 2011 and 2020.

6.3.4 Transit fees and icebreaking assistance

Suez Canal Tolls depend on the type of ship, routeing direction (northbound, southbound), the Suez Canal Net Tonnage (SCNT) of a ship, its draught and beam, laden or ballast condition, and are determined by the special drawing rights (SDR) exchange rates. The Suez Canal tariff rates and average USD per SDR rates during July-November 2019 are used to calculate the Suez Canal Tolls (IMF 2021a; Leth Agencies 2021a) . Additional costs, such as tugs, mooring, pilotage, and disbursements were calculated by using an online calculator from Leth agencies (Leth Agencies 2021b).

[37] A similar relationship between the Dutch and UK gas price indices and crude oil prices exists, as both TTF and NBP prices are highly correlated (Clarksons 2021; BP 2020).

According to the latest rules of the Northern Sea Route Administration (NSRA), icebreaking assistance depends on the prevailing ice and climatic conditions (Gritsenko and Kiiski 2016). Unescorted voyages may occur when sea ice and climatic conditions are favourable. This is evident in the voyage records of the 2011-2020 summer/autumn navigation seasons (CHNL 2021a). However, there are limited data regarding icebreaking assistance operations in general. Notwithstanding the long-term trend of sea ice decline in the Arctic (Parkinson and Comiso 2013; Lindsay and Schweiger 2015), the high inter-month and inter-annual variability of sea ice conditions (Stephenson et al. 2014) along with insurers' policies may deem icebreaking assistance necessary across all navigation zones (Sarrabezoles et al. 2016; Fedi et al. 2018; Fedi et al. 2020). Thus, icebreaking assistance is assumed for all navigation zones across the NSR at the base case scenario. Icebreaking fees depend on the ice class of a ship, gross tonnage, number of escorting zones and period of navigation (summer/autumn: July-November, winter/spring: December-June), and are determined by the US Dollar – Russian Rouble (USD/RUB) currency exchange rates (NSRA 2014; Bank of Russia 2021). The NSRA icebreaking fees and Suez Canal Tolls are presented in Table 6.5. Appendix P presents the assumptions and calculations for transit fees.

Table 6.5. NSRA icebreaking fees and Suez Canal Tolls for LR2 tankers.

Transit Fees in USD	Low USD/RUB rate	Base Case USD/RUB rate	High USD/RUB rate	Discounted rate (US$/t)
USD/RUB Rate	33.28	64.41	64.41	5
NSRA Tariff Rate	446.8	446.8	446.8	446.8
NSR Fees	849238	438,793	438,793	400,000
SCR Fees (Southbound)	320,957	320,957	320,957	320,957
SCR Fees (Northbound)	321,539	321,539	321,539	321,539

Sources: Calculations based on Appendix P.

The USD/RUB exchange rate is assumed to be high at low crude oil prices and vice versa, indicating an inverse relationship between them (Beckmann and Czudaj 2013; Yang et al. 2017; Shibasaki et al. 2018; Chuffart and Hooper 2019). More specifically, a rate of 33.28 is assumed at high fuel/commodity prices, reflecting market conditions between 2011 and 2014, and a rate of 64.41 at both the base case and high fuel/commodity prices reflecting market conditions before 2020 i.e. 2015-2019 (Bank of Russia 2021)[38]. Figures 5.13 and 5.14 in

[38] This modelling case was developed in December 2019, where a USD/RUB rate of 64.41 had still been the highest since 2015. Thus, both the base case and high USD/RUB rates reflect the same period and value. The

Chapter 5 illustrate the inverse relationship between USD/RUB exchange rates and Brent crude oil and fuel oil prices.

Discounted fees are included in the sensitivity analysis, reflecting the practice of negotiated icebreaking fees, that is, 5 US$/t of cargo for laden voyages (Falck 2012; Gritsenko and Kiiski 2016; Moe and Brigham 2016; Tanker Company 2018). Independent navigation i.e. operating within NSR without icebreaking assistance is also considered in the sensitivity analysis with the speed on ice assumed to vary as in other scenarios, albeit with a minimum constraint of 5 knots (MAN Diesel and Turbo 2013b; Trafi 2017a; Solakivi et al. 2018).

6.3.5 Speed through ice on the NSR and seasonal navigation planning

Ice thickness and concentration, ridges, ice floes, icebergs, and other physical factors largely influence the operational environment on the NSR (Löptien and Axell 2014; Aksenov et al. 2017). Consequently, ship speed on ice can vary across the NSR depending on the season, month, navigation zone, local sea ice conditions and the ice class of a ship (Stephenson et al. 2014; Faury and Cariou 2016; Faury, Cheaitou et al. 2020; Cheaitou et al. 2020; Cariou et al. 2021). AIS data were obtained from the Bloomberg ship tracking platform to determine ship speed on ice across the NSR, given that speed optimisation with respect to cost and market factors may not be feasible when operating through ice in the Arctic. Ship speed data of 44 NSR tanker voyages conducted during the 2011-2019 summer/autumn seasons were retrieved, with tanker sizes ranging from MR (47,000 dwt) to Suezmax/LR3 (162,000 dwt). The data comprise 29,964 observations of tanker speeds recorded per minute for every transit between Cape Zhelanya/Kara Strait and Cape Dezhnev from end of June (30th) to mid-November (17th). The average speeds in every Sea per month are calculated by dividing the travelled distances by the time interval between the start and end points of each segment. The speed statistics are included in Appendix Y1, whilst the start and end points of the AIS data for each Sea/Zone are reported in Appendix Y2.

The statistics reported per month and across all Seas show that tanker speeds ranged from a minimum of 2 knots to a maximum of 16.9 knots. This highlights the uncertainty of operating across the NSR during the summer/autumn season. Whilst most of the times the mean speed was between 10 knots and 11.8 knots for a certain zone across every month, with higher speeds (10.9-13.2 knots) reported mostly in September, the standard deviation values indicate a high

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modelling case in Chapter 5 was developed in summer 2020, hence the assumption of a USD/RUB rate of 73.7, drawing from market developments during March-May 2020.

variability. The highest variability is found at the East Siberian Sea (East and West), where almost every month is subject to large departures from mean speeds. These mean speeds were amongst the lowest across every month compared to the other navigation zones.

The East Laptev Sea and Chukchi Sea have the highest variability in July, whereas speeds at Kara Sea are variable every month with standard deviation values between 2.3 (September) and 3.2 (July). Speeds at the West Laptev Sea are found the least variable, with August and October having the largest departures from the mean speed. Another important observation is the very low speeds, below 5 knots, at the East Siberian Sea (East) during July and August, and at the East Siberian Sea (West) and Chukchi Seas during July, respectively, which shows that voyages at the opening of the navigation season still face severe ice conditions. Yet, the East Siberian Sea (West) and East Kara Sea exhibit minimum speeds below 5 knots during October. The lowest variability in tanker speeds across every zone is found in September most of the times, the month which typically has the minimum sea ice extent every year and the navigation season is the longest (Stephenson et al. 2014; NSIDC 2021). The real speed data analysis is in line with Stephenson et al. (2014), who found that the Laptev, East Siberian, and East Kara Seas exhibit inter-annual variability and uneven distribution of sea ice conditions in the medium-term.

Figures 6.3, 6.4, 6.5, 6.6., and 6.7 show average transit time and speed for each month and Sea, and for a whole season, which were calculated based on Equations (17) and (18) provided in Section '6.2.1 Modelling approach', and using the mean speeds reported in Appendix Y1. The calculated speeds and transit times are presented in Appendix Y3. The distances for each Sea are: East Kara Sea: 468 n.m., West Laptev Sea: 265.5 n.m., East Laptev Sea: 265.5 n.m., East Siberian Sea (West): 345 n.m., East Siberian Sea (East): 345 n.m., Chukchi Sea: 370 n.m. (Mulherin 1996; Dataloy 2021). It should be noted that owing to the very low number of speed observations for November (n = 87) , speeds for this month are assumed to be at least equal to those of October, although in reality speeds in November might be lower (Mulherin 1996; Wergeland 1991; Faury and Cariou 2016). The entry/exit point of the NSR from the west is Cape Zhelanya, and therefore only the distance of East Kara Sea (between Cape Zhelanya and Vilkitsky Strait) is included in the analysis and not that of West Kara Sea.

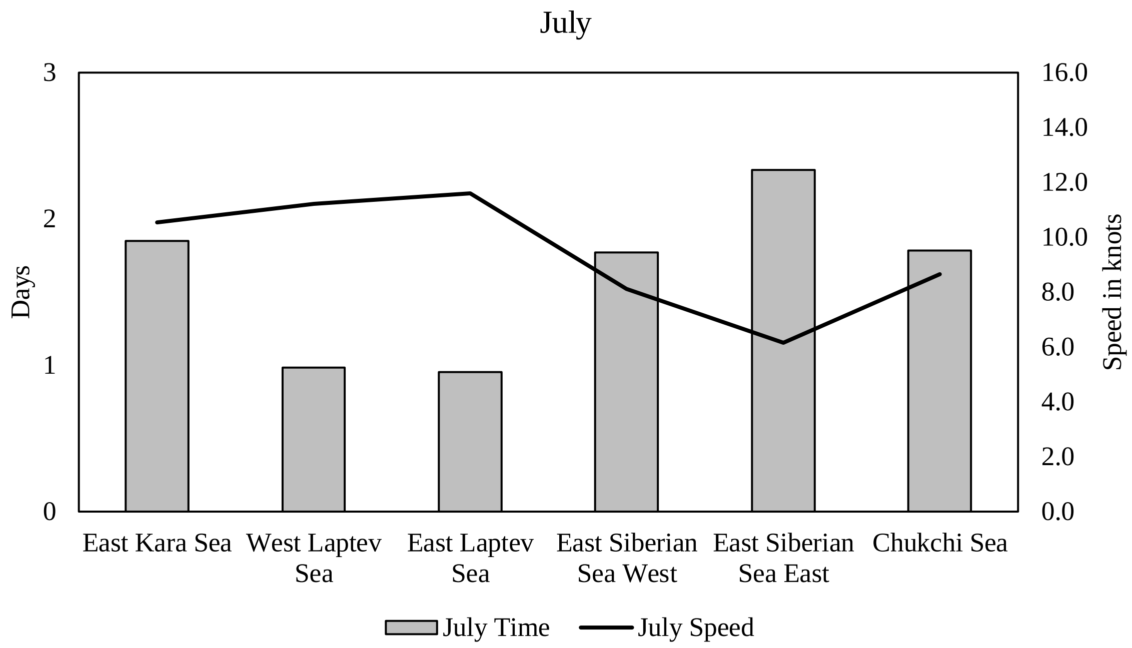


Figure 6.3. Speed and time on the NSR during July.

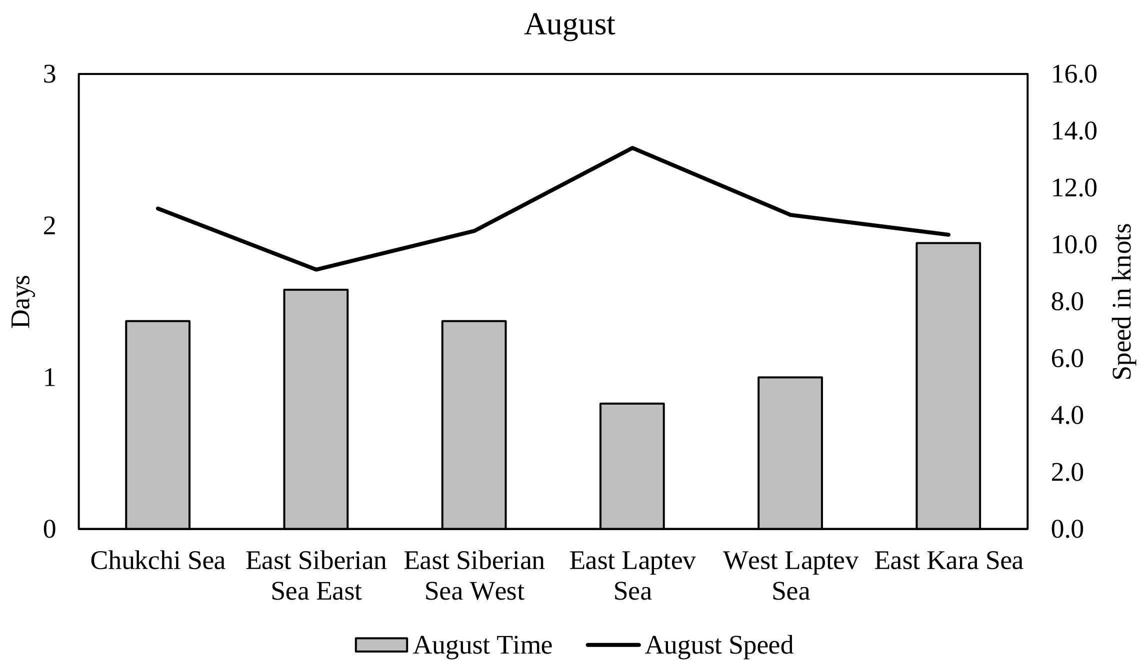


Figure 6.4. Speed and time on the NSR during August.

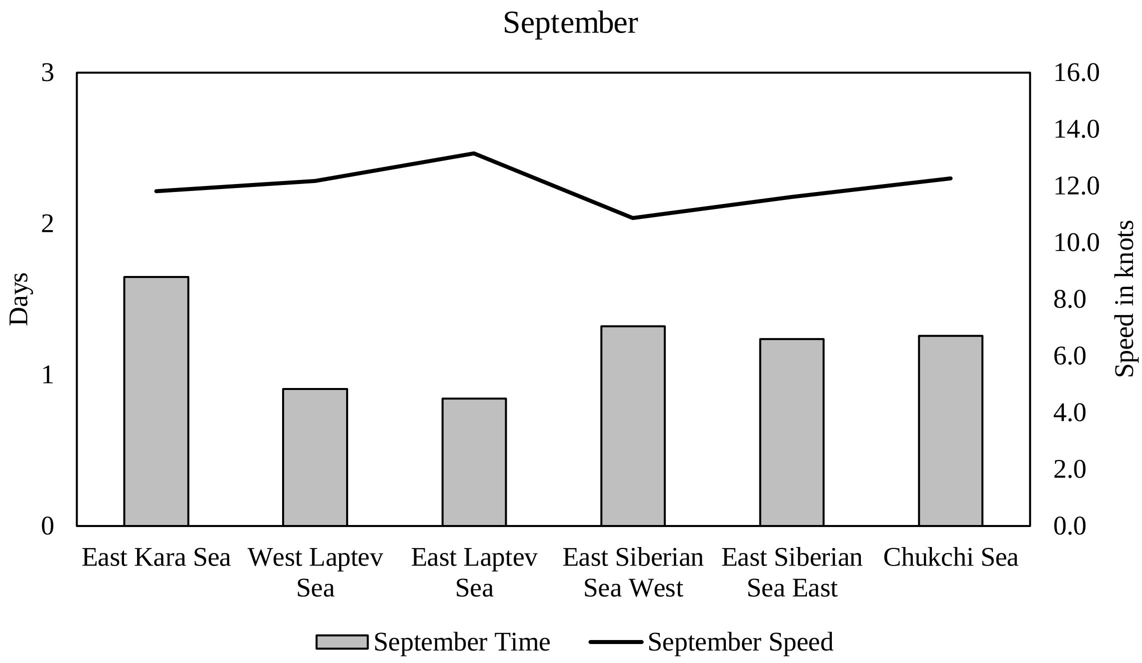


Figure 6.5. Speed and time on the NSR during September.

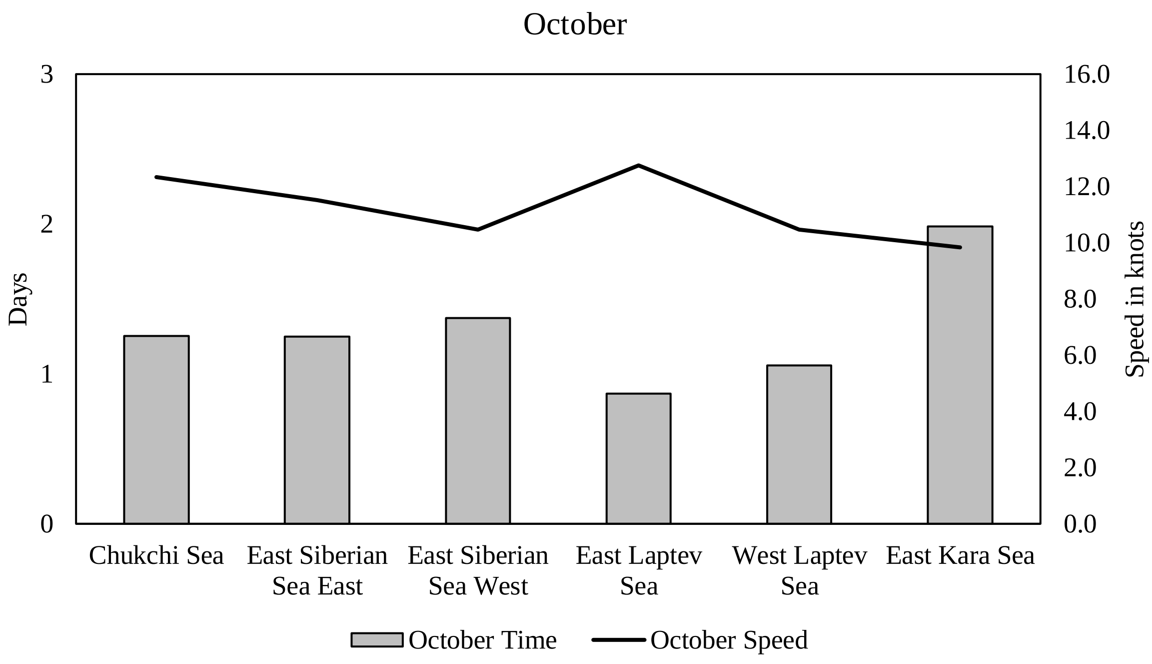


Figure 6.6. Speed and time on the NSR during October.

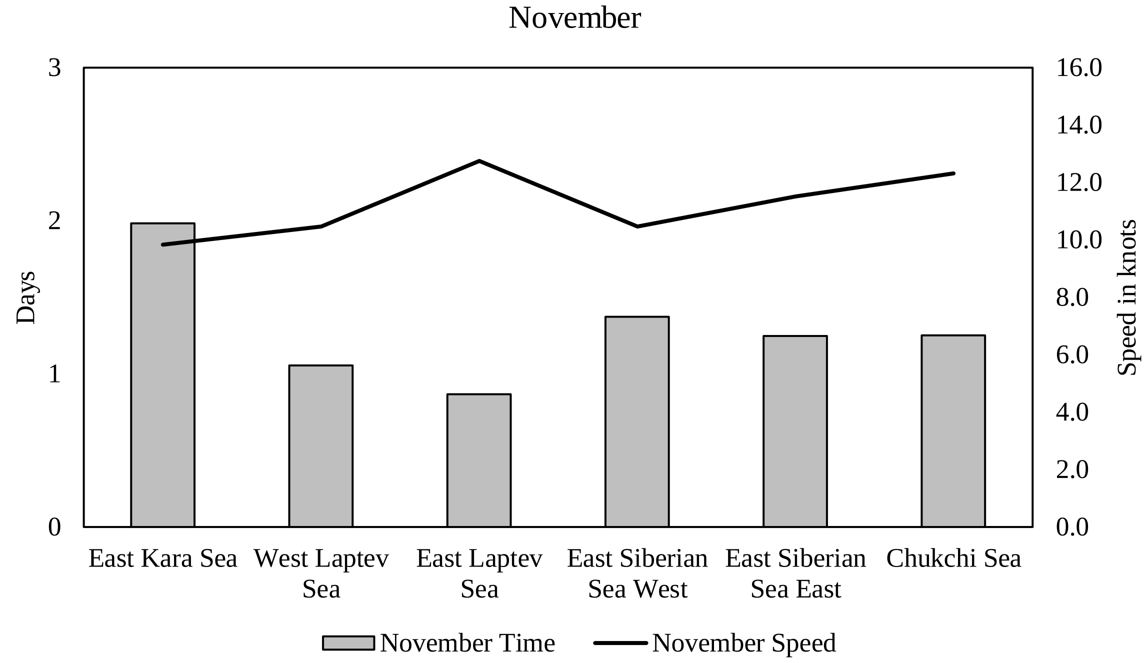
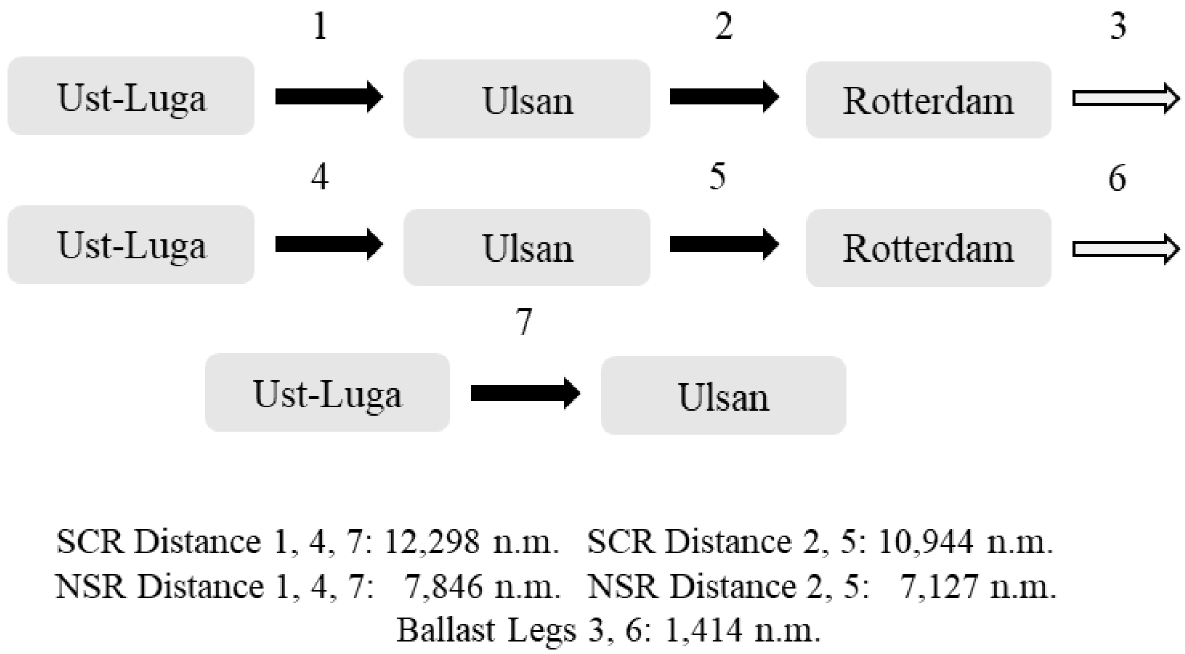


Figure 6.7. Speed and time on the NSR during November.

The planning for seasonal navigation of consecutive round voyages between Northwest Europe or the Baltic and Northeast Asia is based on the following voyage pattern either for the SCR or NSR: a LR2 tanker departs on 1st July from the port of Ust-Luga for its first voyage, loaded with a naphtha cargo, to the port of Ulsan. Then, it is loaded with a cargo of jet fuel/kerosene at the port of Ulsan for the return (second) voyage to the port of Rotterdam. The third voyage is a ballast one from the port of Rotterdam to the port of Ust-Luga in order to load a naphtha cargo and perform the fourth voyage to the port of Ulsan, where the cargo is discharged. The LR2 tanker loads a cargo of jet fuel/kerosene at the port of Ulsan to unload it at the port of Rotterdam (fifth voyage). Finally, the tanker leaves the port of Rotterdam, in ballast (sixth voyage), to load a cargo of naphtha at the port of Ust-Luga for its seventh voyage to the port of Ulsan. Figure 6.8 shows the voyage itineraries and distances for the respective voyage legs. Seasonal round voyages via the NSR adhere to the period between early July and end-November (Figures 6.3 to 6.7 show time and speed within NSR, based on the direction of voyage per month as described above), which means that the tanker does not operate through ice beyond the end of November. Two days in port are assumed for either loading or unloading operations, and one day for a Suez Canal transit when the SCR is used (Clarksons 2021).



Source: Dataloy (2021). The distance through NSR is assumed 2,059 n.m. and refers to the deep-water high-latitude route north of the New Siberian Islands, based on the majority of historic NSR voyages between 2011 and 2019 (Bloomberg 2021).

Figure 6.8. Voyage itineraries and OD pair distances.

6.4 Analysis

Table 6.6 reports the results for voyage SCR-NSR RFR differentials. The number of voyages conducted via the NSR depend on several factors. First, the OD pair distance is important, along with sea ice conditions, which affect ship speed and transit time through ice on the NSR. Second, the prices of different fuels along with technology-related fixed costs influence the optimal ship speed which minimises the NSR RFR, and therefore the transit time outside the NSR. Moreover, port time, canal time, and potential delays also affect seasonal operations.

The choice of VLSFO, including MGO within ECAs, gives the highest SCR-NSR RFR differentials across all voyages, whereas the choice of HSFO-Scrubber gives the lowest RFR differentials. The RFR differentials under the LNG-VLSFO mode are found in between those on the other two modes. This is the result of the combination of a low priced fuel (LNG) with a high priced fuel (VLSFO). Ballast voyages between the port of Rotterdam and the port of Ust-Luga give a negative RFR differential. This is due to the higher fuel consumption of an ice class tanker on open water and, to a lesser extent, of the higher capital and operating costs than those of an ordinary tanker. The highest SCR-NSR RFR differential across all fuel types is found on the 4th voyage of the Ust-Luga - Ulsan pair, owing to higher distance savings than on the Ulsan - Rotterdam pair voyages, as well as to the highest speed achieved through ice in that month, i.e. September, compared to the other voyages.

Table 6.6. Voyage and seasonal SCR-NSR RFR Differential in US$ per tonne.

OD pair	Fuel Type		
	HSFO-Scrubber*	VLSFO*	LNG-VLSFO
1. Ust-Luga - Ulsan	0.82 (0.59)	1.787 (1.784)	1.73
2. Ulsan - Rotterdam	0.75 (0.42)	1.514 (1.510)	1.47
3. Rotterdam - Ust-Luga	-0.36	-0.422	-0.31
4. Ust-Luga - Ulsan	1.62 (1.21)	2.378 (2.372)	2.37
5. Ulsan - Rotterdam	0.83 (0.47)	1.568 (1.563)	1.53
6. Rotterdam - Ust-Luga	-0.36	-0.422	-0.31
7. Ust-Luga - Ulsan	1.46 (1.11)	2.286 (2.281)	2.27
Seasonal Differential	0.95 (0.61)	1.738 (1.733)	1.75
Seasonal Differential incl. ice coating	0.76 (0.43)	1.550 (1.546)	1.56

*Differentials in parentheses refer to results when MGO is used through ice on NSR.

Moreover, the use of multiple fuels has further implications for route competitiveness. The LNG/VLSFO distance ratio varies for both NSR and SCR against a given OD pair. This ratio depends on the overall distance savings when comparing the two routes against a certain OD pair. It also depends on the LNG fuel consumption through ice, which in turn depends on speed, and ultimately on the month and prevailing sea ice conditions. The NSR LNG/VLSFO distance ratio is found 91/9, 85/15, and 87/13, for the 1st, 4th, and 7th voyages, respectively, on the Ust-Luga - Ulsan pair, whereas it is found 96/4, for the 2nd and 5th voyages, respectively, on the Ulsan - Rotterdam pair. The SCR LNG/VLSFO distance ratio is found 63/37, for the 1st, 4th, and 7th voyages, respectively, on the Ust-Luga - Ulsan pair, whereas it is found 71/29 for the 2nd and 5th voyages, respectively, on the Ulsan - Rotterdam pair.

This shows that the shorter NSR is benefitted from the use of the low-priced LNG fuel compared to SCR. More specifically, LNG is used for longer distance legs against a certain OD pair on NSR than on SCR. Moreover, it demonstrates that given the constraint of LNG tank capacity, the use of a low-priced fuel on the NSR, depending on LNG use and OD pair distances, can offer a higher RFR differential than a high-priced fuel (here HSFO), which is used on the entire length of an OD pair against both routes. Appendices W1 and W2 present a distance breakdown per operational mode and LNG/VLSFO distance ratios for each OD pair and route alternative.

The use of MGO within NSR, under the assumption that the use of heavy fuel oils in the Arctic will be prohibited in the future, even with the use of scrubbers, affect the SCR-NSR RFR differential mostly under the HSFO-Scrubber mode. This is due to the price difference of 200 US$/t assumed between HSFO and MGO at the base case scenario. The impact on the VLSFO mode is almost negligible, owing to a price difference of 20 US$/t between HSFO and MGO, which results in a slightly decreased RFR differential at both OD pairs.

Table 6.6 also presents results for the seasonal SCR-NSR RFR differentials with and without ice coating. The RFR differentials for the whole summer/autumn navigation season largely reflect the impact that alternative fuels have on the economics of individual voyages. Yet, LNG-VLSFO is slightly more competitive than VLSFO for seasonal operations on the NSR. This is the result of using only the cheaper LNG fuel on the ballast voyages between the ports of Rotterdam and Ust-Luga. On the other hand, only VLSFO is used on ballast voyages under the VLSFO mode. The factoring of ice coating in the analysis, which allows an ice class tanker to undertake consecutive voyages through ice for a whole season, increases the NSR RFR by 0.2 US$/t across all operational modes.

The RFR differential analysis per voyage is complemented by Figure 6.9, which illustrates ship speed on ice, optimal ship speed for a whole voyage, and time per transit and month. The calculated speeds and days per fuel type/mode, route and OD pair are presented in Appendix Y4. The calculated dates for seasonal operations between July and November on both routes are presented in Appendix Y5.

The variation in SCR-NSR RFR differentials against an OD pair at different transits/months can be explained by monthly sea ice conditions per navigation zone and direction of transit (eastbound/westbound). These factors affect the speed on ice, and therefore the optimal ship speed, transit time and ultimately the minimum NSR RFR. The seasonal navigation allows three transits on the Ust-Luga - Ulsan pair, that is, in July, September, and November. July is found the most challenging month with a ship speed on ice of 8.9 knots, giving the lowest SCR-NSR RFR differentials under fuel prices as of February 2020. September is found the most favourable month with a ship speed on ice of 11.9 knots, giving the highest RFR differentials under fuel prices as of February 2020. The seasonal navigation allows two transits on the Ulsan - Rotterdam pair, that is, in August and October. Ship speed through ice in August is found the second lowest after July, at 10.7 knots. Ship speed through ice in October is found 11 knots, which slightly increases the RFR differentials compared to August voyages under fuel prices as of February 2020.

A lower speed on ice means a lower average speed for a whole voyage at a given month. Thus, the longer the time spent within ice, the longer the overall voyage transit time. Consequently, the minimum NSR RFR at a given transit gets higher when the speed on ice decreases, and vice versa. The lowest minimum NSR RFR on the Ust-Luga - Ulsan pair is achieved in September, where the SCR-NSR RFR differential is also the highest across all transits and fuel types/modes, and the difference between the speed on ice and optimal speed on open water is found 2.5 / 1.0 / 2.4 knots compared to 4.1 / 2.9 / 4.2 knots in July and 3.0 / 1.5 / 3.0 knots in November at HSFO-Scrubber / VLSFO / LNG-VLSFO modes, respectively. Equally, the lowest minimum NSR RFR on the Ulsan - Rotterdam pair is achieved in October, where the SCR-NSR RFR differential is the highest across all transits and fuel types/modes, and the difference between the speed on ice and optimal speed on open water is found 2.9 / 1.6 / 3.0 knots compared to 3.1 / 1.8 / 3.2 knots in August at HSFO-Scrubber / VLSFO / LNG-VLSFO modes, respectively.

Figure 6.10 shows voyage transit times and optimal speeds for all fuel types. Whilst voyage times for a certain OD pair on the SCR are the same across every fuel type, voyage times vary on the NSR owing to different sea ice regimes and the speeds realised through ice. The least time savings are found during July, August, and October voyages, whereas the highest time savings are found during September and November voyages across every fuel type/mode. The transit times for NSR ballast voyages between the ports of Rotterdam and Ust-Luga (3rd and 6th voyages) are found slightly higher than those on SCR due to the lower optimal speeds of ice class tankers on open water.

The use of the expensive VLSFO results in lower optimal speeds, and as a consequence in longer transit times on both routes. Conversely, the use of the cheap HSFO under the HSFO-Scrubber mode results in higher optimal speeds and shorter transit times on both routes. This means that the use of the shorter NSR gives the greatest time savings under VLSFO, and the least time savings under HSFO-Scrubber, all else being equal. Transit times on both routes under the LNG-VLSFO mode are found in between those under the VLSFO and HSFO-Scrubber modes due to the combination of a low priced fuel (LNG) with a high priced fuel (VLSFO).

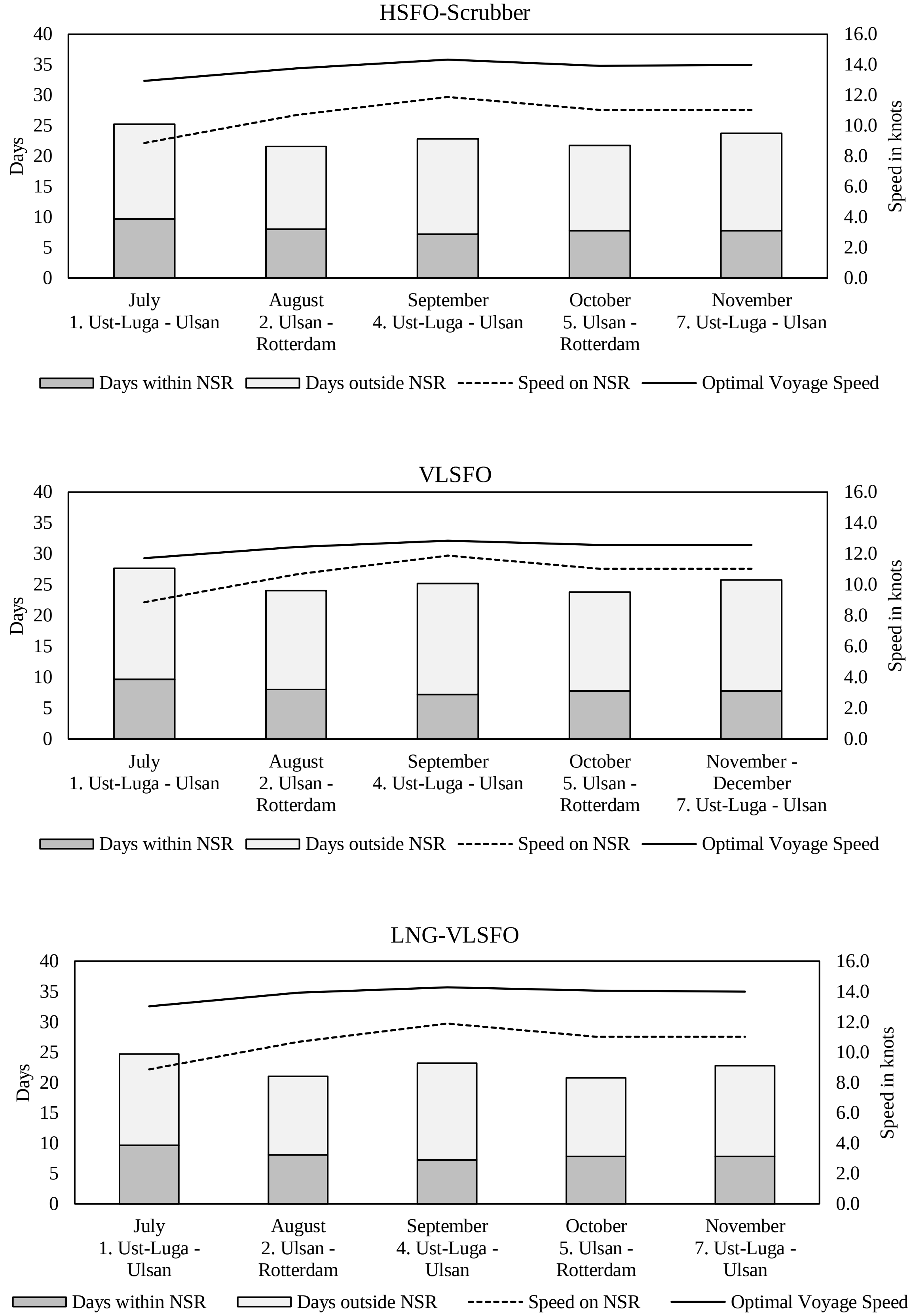


Figure 6.9. Speed – time relationship within and outside NSR across all laden voyages.

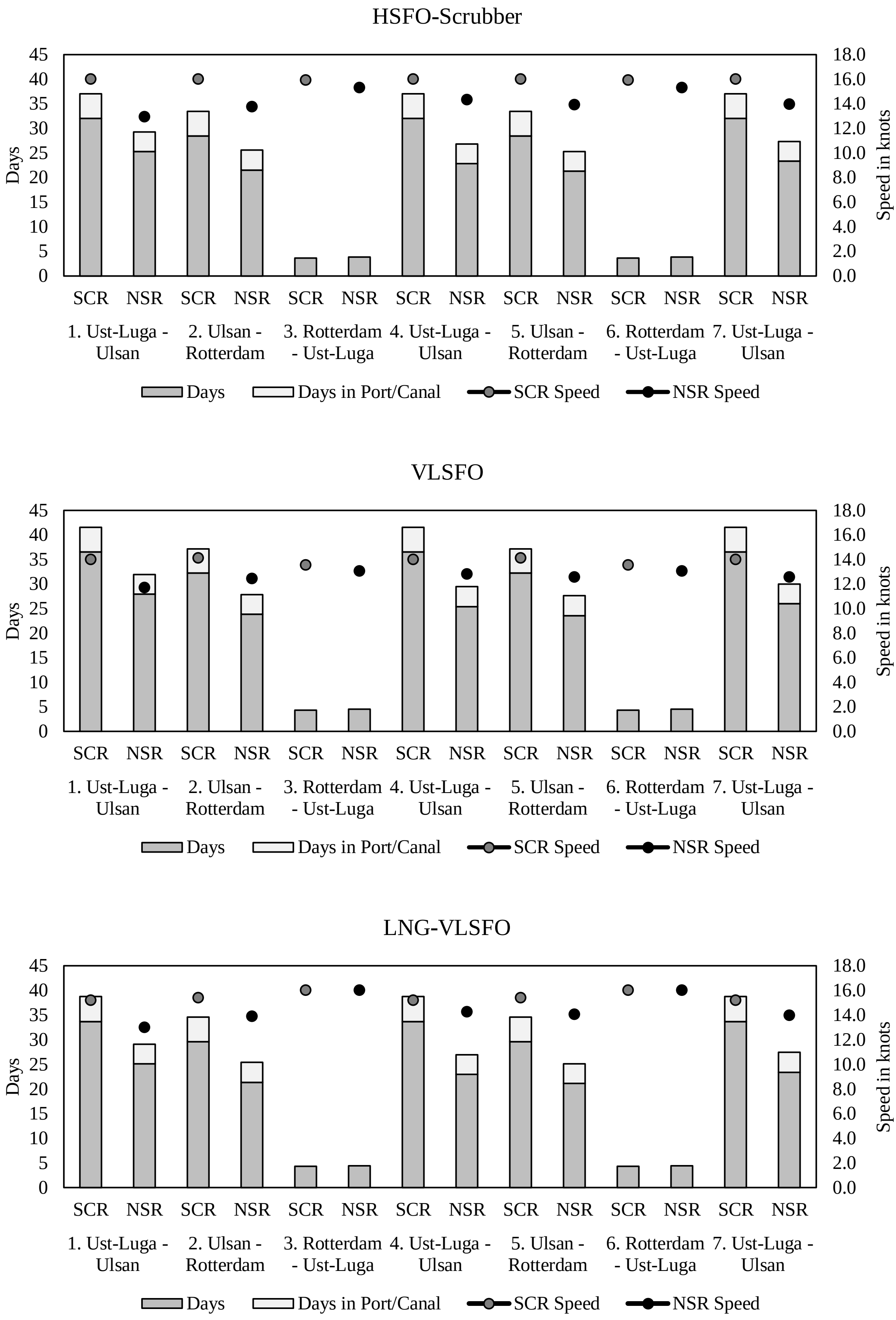


Figure 6.10. Voyage and seasonal time & speed analysis.

Figure 6.11 graphically illustrates the relationship between optimal ship speed and minimum RFR for both route alternatives across all fuel types using voyages 4 (Ust-Luga - Ulsan pair in September) and 5 (Rotterdam-Ulsan pair in October) as examples. The top two graph curves depict the optimal speed - minimum RFR relationship for the HSFO-Scrubber mode, with black dashed curves showing the minimum SCR RFR and grey dashed curves the minimum NSR RFR. The higher SCR RFR on the Ust-Luga - Ulsan pair is the result of a longer distance than that on the Ulsan - Rotterdam pair, even after considering the higher in-transit inventory costs of jet fuel cargo on the latter. Equally, the lower NSR RFR on the Ulsan - Rotterdam pair is the result of a shorter distance than that on the Ust-Luga - Ulsan pair, even with a lower speed through on ice than on voyage 4 (Ust-Luga - Ulsan pair), which results in increased costs and voyage time. Similar observations can be made for the VLSFO and LNG-VLSFO modes, which are depicted in the middle and bottom graph curves, respectively. The lowest RFR for both route alternatives are found under the LNG-VLSFO mode, followed by HSFO-Scrubber and VLSFO modes. Optimal voyage speeds and numerical results are presented in Appendix Z.

Higher in-transit inventory costs due to a more expensive price of jet fuel cargo compared to that of naphtha cargo result in higher optimal speeds for SCR on the Ulsan - Rotterdam pair across all fuel types. Yet, a lower speed through ice offsets the impact of higher in-transit inventory costs for jet fuel cargo, and result in lower optimal speeds for NSR on the Ulsan - Rotterdam pair across all fuel types.

The use of MGO within NSR, under the assumption that the use of heavy fuel oils in the Arctic will be prohibited in the future, is reflected in the dotted RFR curves at the top and middle graphs. The NSR RFR is increased by 0.41 US$/t and 0.35 US$/t for voyages 4 and 5, respectively, under the HSFO-Scrubber option, whereas the NSR RFR remain virtually the same under the VLSFO mode due to a narrow difference between the price of VLSFO and MGO fuels. It should be noted that the use of MGO within NSR does not affect optimal speeds, either under HSFO-Scrubber or VLSFO modes, since ship speed on ice is determined by monthly sea ice conditions and not necessarily by cost and market factors.

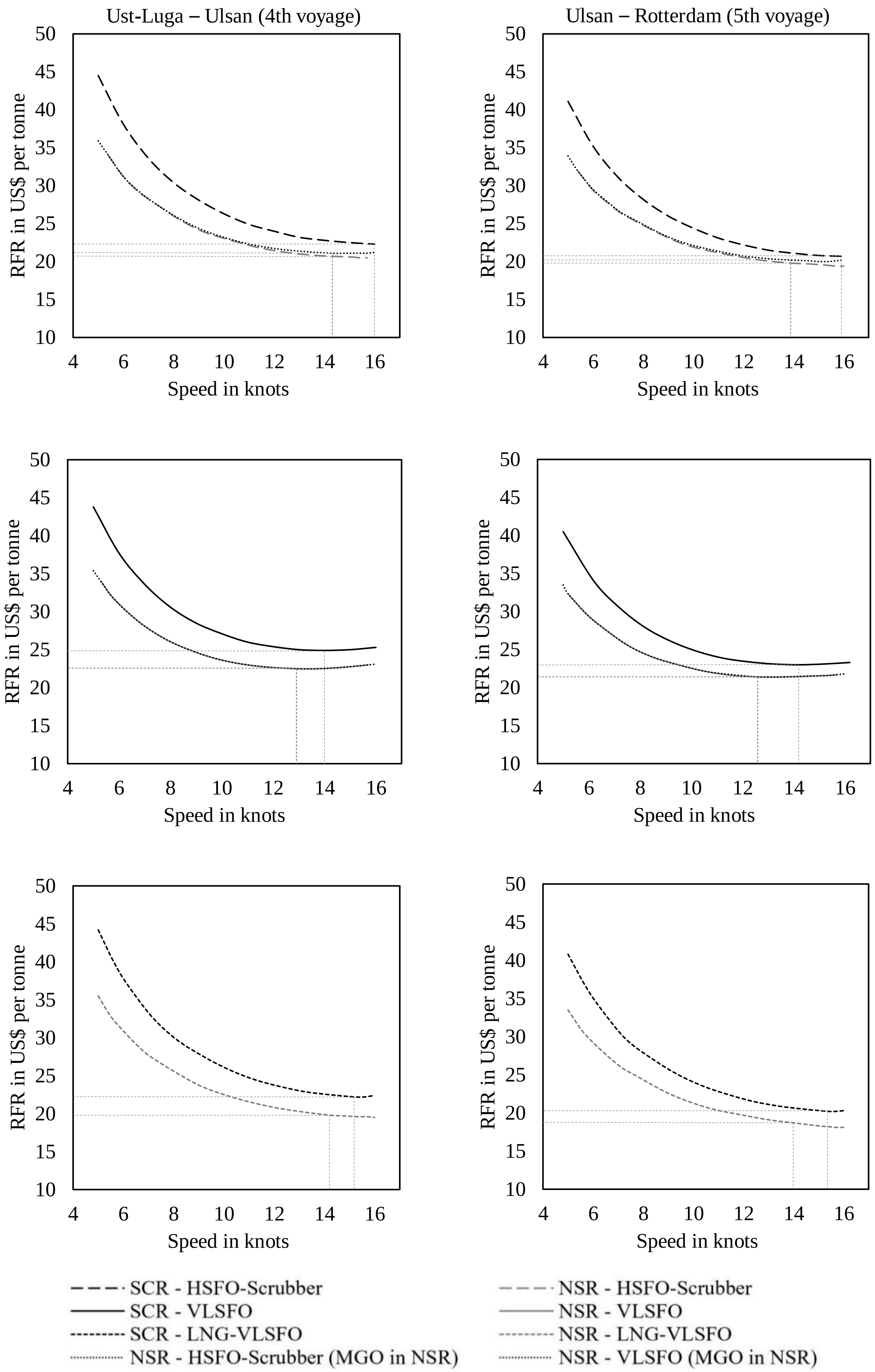


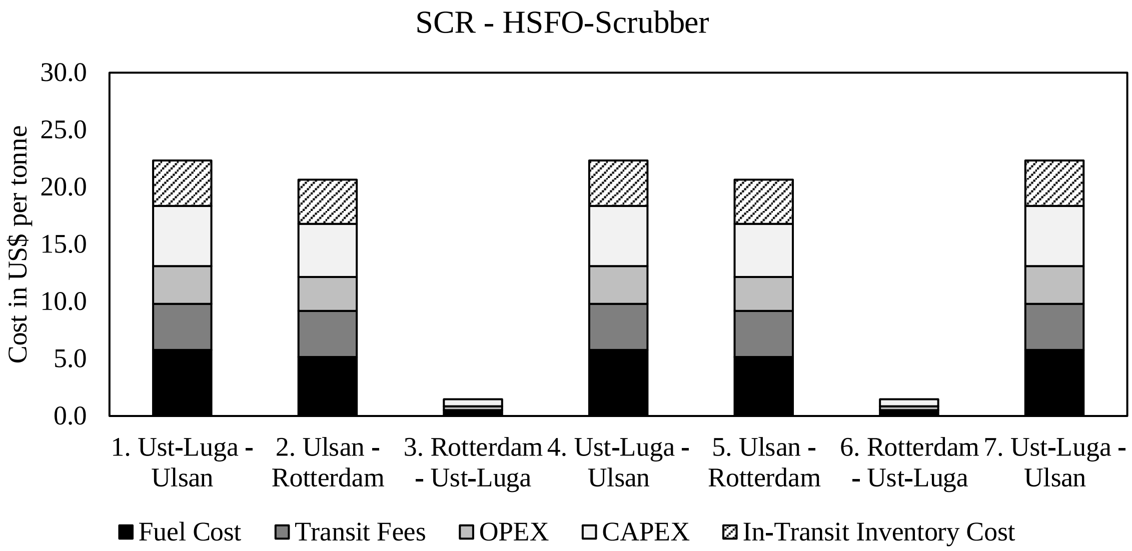
Figure 6.11. Relationship between optimal speed and minimum RFR across all fuel types.

Figures 6.12, 6.13, and 6.14 illustrate a breakdown of fixed and variable costs for all voyages across all fuel types/modes. A numerical cost and time breakdown and results of the analysis are presented in Appendix Z.

Fuel and capital costs are the primary cost factors on the SCR route across all voyages and fuel types, followed by transit fees, in-transit inventory, and operating costs. In-transit inventory costs become more important on the VLSFO and LNG-VLSFO modes (third cost factor after fuel and capital costs) due to longer transit times than at the HSFO-Scrubber mode, whereas fuel costs come second under the LNG-VLSFO mode.

When it comes to the NSR, icebreaking fees are the most important cost factor across all fuel types. Capital costs are the second cost factor across all fuel types, followed by fuel, operating and in-transit inventory costs under HSFO-Scrubber and VLSFO modes. On the other hand, operating and in-transit inventory costs are the third and fourth factors, respectively, followed by fuel costs, under the LNG-VLSFO mode, except for the 4th and 7th voyages where fuel costs are higher than in-transit inventory costs owing to higher speeds through ice. As regards ballast voyages, capital costs come first across all fuel types, followed by fuel and operating costs for HSFO-Scrubber and VLSFO modes, whereas fuel costs come third after operating costs under the LNG-VLSFO mode.

Figure 6.15 shows cost factors in US$/t for the summer/autumn navigation season. The seasonal cost breakdown largely confirms the results of the individual voyage cost breakdown.



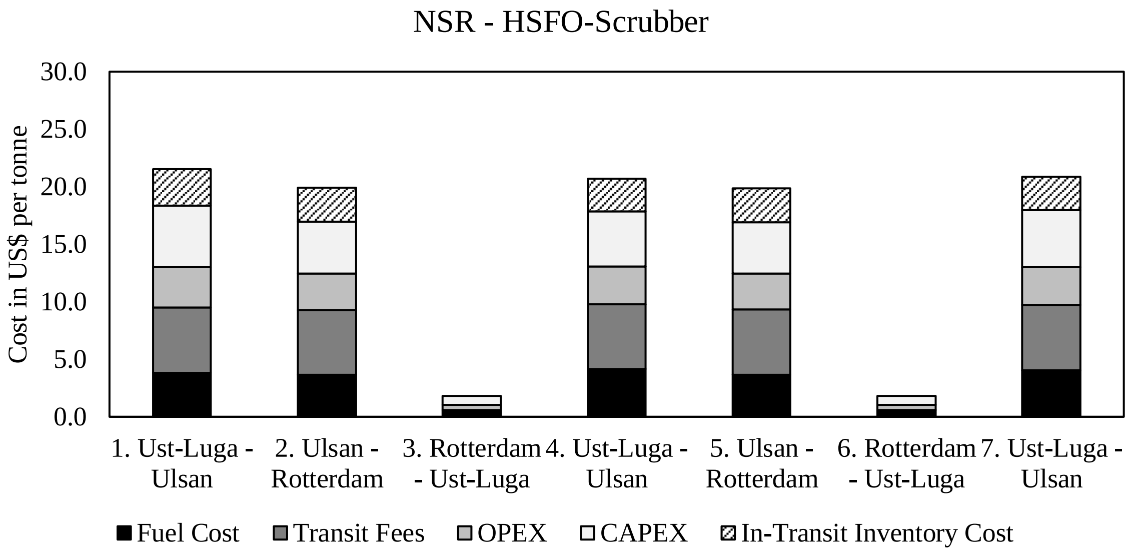
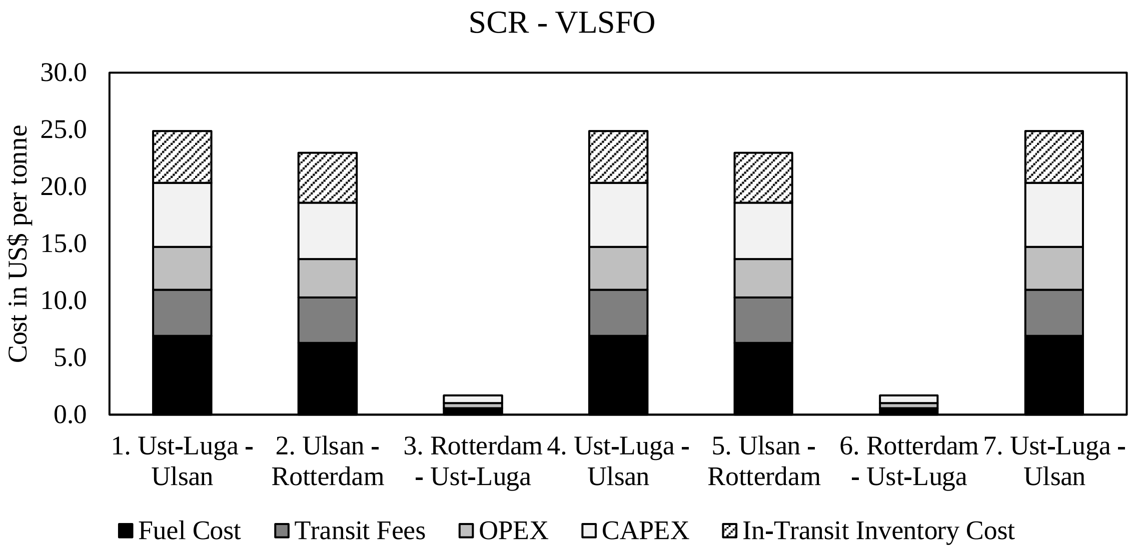


Figure 6.12. Voyage cost analysis for HSFO-Scrubber mode.



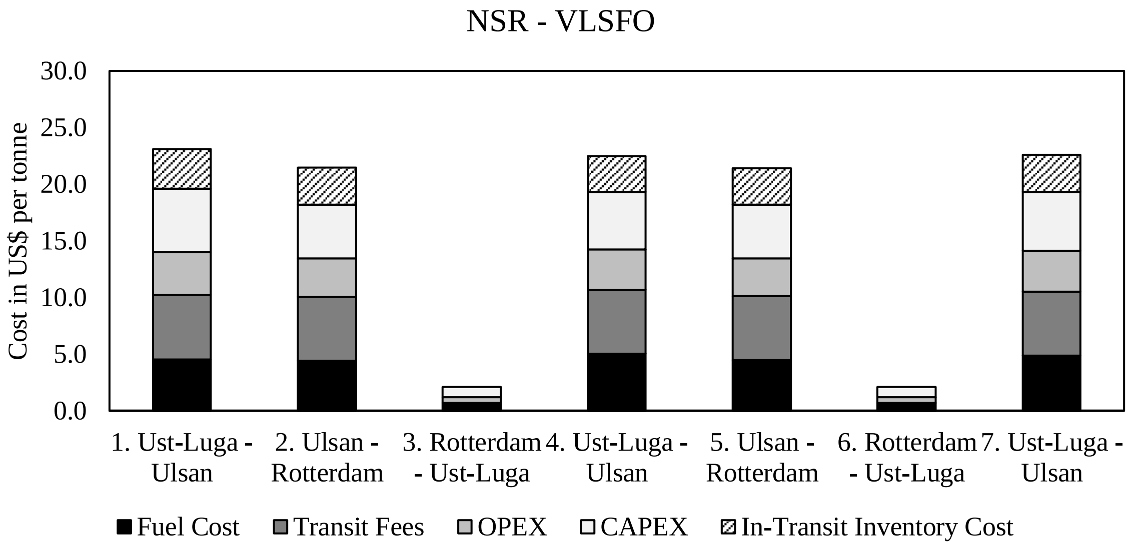
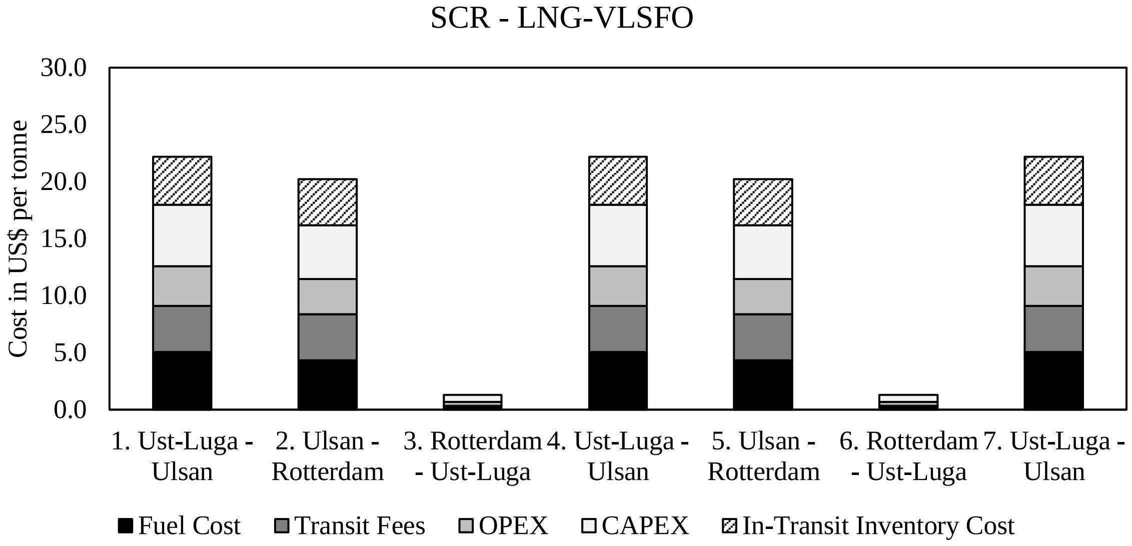


Figure 6.13. Voyage cost analysis for VLSFO mode.



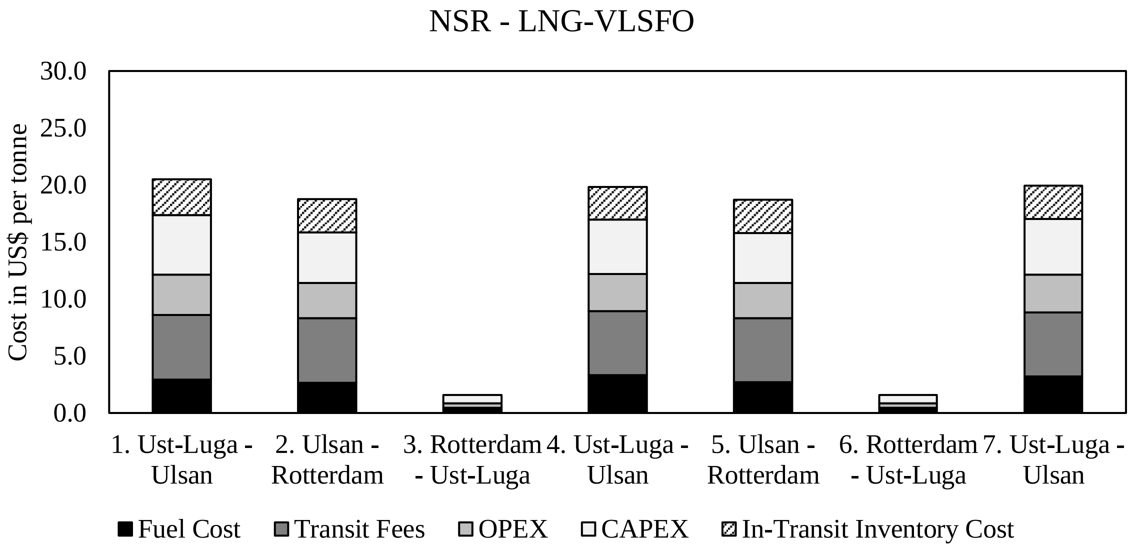
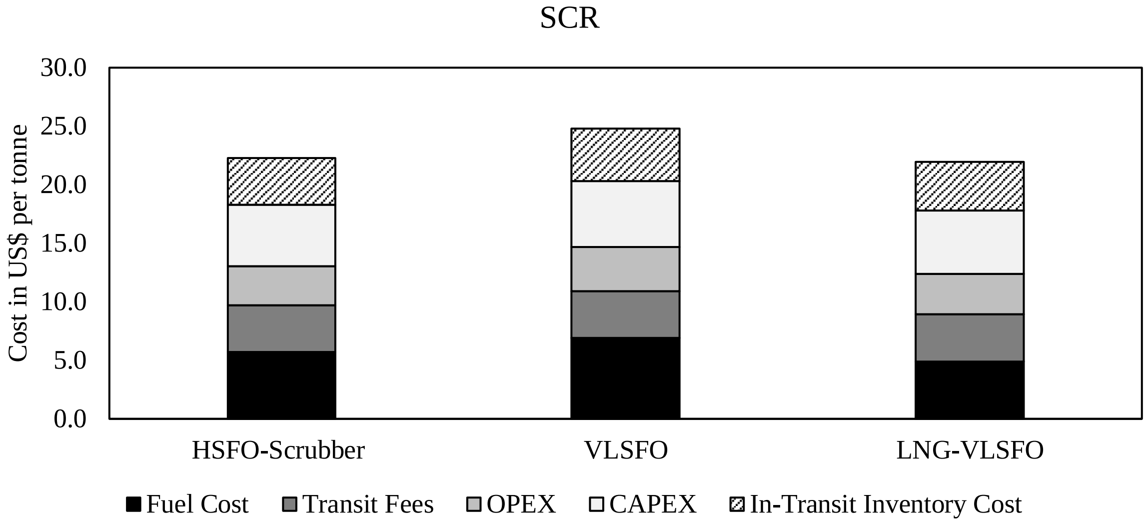


Figure 6.14. Voyage cost analysis for LNG-VLSFO mode.



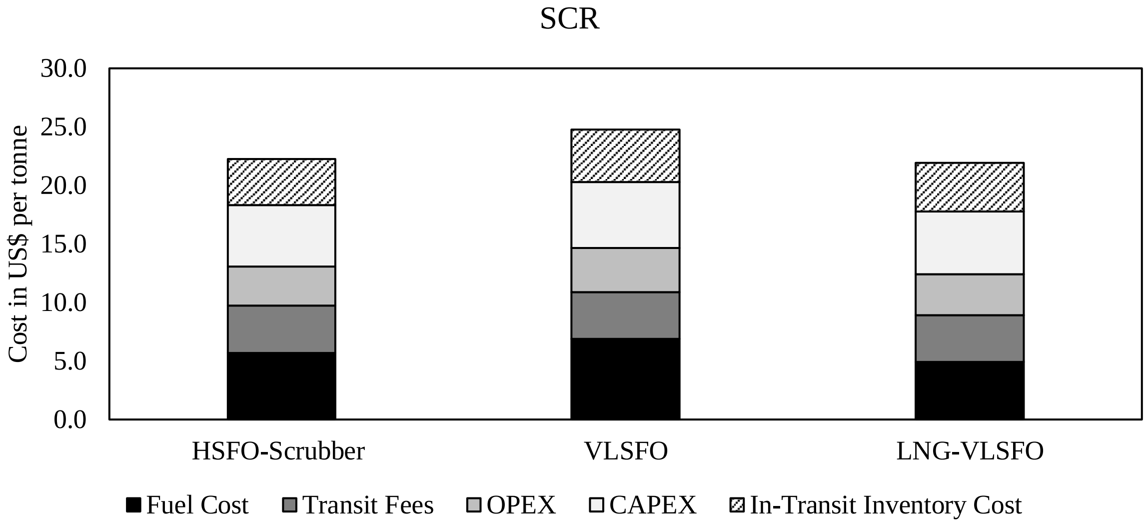


Figure 6.15. Seasonal cost analysis.

6.5 Sensitivity Analysis

A sensitivity analysis is conducted to control for important cost and navigational factors, such as fuel and commodity prices, icebreaking fees, USD/RUB exchange rates, transit times, and speed on ice when operating without icebreaking assistance.

Tables 6.7, 6.8, 6.9, and 6.10 include the assumptions for all scenarios along with sensitivity analysis results of voyage time, seasonal time, and SCR-NSR RFR differentials. It can be seen that the NSR is not competitive when assuming official icebreaking fees at high fuel and commodity prices across all fuel types, whilst it is found competitive for certain voyages at low fuel prices across all fuel types. The competitiveness at low fuel prices depends on actual fuel prices per fuel type, the LNG/VLSFO distance ratio on NSR and, to a lesser extent, speed on ice for certain voyages. A low USD/RUB exchange rate means that the NSR is even less competitive at high than at low fuel and commodity prices. High fuel/commodity prices influence the competitiveness of the NSR at discounted fees and independent navigation scenarios, especially under the VLSFO mode. The NSR is always competitive when assuming independent navigation under all operational modes and even at low fuel and commodity prices. The SCR-NSR RFR differentials for ballast voyages against the same OD pairs are the exception. More specifically, higher fuel consumption and fixed costs for an ice class tanker result in negative RFR differentials, regardless of fuel and commodity price movements.

It can be seen that the use of MGO through ice on NSR by oil-powered tankers reduces the competitiveness of the NSR compared to SCR on the HSFO-Scrubber mode, especially when moving towards high fuel/commodity prices. This is the result of wide HSFO-MGO price differentials i.e. between 100 US$/t (low prices) and 300 US$/t (high prices) assumed in the analysis. The difference is negligible on the VLSFO mode, where the VLSFO-MGO price differential ranges between 10 US$/t (low prices) and 30 US$ (high prices), based on prices as of February 2020 as a reference.

The results for seasonal operations largely reflect those of individual voyages, especially the influence of a low USD/RUB exchange rate at high fuel/commodity prices (Table 6.10). The NSR is primarily competitive at the base case scenario, and across all fuel/commodity prices when assuming discounted fees or independent navigation.

Transit time savings increase with higher fuel/commodity prices across all scenarios. However, transit times under high HSFO/commodity prices are similar to those at the base case scenario and under low HSFO/commodity prices. This is the result of the generally high optimal speeds on SCR across all price levels, which result in increased transit times, and therefore reducing the advantage of the shorter NSR.

Table 6.7. Voyage SCR-NSR RFR Differential sensitivity of HSFO-Scrubber in US$ per tonne.

HSFO/MGO Price (US$ per tonne)	Commodity Price (US$ per tonne)	USD/RUB Exchange Rate	Voyage	Official Fees*	Discounted Fees*	Independent Navigation*	Time Differential
			1. Ust-Luga - Ulsan	-0.49 (-0.61)	-0.01 (-0.12)	4.99 (4.88)	8
			2. Ulsan - Rotterdam	-0.42 (-0.59)	0.06 (-0.10)	5.06 (4.90)	8
			3. Rotterdam - Ust-Luga	-0.28	-0.28	-0.28	
150/250	Naphtha: 228, Jet Fuel: 249	64.41	4. Ust-Luga - Ulsan	0.31 (0.10)	0.79 (0.59)	5.79 (5.59)	11
			5. Ulsan - Rotterdam	-0.34 (-0.52)	0.14 (-0.03)	5.14 (4.97)	9
			6. Rotterdam - Ust-Luga	-0.28	-0.28	-0.28	
			7. Ust-Luga - Ulsan	0.14 (-0.04)	0.62 (0.45)	5.62 (5.45)	10
			1. Ust-Luga - Ulsan	0.82 (0.59)	1.30 (1.08)	6.30 (6.08)	8
			2. Ulsan - Rotterdam	0.75 (0.42)	1.23 (0.90)	6.23 (5.90)	8
			3. Rotterdam - Ust-Luga	-0.36	-0.36	-0.36	
300/500	Naphtha: 457, Jet Fuel: 498	64.41	4. Ust-Luga - Ulsan	1.62 (1.21)	2.10 (1.69)	7.10 (6.69)	10
			5. Ulsan - Rotterdam	0.83 (0.47)	1.31 (0.96)	6.31 (5.96)	8
			6. Rotterdam - Ust-Luga	-0.36	-0.36	-0.36	
			7. Ust-Luga - Ulsan	1.46 (1.11)	1.95 (1.59)	6.95 (6.59)	10
			1. Ust-Luga - Ulsan	-2.90 (-3.24)	2.72 (2.38)	7.72 (7.38)	8
			2. Ulsan - Rotterdam	-3.12 (-3.61)	2.50 (2.00)	7.50 (7.00)	8
			3. Rotterdam - Ust-Luga	-0.42	-0.42	-0.42	
450/750	Naphtha: 685, Jet Fuel: 747	33.28	4. Ust-Luga - Ulsan	-2.11 (-2.72)	3.51 (2.89)	8.51 (7.89)	11
			5. Ulsan - Rotterdam	-3.04 (-3.57)	2.57 (2.04)	7.57 (7.04)	8
			6. Rotterdam - Ust-Luga	-0.42	-0.42	-0.42	
			7. Ust-Luga - Ulsan	-2.25 (-2.77)	3.37 (2.84)	8.37 (7.84)	10

*Differentials in parentheses refer to results when MGO is used through ice on NSR.

Table 6.8. Voyage SCR-NSR RFR Differential sensitivity of VLSFO in US$ per tonne.

VLSFO/MGO price (US$ per tonne)	Commodity Price (US$ per tonne)	USD/RUB Exchange Rate	Voyage	Official Fees*	Discounted Fees*	Independent Navigation*	Time Differential
			1. Ust-Luga - Ulsan	-0.067 (-0.069)	0.418 (0.416)	5.418 (5.416)	8
			2. Ulsan - Rotterdam	-0.098 (-0.100)	0.387 (0.385)	5.387 (5.385)	8
			3. Rotterdam - Ust-Luga	-0.332	-0.332	-0.332	
240/250	Naphtha: 228, Jet Fuel: 249	64.41	4. Ust-Luga - Ulsan	0.619 (0.617)	1.104 (1.101)	6.104 (6.101)	11
			5. Ulsan - Rotterdam	-0.031 (0.033)	0.454 (0.452)	5.454 (5.452)	8
			6. Rotterdam - Ust-Luga	-0.332	-0.332	-0.332	
			7. Ust-Luga - Ulsan	0.484 (0.482)	0.969 (0.966)	5.969 (5.966)	10
			1. Ust-Luga - Ulsan	1.787 (1.784)	2.272 (2.269)	7.272 (7.269)	10
			2. Ulsan - Rotterdam	1.514 (1.510)	1.999 (1.994)	6.999 (6.994)	9
			3. Rotterdam - Ust-Luga	-0.422	-0.422	-0.422	
480/500	Naphtha: 457, Jet Fuel: 498	64.41	4. Ust-Luga - Ulsan	2.378 (2.372)	2.863 (2.857)	7.863 (7.857)	12
			5. Ulsan - Rotterdam	1.568 (1.563)	2.053 (2.048)	7.053 (7.048)	10
			6. Rotterdam - Ust-Luga	-0.422	-0.422	-0.422	
			7. Ust-Luga - Ulsan	2.286 (2.281)	2.771 (2.766)	7.771 (7.766)	12
			1. Ust-Luga - Ulsan	-1.687 (-1.692)	3.928 (3.923)	8.928 (8.923)	11
			2. Ulsan - Rotterdam	-2.170 (-2.177)	3.446 (3.439)	8.446 (8.439)	11
			3. Rotterdam - Ust-Luga	-0.483	-0.483	-0.483	
720/750	Naphtha: 685, Jet Fuel: 747	33.28	4. Ust-Luga - Ulsan	-1.192 (-1.201)	4.424 (4.415)	9.424 (9.415)	14
			5. Ulsan - Rotterdam	-2.128 (-2.136)	3.487 (3.480)	8.487 (8.480)	11
			6. Rotterdam - Ust-Luga	-0.483	-0.483	-0.483	
			7. Ust-Luga - Ulsan	-1.241 (-1.249)	4.374 (4.367)	9.374 (9.367)	13

*Differentials in parentheses refer to results when MGO is used through ice on NSR.

Table 6.9. Voyage SCR-NSR RFR Differential sensitivity of LNG-VLSFO in US$ per tonne.

LNG/VLSFO/MGO price (US$ per tonne)	Commodity Price (US$ per tonne)	USD/RUB Exchange Rate	Voyage	Official Fees	Discounted Fees	Independent Navigation	Time Differential
			1. Ust-Luga - Ulsan	0.01	0.50	5.50	8
			2. Ulsan - Rotterdam	-0.02	0.46	5.46	8
			3. Rotterdam - Ust-Luga	-0.26	-0.26	-0.26	
150/240/250	Naphtha: 228, Jet Fuel: 249	64.41	4. Ust-Luga - Ulsan	0.71	1.19	6.19	11
			5. Ulsan - Rotterdam	0.04	0.53	5.53	9
			6. Rotterdam - Ust-Luga	-0.26	-0.26	-0.26	
			7. Ust-Luga - Ulsan	0.57	1.06	6.06	10
			1. Ust-Luga - Ulsan	1.73	2.21	7.21	10
			2. Ulsan - Rotterdam	1.47	1.95	6.95	9
			3. Rotterdam - Ust-Luga	-0.31	-0.31	-0.31	
250/480/500	Naphtha: 457, Jet Fuel: 498	64.41	4. Ust-Luga - Ulsan	2.37	2.85	7.85	12
			5. Ulsan - Rotterdam	1.53	2.01	7.01	9
			6. Rotterdam - Ust-Luga	-0.31	-0.31	-0.31	
			7. Ust-Luga - Ulsan	2.27	2.75	7.75	11
			1. Ust-Luga - Ulsan	-1.86	3.76	8.76	11
			2. Ulsan - Rotterdam	-2.30	3.31	8.31	10
			3. Rotterdam - Ust-Luga	-0.35	-0.35	-0.35	
350/720/750	Naphtha: 685, Jet Fuel: 747	33.28	4. Ust-Luga - Ulsan	-1.24	4.37	9.37	13
			5. Ulsan - Rotterdam	-2.24	3.37	8.37	10
			6. Rotterdam - Ust-Luga	-0.35	-0.35	-0.35	
			7. Ust-Luga - Ulsan	-1.32	4.29	9.29	12

Table 6.10. Seasonal SCR-NSR RFR Differential sensitivity in US$ per tonne.

Fuel Type	Fuel Price (US$ per tonne)	Commodity Price (US$ per tonne)	USD/RUB Exchange Rate	Official Fees*	Discounted Fees*	Independent Navigation*	Time Differential
	150	Naphtha: 228, Jet Fuel: 249	64.41	-0.46 (-0.63)	0.02 (-0.14)	5.02 (4.86)	46
HSFO-Scrubber	300	Naphtha: 457, Jet Fuel: 498	64.41	0.76 (0.43)	1.25 (0.91)	6.25 (5.91)	43
	450	Naphtha: 685, Jet Fuel: 747	33.28	-3.04 (-3.54)	2.58 (2.08)	7.58 (7.08)	45
	240/250	Naphtha: 228, Jet Fuel: 249	64.41	-0.139 (-0.141)	0.346 (0.344)	5.346 (5.344)	47
VLSFO	480/500	Naphtha: 457, Jet Fuel: 498	64.41	1.550 (1.546)	2.035 (2.031)	7.035 (7.031)	53
	720/750	Naphtha: 685, Jet Fuel: 747	33.28	-2.065 (-2.072)	3.551 (3.544)	8.551 (8.544)	58
	150/240/250	Naphtha: 228, Jet Fuel: 249	64.41	-0.03	0.46	5.46	46
LNG-VLSFO**	250/480/500	Naphtha: 457, Jet Fuel: 498	64.41	1.56	2.05	7.05	51
	350/720/750	Naphtha: 685, Jet Fuel: 747	33.28	-2.12	3.49	8.49	55

*Results refer to both HSFO-Scrubber/VLSFO and HSFO-Scrubber/VLSFO (MGO in NSR). **The VLSFO and LNG-VLSFO options include MGO consumption (within ECAs for the VLSFO option and pilot MGO for the LNG option), hence the inclusion of MGO price sensitivity.

6.6 Discussion and concluding remarks

This modelling case examines the use of the NSR for seasonal navigation operations. The factors considered are distance, fuel prices, ship speed through ice on NSR, seasonal navigation, icebreaking fees, commodity prices and in-transit inventory costs, and fuel types and operational modes.

The analysis in this chapter complements Chapter 4 and Chapter 5, by developing seasonal navigation scenarios and considering real hourly AIS speed data of historic tanker voyages conducted on NSR to determine the varying speed through ice on NSR. The NSR is compared to the SCR for oil product tanker voyages between Northwest Europe, the Russian Baltic, and Northeast Asia at the strategic level (choice of oil products and routes as an expert-based scenario) during the summer/autumn season. The choice of OD pairs reflects the main oil product trades between the Atlantic and the Pacific Ocean as well as historic seasonal round voyages conducted on the NSR during 2011-2019.

A required freight rate (RFR) model is developed based on speed optimisation to assess the minimum cost per tonne from the shipowner's perspective. The methodological approach considers ship speed through ice per month, navigation zone and voyage direction. Automated Identification System (AIS) data are used to extract real hourly speed data of historic tanker voyages conducted on NSR to inform the analysis. The relationship between optimal speed, speed through ice on NSR and minimum RFR is considered in the analysis. A sensitivity analysis is conducted to control for important cost and navigational factors. A cost breakdown is provided to show how operating, voyage, and capital costs affect route competitiveness.

The analysis considers alternative fuel types and operational modes to address current and future emissions reductions policies (ECAs, IMO sulphur limit, Initial IMO GHG Strategy, future prohibition on the use of heavy fuels in the Arctic).

The analysis of this chapter addresses **Research Question 1**: *Why did the NSR emerge as an alternative route for oil product tankers between Europe and Asia since the 2010s?*, **Research Question 2**: *How do cost and market factors affect the use of the NSR for oil product tankers?*, **Research Question 3**: *How does ship speed on ice affect the feasibility of the NSR for oil product tankers?*, **Research Question 4**: *How do different approaches to ship speed choice and cost modelling affect the feasibility of the NSR for oil product tankers?*, and **Research Question 5**: *How do emissions regulations and alternative operational modes and fuel types affect the feasibility of the NSR compared to the traditional routes for oil product tankers?*

Whilst there have been studies which used sea ice thickness data to estimate speed on ice (von Bock und Polach et al. 2015; Faury and Cariou 2016; Cariou and Faury 2020; Faury, Cheaitou et al. 2020; Cheaitou et al. 2020; Cariou et al. 2021), this is the first study where real speed data are used to assess the economics of the NSR. More specifically, real hourly AIS speed data are employed in the analysis, drawing from tanker voyages conducted on the NSR during 2011-2019. Thus, this Thesis offers a new approach to estimate ship speed through ice on NSR per month, navigation zone and voyage direction.

Seasonal voyage planning and navigation for oil product tankers on the NSR, in a speed optimisation context aiming to minimise the RFR, depends on many factors which can affect the competitiveness of the route. The main factors that increase the competitiveness of the NSR are a combination of discounted icebreaking fees, higher fuel and commodity prices, shorter OD pair distances, and relatively high ship speed through ice. Yet, independent navigation significantly increases the competitiveness of the NSR, even at low fuel and commodity prices, and across all fuel types.

Whilst voyage times for a certain OD pair on the SCR are the same across every fuel type, voyage times vary on the NSR owing to different sea ice regimes and the speeds realised through ice. A lower speed on ice means a lower average speed for a whole voyage at a given month. Thus, the longer the time spent within ice, the longer the overall voyage transit time. Consequently, the minimum NSR RFR at a given transit gets higher when the speed on ice decreases, and vice versa. This means that the use of the shorter NSR gives the greatest time savings under VLSFO, and the least time savings under HSFO-Scrubber, all else being equal. Time savings under the LNG-VLSFO mode are found in between those under the VLSFO and HSFO-Scrubber modes due to the combination of a low priced fuel (LNG) with a high priced fuel (VLSFO).

The results show that July is the most challenging month, whereas September is the most favourable month, when assessing voyages between the ports of Ust-Luga, Rotterdam and Ulsan for naphtha and jet fuel/kerosene trades. The highest SCR-NSR RFR differential across all fuel types is found on the 4th and 7th voyages (both at Ust-Luga - Ulsan pair), owing to higher distance savings than on the Ulsan - Rotterdam pair voyages, as well as to the higher speeds achieved through ice compared to other months and voyages. The lowest minimum NSR RFR on the Ust-Luga - Ulsan pair is achieved in September, where the SCR-NSR RFR differential is the highest across all voyages and fuel types/modes, and the difference between the speed on ice and optimal speed on open water is the lowest compared to July and November voyages across all fuel types. Equally, the lowest minimum NSR RFR on the Ulsan - Rotterdam pair is achieved in October, where the SCR-NSR RFR differential is the highest RFR across all voyages and fuel types/modes, and the difference between the speed on ice and optimal speed on open water is lower than that in the August voyage across all fuel types.

Although VLSFO offers the highest cost and time savings given that it is the most expensive fuel, LNG-VLSFO can be an interesting alternative in terms of cost savings, compliance with ECAs and a future prohibition on the use of heavy fuel oils in the Arctic as well as emissions reductions in the long-term. More specifically, a higher LNG/VLSFO distance ratio for the NSR compared to the SCR means that the former is more competitive compared to the latter even if LNG is the cheapest alternative fuel option. LNG becomes even more attractive compared to HSFO-Scrubber option when considering the use of MGO through ice on NSR based on the assumption of a future prohibition on the use of heavy fuel oils in the Arctic. Yet, this depends on the relative price of LNG compared to heavy fuel oils. Whilst LNG is assumed to be a low-cost fuel, this may not always be the case since bunker fuel market developments as well as crude oil and gas prices can vary considerably.

The LNG/VLSFO ratio depends on OD pair distance and LNG fuel tank capacity. The consideration of in-transit inventory costs in the analysis increases the competitiveness of the NSR under high fuel and commodity price scenarios since transit times on SCR become even longer. This is also evident from the SCR cost breakdown analysis at the base case scenario, where in-transit inventory costs come third after capital and fuel costs under the VLSFO and LNG-VLSFO modes. The use of ice coating for seasonal operations reduces the potential cost savings that the NSR provides by 0.2 US$ per tonne, but it is considered an essential measure to prevent damages in the hull of the ship when operating for more than one voyages through ice (Tanker Company 2019).

The analysis is based on real speed data of historic NSR tanker voyages during 2011-2019. The results of this modelling case are not directly comparable to results of other studies which used historic sea ice thickness data to determine the theoretical speed on ice. However, they are in line with Faury and Cariou (2016) and Cheaitou et al. (2020) who assessed the economics of the NSR by assuming the use of an ice class IA tanker and including the period between July and November in their analysis. Both Faury and Cariou (2016) and this Thesis find September to be the most favourable month in terms of cost competitiveness (here for the Ust-Luga - Ulsan pair, 4th voyage), followed by October (here for the Ulsan - Rotterdam pair, 5th voyage) and November (Ust-Luga - Ulsan pair, 3rd voyage). Cheaitou et al. (2020) find that highest profits can be achieved during September and October either by using VLSFO or MGO. Yet, the OD pair distance and initial date of the first voyage are important considerations when assessing the impact of speed through ice on NSR for seasonal operations.

The NSR was used for exploratory destination and transit voyages primarily due to high fuel prices and competitive icebreaking fees during 2011-2013. A comparison between the fuel and commodity price levels, especially at high levels combined with discounted icebreaking fees, assumed in this analysis and those occurred during 2011-2013 can be attempted to validate the methodological process and assumptions of this modelling case.

According to base case scenario assumptions, a HSFO price of 300 US$/t and a naphtha price of 458 US$/t result in a SCR-NSR RFR differential of 1.62 US$/t for a cargo of 80,000 metric tonnes in September, that is, cost savings of 129,207 US$ for a LR2 tanker voyage between Ust-Luga and Ulsan. Equally, a VLSFO price of 500 US$/t and a naphtha price of 458 US$/t result in a RFR differential of 2.38 US$/t, that is, cost savings of 190,249 US$ for the same voyage. The RFR differentials are found 3.51 US$/t and 4.42 US$/t, respectively, at high prices and discounted fees, that is, at HSFO and VLSFO prices of 450 US$/t and 720 US$/t, respectively, and at a naphtha price of 685 US$/t. Thus, the cost savings are 280,571 US$ for HSFO and 353,884 US$ for VLSFO when using the NSR instead of the SCR.

The VLSFO price of 720 US$/t is relatively close to the HSFO price in Rotterdam during 2011-2013, that is, about 600 US$/t (Clarksons 2021), whilst spot naphtha prices in Rotterdam were 910 US$/t during the same period (OPEC 2021). Thus, it can be argued that at 353,884 US$ savings per voyage, the NSR is an attractive choice for a shipowner who wants to offer a competitive freight rate even when factoring ice damage repairs in the calculations (about 170-190,000 US$ depending on the location of the repair yard, either Ulsan or Qushan, China – Tanker Company 2020). However, for fuel prices used at the base case scenario, the potential is smaller, even if the RFR differentials are positive for certain voyages. The limited potential is reflected in the seasonal SCR-NSR RFR differentials. On the one hand, the consideration of ice damage repairs and a possible deviation of an ice class tanker from the seasonal schedule to visit a repair yard would result in negative SCR-NSR RFR differentials. On the other hand, proceeding with slow speed through ice on NSR, and provided that ice coating is applied on the ice class tanker, can reduce the possibility of ice damages (Tanker Company 2019). Similar results are obtained for voyages between the ports of Ulsan and Rotterdam.

Both the cost breakdown and the sensitivity analysis confirm that first, icebreaking fees are the most important cost factor for the NSR route, and second that the inverse relationship between icebreaking fees, determined by USD/RUB exchange rates, and fuel prices (Shibasaki et al. 2018) have had important implications for the potential of the NSR since the introduction of the latest official icebreaking fees (NSRA 2014). More specifically, the NSR is neither competitive at low fuel prices nor at high fuel prices given that icebreaking fees increase at high fuel prices in tandem with high crude oil prices and a low USD/RUB rate. Yet, discounted fees can still be offered since the NSRA explicitly refers to 'maximum rates' applied, implying that discounted icebreaking fees can be offered (NSRA 2014).

The planning for seasonal navigation in the analysis allows for five laden voyages, provided that these occur between Ust-Luga and Ulsan and between Ulsan and Rotterdam with additional time spent outside the NSR to allow a tanker to transit from Rotterdam to Ust-Luga for its next laden voyage. All else being equal, the impact of fuel and commodity prices in a speed optimisation context is evident. The last day through ice on NSR is 8th November under LNG-VSLFO, 16th November under HSFO-Scrubber, and 30th November under VLSFO at high fuel/commodity price scenario. The calculated dates for seasonal operations between July and November for both the SCR and NSR are presented in Appendix Y5.

A seasonal planning approach is adopted in the analysis rather than planning for annual operations and/or combined NSR/SCR annual operations. Generally, more than one strategies and routeing options may exist for oil product tankers depending on various trades and market conditions (fuel prices, freight rates, commodity prices in various geographic regions). Second, there may not exist any arbitrage opportunities between two regions every month or even week throughout the year. This reflects the dynamics of commodity and spot freight markets, where tankers do not operate on fixed itineraries in general, except in some very specific trade routes. Thus, the seasonal operations planning of five consecutive laden voyages may not always materialise in practice. In addition, the number of consecutive round voyages could have been different under real speeds, which may not be close to optimal speeds as it is found in Chapter 5. This can have further implications for route competitiveness depending on cost and navigational factors.

Moreover, the positioning of a tanker at the beginning of the season may not be such that the full summer/autumn navigation season can be exploited. Besides, employment opportunities may not always exist to conduct all possible consecutive round voyages. Examples are some of the historic NSR voyages listed in Table 6.2, where all tankers except *Anichkov Bridge* could have conducted more voyages during the summer/autumn season, depending on OD pair distances and sea ice conditions.

Furthermore, different assumptions regarding the relationship between ship speed and fuel consumption could result in different RFR differentials and number of voyages per route and OD pair in a speed optimisation context. Adland et al. (2020) find that for Aframax/LR2 tankers the cubic law between speed and fuel consumption holds only close to the design speed with elasticities ranging from 3.8 to 0.7 for a speed range between 16 knots to 8.4 knots. On the one hand, this could mean significantly higher fuel consumption at very low speeds, such as the speeds realised when operating through ice. Fuel consumption can be further increased depending on sea ice conditions (Solakivi et al. 2018). On the other hand, higher total fuel consumption and costs could also occur for longer routes, depending on OD pair distances and optimal speeds. The relative difference between the NSR, and any other routes would then depend on the speed through ice and the difference between the design speed and the optimal speed for a given route. The higher the departure from design speed, especially at low speed levels, the higher the costs for a given route.

Last but not least, AIS data should be considered with caution, since reported speeds cannot always be defined and assigned to a specific state accurately (e.g. drifting, stuck on ice, stoppage). This uncertainty can have implications on both the assumptions of ship speed through ice, as well as on costs and the total number of voyages for seasonal planning.

7. Conclusion

7.1 Addressing the systematic review questions

Main Systematic Review Question: *According to the extant literature, what is the cost effectiveness, and what is the likely impact on emissions, of using the Arctic routes compared to traditional routes, between 1980 and 2021?*

The results suggest that Arctic routes are considered more competitive than their traditional rivals in 15 of the 44 papers reporting research on their economic assessment. On the other hand, they are found to be less competitive in 11 papers, whereas 21 papers report mixed results, depending on the assumptions of the basic scenarios. The Arctic routes are shown to be competitive in nine out of 14 papers that consider single or round voyages, as well as in one paper where the time frame is not defined explicitly. On the other hand, two find the NSR uncompetitive, whereas three papers report mixed results.

When it comes to papers that consider seasonal operations, two find the Arctic routes uncompetitive, whereas two find them to be competitive, with the rest three reporting that these are more competitive than other routes in specific trades and/or scenarios. The competitiveness of Arctic routes decreases when moving towards year-round operations. More specifically, the Arctic routes are shown not to be competitive in four out of eight papers that consider year-round operations, with the rest four reporting mixed results.

Moreover, most of the papers concluding that the Arctic routes are competitive in specific trades or scenarios, assume annual combined Northern Sea Route (NSR)/Traditional Routes schedules (11 out of 17). Of these 17 papers, 13 refer to liner shipping and three evaluate bulk or specialised shipping sectors. In contrast, Arctic routes are found competitive in most of the studies that assume round or single voyages, mainly for bulk or specialised shipping.

This means that under the current winter navigational and climatic conditions they could serve mainly as seasonal alternatives for a limited period of about five months rather than offering regular access to ships on an annual basis. Consequently, Arctic routes appear to be more suitable for bulk and/or specialised shipping rather than liner shipping in the short to medium-term.

14 studies assess emissions comparing the Arctic with traditional routes, with five papers concluding that Arctic routes are more energy efficient than their traditional rivals, whereas three find that energy efficiency depends on certain assumptions and scenarios, including load

factors, ship size, fuel consumption and transit times on ice, distance, transit fees between competing routes, and ship network and allocation of ships between competing routes. The use of Global Warming Potential (GWP) factors in the emissions analysis increases the complexity of estimating emissions and environmental costs, especially when comparing transport routes against alternative fuel types and at different time frames. The adoption of emissions taxation favours the use of shorter routes, and as a result, Arctic routes are advantaged. Yet, the use of fuels in the Arctic which are more expensive than those used in competing routes reduces the competitiveness of Arctic routes.

Systematic Review Question 1: *Which research methods and data analysis techniques are employed to address the research questions in comparative studies on Arctic shipping literature?*

Analytical mathematical methods are primarily used in the literature and, to a lesser extent, empirical statistical and case study research. As regards data analysis techniques, the literature shows a particular preference for scenario-based transport cost models. Other data analysis techniques used include optimisation, emissions models, simulation, game theory, interviews, and regression analysis. Some papers are informed by climate science models or mathematical equations and/or statistical analysis to model the sea ice-ship speed relationship. Other data analysis techniques are also reported in some of the reviewed papers. However, these techniques refer to research aims or purposes other than the comparison of competing routes at the micro-economic level of analysis, and therefore they are not included in the review.

Systematic Review Question 2: *What are the emerging issues that need to be addressed?*

The systematic literature review identified several issues that could be addressed in future research. These relate to both the research and methodological aspects of the reviewed papers. Future research could consider route comparisons between the Northwest Passage (NWP), the Transpolar Sea Route (TSR), and variations of the NSR, as well as other routes, such as the Trans-Siberian Railway and the New Eurasian Land Bridges, and other established or future trade routes. Attention should be paid to revenue attributes, commodity and fuel prices, alternative fuel types and technologies, and how these factors along with sea ice conditions affect the feasibility of the Arctic routes. More model-based research with sensitivity analysis is needed in order to overcome discrepancies in the assumptions regarding cost variables. The adoption of several variant scenarios and combinations of factors in model-based research could provide deeper insights than simply trying to assess whether the Arctic routes are competitive or not. The trend towards building more than one main scenarios based on various factors is also reflected in the results of the review, especially for papers that report mixed results.

As regards navigational factors, future research could take into account studies related to climate models and variations in Arctic sea ice, the relationship between sea ice thickness, ship speed, and icebreaker assistance, and the relationship between fuel consumption and sea ice. Sea ice conditions as well as other physical constraints, such as regional bottlenecks, are critical factors that affect the speed or ship size used on Arctic waters, which in turn can affect revenue, transit times, operating and voyage costs, as well as the overall competitiveness of the Arctic routes.

Emissions and environmental assessment modelling should focus on GWP factors apart from fuel consumption conversions, alternative fuel types and technologies, and different scales (e.g. ship/fleet, number of ships per voyage/season/year). The literature focuses mainly on liner shipping and, to a lesser extent, on bulk shipping. However, bulk (liquid, dry) and specialised shipping (Liquefied Natural Gas/LNG, reefer) will mostly benefit from Arctic routes in the short to medium-term. As regards liner shipping, more emphasis could be given to network structure/configuration and/or reconfiguration of the existing networks as part of scenario-based modelling approaches.

As a relatively new topic in maritime transport literature, Arctic shipping research could be addressed by many methodologies and data analysis techniques used in social sciences, namely, operational research, case studies, econometric modelling, regression and panel data analysis, as well as discrete choice and multi-criteria decision-making models (MCDM) techniques amongst others.

The systematic literature review included studies reporting on cost and emissions assessments of Arctic routes. However, the Arctic shipping literature spans several research areas and topics. A broader review of the literature could include conceptual and descriptive studies, theoretical studies, surveys, as well as studies focusing on factors other than costs/profits, such as time/distance effects, ice class ship evaluation, or the overall environmental impact of future shipping traffic volumes in the Arctic. Moreover the ‘grey literature’ should be considered, as well as studies reporting research findings in languages other than English.

7.2 Review of research questions

Research Question 1: *Why did the NSR emerge as an alternative route for oil product tankers between Europe and Asia since the 2010s?*

There has been a growing interest in the use of the NSR as an alternative to traditional sea routes and ship canals, especially between Europe and Asia, since the 2010s. The main reasons include the gradual Arctic sea ice retreat, distance savings, high fuel prices during 2011-2014, a competitive icebreaking tariff policy until 2013, Russia's policy to develop the route, and increased piracy premiums and risk for voyages via the Gulf of Aden and the Suez Canal.

Favourable sea ice conditions and distance savings explain only part of the surge in exploratory voyages through the NSR during the last ten years. Although general cargo ships, heavy lift cargo ships, and ships involved in destination voyages from the Arctic to ports outside the Arctic are benefitted by using the NSR, other factors largely determine route choice for oil tankers. These factors include commodity price developments, arbitrage opportunities, marine fuel price developments, and geopolitics amongst others.

A large number of oil product tankers were involved in destination and transit voyages between 2011 and 2014. These tankers transported jet fuel/kerosene, gasoil/diesel, condensate, naphtha, and fuel oil between the Russian Arctic, Europe, and Asia. High marine fuel and spot oil products prices, discounted transit fees, a rising value of cargo and declining futures prices of oil products prompted certain traders and shipowners to test the NSR as an alternative route for tankers between Asia and Europe in 2012 and 2013.

A mix of geopolitical factors and shifts in oil products flows from the Arctic to other regions significantly reduced the number of transit and destination voyages in 2014. The NSR was mainly used for fuel oil supplies between Russian ports rather than for transit and destination voyages.

Following the steep drop in crude oil prices during 2014-2015, the interest for the route declined owing to low marine fuel and oil products prices, reduced piracy premiums for Suez Canal transits, and a lower required freight rate (RFR) which was insufficient to cover potential ice damage repairs amongst others. In addition, the official icebreaking fees introduced in 2014 were relatively low in 2015-2017 due to the depreciation of the Russian Rouble, but higher than the discounted fees offered before 2013. Not only did the cost differential between the NSR and other traditional routes narrow, but also low oil products prices and hence a lower value of cargo on board meant that transit time was not very important. Oil oversupply, low spot oil products prices and rising futures prices favoured longer routes and the delay of arrivals at the destination. Not only did tankers use the Suez Canal route (SCR), but also the Cape of Good Hope route was used extensively for certain oil products trades between Asia and Europe in 2015-2017 and 2020.

The analysis in Chapter 4 and Chapter 5 explains quantitatively route choice with respect to market, cost, and navigational factors. The cost comparison confirms the competitiveness of the NSR over longer routes during 2011-2014, as well as the competitiveness of the Cape route over the SCR and NSR during 2015-2017 and in 2020.

The analysis in Chapter 4 draws from representative ports, distance savings, and tanker sizes to compare the NSR and SCR routes between Europe and Asia in 2011-2020. The results in Chapter 4 show that the NSR was more competitive than the SCR across all origin-destination (OD) pairs at high fuel prices and discounted icebreaking fees (2011-2014). Yet, the RFR differential on the Yeosu-Rotterdam pair was negative across all tanker sizes, whereas it narrowed significantly for Long Range 2 (LR2) and Long Range 3 (LR3) tankers on the Mongstad-Mizushima pair, when including ice damage repairs in the analysis. The RFR differential on the Vitino-Daesan pair was less impacted across all tanker sizes when including ice damage repairs. The majority of oil product tanker voyages (17 out of 32) were conducted between the Russian Arctic, Arctic Europe and Northeast Asia in 2011-2013. This confirms the results based on the Vitino-Daesan pair, since it is the most competitive OD pair for the NSR, either with or without considering ice damage repairs. On the other hand, six voyages were conducted from Mongstad to Japan (1), and South Korea to the Amsterdam-Rotterdam-Antwerp (ARA) region (5) in 2011-2013 (CHNL 2021a; Bloomberg 2021; Refinitiv Eikon 2021). Although more voyages occurred between the Far East and ARA region than between Mongstad and the Far East, this can be explained by other factors, such as differences in spot and futures oil products prices between the origin and destination regions during that period. Besides, the NSR retains its competitiveness across all OD pairs in 2011-2014, when ice damage repairs are not factored in the analysis.

The results in Chapter 4 show that the NSR was less competitive in 2015-2017 than in 2011-2014. More specifically, the SCR-NSR RFR differential was narrow for Medium Range (MR), Long Range 1 (LR1), and LR2 tankers, and negative for LR3 tankers on the Yeosu-Rotterdam pair, whilst it also narrowed across all tanker sizes on the Mongstad-Mizushima pair. The RFR differential on the Yeosu-Rotterdam pair was negative across all tanker sizes, whilst it was also negative for all tanker sizes except for LR1 tankers on the Mongstad-Mizushima pair, when considering ice damage repairs in the analysis. The RFR differential on the Vitino-Daesan pair was less impacted across all tanker sizes either with or without including ice damage repairs in the analysis. Yet, oil products flows shifted from the White and Barents Seas to the Baltic Sea in 2014. The results reflect the NSR traffic records in 2015-2017. The NSR was used only for fuel oil supplies between Russian ports during that period. Not only did the SCR become more competitive than NSR, but also the Cape route became a viable alternative for voyages between east and west.

The analysis in Chapter 5 is based on OD pairs between Northeast Asia and Europe. The results regarding the comparison between Cape, SCR and NSR for LR2 tankers at the High Sulphur Fuel Oil (HSFO) and Very Low Sulphur Fuel Oil (VLSFO) modes[39] can be used to validate the assumptions and scenarios for the period 2015-2017. The RFR differentials with and without in-transit inventory costs are considered, since in-transit inventory is not important at low commodity prices, such as during 2015-2017 and 2020.

The Cape RFR is found on par with SCR RFR, and higher than NSR RFR by 0.5 US$/t at low fuel/commodity prices and optimal speeds, based on results for the Ulsan-Rotterdam pair under the VLSFO mode. However, if in-transit inventory costs are not considered in the analysis, the Cape route becomes more competitive than SCR and NSR, by 0.6 US$/t and 0.5 US$/t, respectively. Equally, the Cape RFR is higher than the SCR RFR and NSR RFR by 0.4 US$/t and 1.6 US$/t, respectively, when assuming a constant speed of 12 knots. However, if in-transit inventory costs are not considered in the analysis, the Cape route becomes more competitive than SCR by 0.4 US$/t, whereas is found on par with NSR.

The Cape RFR is lower than SCR RFR by 0.4 US$/t, and lower than NSR RFR by 0.2 US$/t at low fuel/commodity prices and optimal speeds, based on results for the Ulsan-Rotterdam pair under the HSFO mode. If in-transit inventory costs are not considered in the analysis, the Cape route is found even more competitive than both the SCR and NSR by 1.0 US$/t and 1.3 US$/t, respectively. The Cape RFR is higher than the SCR RFR and NSR RFR by 0.2 US$/t and 1.4 US$/t, respectively, when assuming a constant speed of 12 knots. However, if in-transit

[39] Results at the VLSFO mode are used as an example, given that a low VLSFO price of 240 US$/t is assumed in Chapter 5, which is close to the 2015-2017 HSFO average of 260 US$/t assumed in Chapter 4. Besides, the heating (calorific) values of HSFO and VLSFO are very close, and result in similar fuel consumption at the design speed. Results at the HSFO mode are also used as an example, given that a low price of 150 US$/t is assumed in Chapter 5, which is close to HSFO prices in December 2015, January-April 2016 and April-May 2020.

inventory costs are not considered in the analysis, the Cape route is more competitive than both the SCR and NSR by 0.6 US$/t and 0.2 US$/t, respectively.

Moreover, the NSR is less competitive than Cape when including ice damage repairs in the analysis, either at optimal or constant speed regimes. The Cape route could have still been chosen as an alternative route, even if it were not for the consideration of ice damage repairs on NSR. It could have also been chosen if its RFR was higher than those of the SCR and NSR. More specifically, if the difference between the spot commodity price at the origin and the future commodity price at the destination was high enough to compensate for the increased freight, the Cape route could have still been a viable alternative. The reason is that the contango structure in the market favours the delay of arrivals so that profits could increase based on the difference between the low cargo price at the origin including transport costs, and the high cargo price at the destination. It should be noted that regional supply and demand factors determine the actual freight rate levels for either route alternative. This implies that freight rates may be higher, lower or very close to the RFR of a voyage or route alternative. Similar observations can be made for the other OD pairs included in the analysis in Chapter 5. The results vary depending on the distance differences between competing routes. Records of LR2 tanker voyages between Northeast Asia and Europe in 2013-2020 show that the Cape of Good Hope route was used extensively along with the SCR in 2015-2016 and 2020, and, to a lesser extent, in 2013, 2017, and 2018. These voyage records confirm the results of the analysis in Chapter 5.

There are a number of OD pairs chosen by certain shipowners and charterers in 2011-2013 which provide minimal distance savings for the NSR. This is due to the fact that discounted icebreaking fees varied from case to case in 2011-2013 (Falck 2012). According to Tanker Company (2018), Tanker Company (2020) and Moe and Brigham (2016), regular users of the route could be granted even lower discounted fees than those used in the analysis in Chapters 4, 5, and 6 (Falck 2012; Gritsenko and Kiiski 2016). This explains the reason why certain voyages were conducted from the ports of Vitino or Mongstad to ports located in countries, such as Thailand, Taiwan, Singapore and Malaysia before 2014. The tankers which were involved in these voyages were either owned or chartered by companies which conducted 25 of the 32 destination and transit product tanker voyages in 2011-2013.

The NSR was found competitive mainly on the Mongstad-Mizushima and Vitino-Daesan pairs without considering ice damage repairs during 2018-2020. More specifically, the NSR was found competitive on the Yeosu-Rotterdam pair during 2020, but marginally competitive during 2018 and 2019, whereas it was found uncompetitive when ice damage repairs are included in the analysis, across all years and tanker sizes. Similarly, the NSR was relatively more competitive than the SCR on the Mongstad-Mizushima pair across all years, albeit with diminishing RFR differentials when moving towards larger tanker sizes. Yet, it was found uncompetitive when ice damage repairs are included in the analysis across all years and tanker sizes. The NSR was mostly competitive on the Vitino-Daesan pair, marginally competitive when including ice damage repairs across all years and tanker sizes, but uncompetitive for LR3 tankers in 2018 and 2019. However, very few destination or transit tanker voyages were conducted on the NSR in 2018-2020. One Aframax voyage of oil products was conducted in 2018, whilst three Aframax voyages of crude oil were conducted in 2019. Yet, these voyages relate to renewed attempts to promote the route and test dual-fuel Oil/LNG-powered tankers. The limited potential of the NSR during 2018-2020 is also attributed to shifts in oil products flows and market conditions, especially those on commodity markets, which resulted in the use of longer routes as described earlier in this Chapter.

Notwithstanding the state of the commodity and marine fuel markets lately, destination and transit voyages on the NSR are still exploratory in nature not least because of the uncertainty related to climatic and ice conditions, transit times, minimal infrastructure, remoteness and safety factors. Exceptions include ships which are used for transport of cargoes related to specific projects in the Arctic, or ships owned by industrial carriers, such as the Yamal LNG tankers or the fleet of Norilsk Nickel. Geopolitical developments may also affect petroleum flows, even if the NSR is a viable alternative to traditional routes. This is clearly reflected in the shift of flows from the Barents Sea and White Sea regions to the Baltic Sea since 2014. Moreover, other factors can affect the use of the NSR for oil tanker trades. These include the availability of ice class tankers globally, contract obligations e.g. time charters, and a preference to operate ice class tankers in other ice-bound regions with more established oil trades, such in the Baltic, in Canada, or in the Sea of Okhotsk. Moreover, the ice class notation, size, and age of ice class tankers are all important factors, which can affect the development of tanker trades on the NSR in various ways. For example, ice class tankers of old age tend to be used only on conventional trade routes due to increased repairs and maintenance costs (Gibson 2018). According to Gibson (2018), 70% of MR/Handysize, 57% of LR1, 50% of Panamax, 35% of LR2, 72% of Aframax, and 78% of Suezmax ice class tankers were over 10 years old in 2018. These statistics reflect the limited availability of certain ice class tanker types/sizes of new age, which could be used to further explore the feasibility of the NSR.

Research Question 2: *How do cost and market factors affect the use of the NSR for oil product tankers?*

A cost-based route comparison establishes the break-even point for a route and considers fixed and variable cost factors, including operating and capital costs for different ship types and technologies, fuel costs, transit fees, and other voyage-related costs. The factors considered in the analysis in Chapters 4, 5, and 6, are distance, fuel prices, ship speed through ice, seasonal navigation, icebreaking fees, ice damage repairs, ship size, capital and operating costs, commodity prices and in-transit inventory costs, as well as fuel types and operational modes, concerning commercial factors and environmental regulations.

Chapters 4, 5 and 6 consider distance, fuel types and prices, and icebreaking fees. Chapter 4 considers ship size and varying operating costs and capital costs. Chapters 5 and 6 consider commodity prices and in-transit inventory costs. Chapters 4 and 5 consider ice damage repairs. Chapters 4 and 5 consider average ship speed through ice on NSR, whereas Chapter 6 considers ship speed through ice on NSR per month, navigation zone, and voyage direction. All factors are closely related and all contribute to route choice through various ways.

The factors of ship speed through ice and seasonal navigation are described elsewhere in this Chapter. Other cost factors, such as piracy insurance premiums, and ship-to-ship (STS) transfer operations costs, which belong to the category of voyage costs, are included in the analysis in Chapters 4, 5, and 6, or described earlier in this Chapter.

Distance: The impact of distance on the competitiveness of the NSR is examined in Chapters 4, 5, and 6. The competitiveness of a shorter route over a longer route, such as NSR versus SCR and Cape, or SCR versus Cape, increases when moving from longer to shorter origin-destination (OD) pairs and vice versa.

The impact of distance is closely related with fuel prices, icebreaking fees, ice damage repairs, ship size, capital and operating costs, commodity prices and in-transit inventory costs, and fuel types and operational modes.

Fuel Prices: The impact of fuel prices on the competitiveness of the NSR is examined in Chapters 4, 5, and 6. Fuel prices are one of the most important factors which determine the competitiveness of the NSR along with distance, icebreaking fees, and ice damage repairs. One of the main reasons behind the early exploration of the NSR was the historically high fuel prices in 2011-2014. Generally, high fuel prices favour shorter routes, and vice versa. Yet, this depends on other factors amongst others. It is shown that icebreaking fees are very high when assuming high fuel prices due to the inverse relationship between the U.S. Dollar – Russian Rouble (USD/RUB) exchange rate and oil prices. These findings are in line with Wergeland (1992), Liu and Kronbak (2010), Lu et al (2014), and Xu et al. (2018). Lasserre argues in Lasserre (2014) and Lasserre (2015) that fuel cost savings alone cannot determine the competitiveness of the NSR.

The impact of fuel prices is closely related with distance, icebreaking fees, ice damage repairs, ship size, commodity prices and in-transit inventory costs, and fuel types and operational modes.

Icebreaking fees: The impact of icebreaking fees on the competitiveness of the NSR is examined in Chapters 4, 5, and 6. Icebreaking fees significantly influence the competitiveness of the NSR along with distance and fuel prices. As it is shown in the analysis in Chapters 4, 5, and 6, high fuel prices are important but cannot determine the competitiveness of the NSR alone. The route is less competitive at both low and high fuel prices, when assuming official icebreaking fees. It is found that high icebreaking fees based on official tariffs, owing to a low USD/RUB exchange rate, outweigh any benefit of using the NSR under a high fuel price environment. This is attributed to the inverse relationship between USD/RUB exchange rates and crude oil prices, which are highly correlated with fuel oil prices. The USD/RUB exchange rate is high at low oil prices, and vice versa. This relationship largely explains the practice of discounted fees compared to official tariff rates determined by the USD/RUB exchange rate.

The importance of icebreaking fees is also observed in the analysis of the period 2018-2020 in Chapter 4. An increase in the USD/RUB exchange rate in 2018 and 2020 resulted in relatively low ice breaking fees, which more than offset the negative impact that lower fuel price levels could have had for the competitiveness of the NSR during that period. On the one hand, fuel prices were not substantially low during 2018-2020, when considering annual averages. On the other hand, the steep drop of oil price levels during 2020 resulted in lower icebreaking fees levels, given the inverse relationship between oil prices and the value of the Russian Rouble. The combined effect on the competitiveness of the NSR depends on the relative differences between fuel costs and icebreaking fees. The analysis in Chapters 4, 5, and 6 shows that discounted icebreaking fees improve the feasibility of the NSR across all OD pairs, fuel types and price levels, all else being equal. Most importantly, the influence of high fuel prices on the competitiveness of the NSR is evident under discounted fees. The analysis in Chapters 5 and 6 shows that the NSR is always more competitive than both the SCR and Cape routes when independent navigation is assumed in the analysis. This holds true for all OD pairs, under all scenarios and operational modes, when including ice damage repairs, and even at low fuel and commodity prices.

The impact of icebreaking fees is closely related with distance, fuel prices, ice damage repairs, ship size, and fuel types and operational modes.

Ship size: The impact of ship size on the competitiveness of the NSR is examined in Chapter 4. Larger ships achieve a lower RFR across every OD pair and route alternative, all else being equal. Not only do costs fall with the increase in tanker size, but also this decline is bigger in absolute terms at higher fuel prices for a given OD pair and route alternative. The economies of scale derived from larger tanker sizes in absolute terms diminish when moving towards the shortest OD pair for a given route alternative. This means that scale economies are larger for the NSR on the Yeosu-Rotterdam pair and smaller on the Vitino-Daesan pair, whereas the opposite holds true for the SCR. The relationship between distance and ship size is largely influenced by fuel price levels, with the use of smaller tanker sizes on the NSR being more competitive than the use of larger tanker sizes on the SCR when moving towards shorter OD pairs and high fuel prices. The shorter the distance, the lower the critical fuel price level a smaller tanker size becomes more competitive on the NSR than a larger tanker size on the SCR.

The impact of ship size is closely related with distance, fuel prices, icebreaking fees, ice damage repairs, and fuel types and operational modes.

Ice damage repairs: The impact of ice damage repairs on the competitiveness of the NSR is examined in Chapters 4 and 5. Ice damage repairs is another crucial factor which can render the NSR uncompetitive even when assuming high fuel prices and discounted icebreaking fees, depending on fuel types and OD pair distances. Moreover, it significantly reduces the competitiveness of the NSR at low fuel prices. Generally, the higher the fuel prices the lesser the impact of ice damage repairs on the NSR, all else being equal. It should be mentioned that total ice damage repairs costs for a certain voyage, when these are factored in the analysis, comprise repairs costs and the costs of the voyage between the unloading port and the repair yard. This implies that a repair yard which is located farther than one which is located nearer to the unloading port might be chosen, depending on the influence of the two cost elements in the overall costs, and vice versa.

The impact of ice damage repairs is closely related with distance, fuel prices, icebreaking fees, ship size, and fuel types and operational modes.

Capital costs and operating costs: The impact of capital costs and operating costs on the competitiveness of the NSR is examined in Chapter 4. Generally, the cost structure per voyage and route is significantly affected when major cost factors are included in the analysis or not. An increase in costs makes a shorter route more competitive than a longer route. Operating costs are relatively stable during 2011-2020 and do not significantly influence the results in the analysis in Chapter 4. As regards capital costs, a comparison between tankers which incur capital costs and tankers which do not incur capital costs, shows that a shorter route is significantly benefitted by the former, with increased RFR differentials across all OD pairs and tanker sizes. Moreover, the shorter the OD pair, the higher the RFR differential between the NSR and any traditional routes. The economic explanation is that a tanker will need to increase the frequency of voyages or to operate through shorter routes in order to increase earnings at a given period of time to cover the capital costs now added in total costs.

The effect of capital and operating costs is closely related with distance, fuel prices, and fuel types and operational modes.

Commodity prices and in-transit inventory costs: The impact of commodity prices and in-transit inventory costs on the competitiveness of the NSR is examined in Chapters 5 and 6. Generally, the cost structure per voyage and route is significantly affected when major cost factors are included in the analysis or not. An increase in costs makes a shorter route more competitive than a longer route. When in-transit inventory costs are considered in the analysis, shorter route alternatives are always benefitted, depending on the interest rate, the price of the commodity and its price relationship with fuel prices. In-transit inventory costs become the most important cost factor when moving from lower to higher commodity prices, and from longer to shorter distances.

The impact of commodity prices and in-transit inventory costs is closely related with distance, fuel prices, and fuel types and operational modes.

Fuel types and operational modes: The impact of fuel types and operational modes on the competitiveness of the NSR is examined in Chapters 4, 5, and 6. Route competitiveness depends on operational mode and technology as much as it depends on fuel price levels. The competitiveness of a shorter route, such as NSR versus SCR and Cape, or SCR versus Cape increases under high-priced fuel types/operational modes e.g. VLSFO, LNG-VLSFO 1,700 m^3, and high relative LNG/VLSFO distance ratios between a shorter and a longer route. The competitiveness of a longer route over a shorter route, such as SCR versus NSR, or Cape versus SCR and NSR increases under low-priced fuel types/operational modes e.g. HSFO, LNG-VLSFO 3,600 m^3, and high relative LNG/VLSFO distance ratios between a longer and a shorter route. The use of the NSR is favoured at VLSFO and LNG-VLSFO 1,700 m^3, across all OD pairs and optimal speed regimes. Although a low-priced LNG favours the shorter NSR at LNG-VLSFO 1,700 m^3 mode, depending on OD pair distances, a larger LNG tank capacity reduces this benefit and results in higher capital costs, and an increasing LNG/VLSFO ratio in favour of longer routes. The ranking of operational modes and fuel types with respect to route competitiveness depends on distances, fuel tank capacities, and fuel prices.

The impact of fuel types and operational modes is closely related with distance, fuel prices, icebreaking fees, ice damage repairs, ship size, capital and operating costs, and commodity prices and in-transit inventory costs.

Research Question 3: *How does ship speed on ice affect the feasibility of the NSR for oil product tankers?*

The analysis in Chapter 4, Chapter 5, and Chapter 6 is informed by Automatic Identification System (AIS) speed data of oil product tanker destination and transit voyages conducted on the NSR during the summer/autumn seasons of 2011-2019. These data refer to ship speeds of 44 voyages of tankers ranging from MR (47,000 dwt) to Suezmax/LR3 (162,000 dwt) sizes. The data comprise 29,964 observations of tanker speeds recorded per minute for every transit between Cape Zhelanya/Kara Strait and Cape Dezhnev, from end of June (30th) to mid-November (17th). For Chapters 4 and 5, the average speed on ice is calculated by dividing the travelled distances by the time interval between the start and end points of each voyage on the NSR. Then, the average speed of all voyages is calculated and used in the analysis. For Chapter 6, the average speeds in every Arctic Sea per month are calculated by dividing the travelled distances by the time interval between the start and end points of each segment i.e. navigation zone per Arctic Sea.

The analysis in Chapter 6 examines the impact of ship speed through ice on the competitiveness of the NSR for seasonal operations. Arctic sea ice exhibits inter-annual variability and uneven distribution along the NSR (Stephenson et al. 2014; Yumashev et al. 2017). Therefore, ship speed on ice is determined by local sea ice conditions, which vary within the same season, across different zones and also depend on the ice class of a ship (Faury and Cariou 2016; Cariou and Faury 2020; Faury et al. 2020; Cheaitou et al. 2020; Cariou et al. 2021).

Ship speed on ice affects the RFR differentials per month, navigation zone and direction of voyage, all else being equal. A lower speed on ice means a lower average speed for a whole voyage at a given month. Thus, the longer the time spent within ice, the longer the overall voyage transit time. Consequently, the minimum NSR RFR at a given transit gets higher when the speed on ice decreases, and vice versa. Whilst voyage times for a certain OD pair on the SCR are the same across every fuel type, voyage times vary on the NSR owing to different sea ice regimes and the speeds realised through ice. The least time savings are found during July, August, and October voyages, whereas the highest time savings are found during September and November voyages across every fuel type/mode. It should be mentioned that transit times for NSR ballast voyages between the ports of Rotterdam and Ust-Luga are found slightly higher than those for SCR due to the lower optimal speeds of ice class tankers on open water. This is due to the higher fuel consumption of an ice class tanker on open water and, to a lesser extent, of the higher capital and operating costs than those for an ordinary tanker. The combined effect leads to a lower optimal speed.

The seasonal navigation planning allows three transits on the Ust-Luga - Ulsan pair, that is, in July, September, and November. July is found the most challenging month with a ship speed on ice of 8.9 knots, which results in lowest SCR-NSR RFR differentials under fuel prices as of February 2020. September is found the most favourable month with a ship speed on ice of 11.9 knots, which results in highest RFR differentials under fuel prices as of February 2020. The seasonal navigation allows two transits on the Ulsan - Rotterdam pair, that is, in August and October. Ship speed through ice in August is found the second lowest after July, at 10.7 knots. Ship speed through ice in October is found 11 knots, which slightly increases the RFR differentials compared to August voyages under fuel prices as of February 2020.

The lowest minimum NSR RFR on the Ust-Luga - Ulsan pair is achieved in September, where the SCR-NSR RFR differential is also the highest across all transits and fuel types/modes, and the difference between the speed on ice and optimal speed on open water is lower than in July and November. The lowest minimum NSR RFR on the Ulsan - Rotterdam pair is achieved in October, where the SCR-NSR RFR differential is the highest across all transits and fuel types/modes, and the difference between the speed on ice and optimal speed on open water is lower than in August.

Research Question 4: *How do different approaches to ship speed choice and cost modelling affect the feasibility of the NSR for oil product tankers?*

The analysis in Chapter 4 and Chapter 6 is based on speed optimisation which minimises the RFR of a route alternative. The analysis in Chapter 5 is based on a methodological approach which has two objectives. First, the cost assessment is based on speed optimisation, which minimises the RFR of a route alternative. Second, the cost assessment is based on real speeds to assess the RFR of a route alternative, drawing from AIS data.

Classical maritime economic theory holds that the (theoretical) optimal speed which minimises the cost per tonne is not affected by short-term freight rate volatility, port time or delays, and therefore is more appropriate for long-term planning than one which aims to maximise profit (Alderton 1981; Evans and Marlow 1990). Alderton (1981) refers to this speed as the *least cost speed* (LCS). This speed determines the minimum cost per tonne in the long-term period or in other words, the *break-even point* of operations. The minimum cost per tonne is the long-run equilibrium point between supply and demand, where revenue equals cost (Alderton 1981). This optimal ship speed depends on operating and capital costs, payload and fuel prices, all else being equal. The cost minimising speed which considers both the value of ship and cargo carried on board is referred as the *least cost inventory speed* (Alderton 1981). This optimal speed depends on operating and capital costs, in-transit inventory costs, fuel prices, and payload, all else being equal.

Real speeds are less responsive than optimal speeds to cost and market factors. They tend to depart from optimal points determined by market factors owing to organisational and technical constraints, ship and voyage specific variables as well as weather factors amongst others (Adland et al. 2017; Adland and Jia 2018). Moreover, speeds through ice are assumed to not vary with respect to cost and market factors due to the influence of sea ice on ship speed, and therefore could be determined based on recorded speeds of tanker voyages conducted on NSR.

The U-shaped RFR curves derived from speed optimisation demonstrate the trade-off between fixed and variable costs with any departure from the optimal speed being cost-wise inefficient, always subject to constraints. At speeds lower that the optimal one, fuel costs decrease non-linearly whereas capital and operating costs increase with more days per voyage. At speeds higher that the optimal one, fuel costs increase non-linearly whereas capital and operating costs decrease with less days per voyage. High fuel prices reduce the optimal speed which minimises the RFR. Low fuel prices increase the optimal speed which minimises the RFR.

Optimal laden speeds are always lower than optimal ballast speeds regardless of fuel price levels and route alternatives. The explanation is that when a ship is loaded with cargo, fuel consumption and resistance are higher than when operating in ballast. As a result, the minimum RFR is higher when a ship is laden than when it is not, owing to higher fuel costs, and operating and capital costs. The higher the fuel prices, the higher the minimum RFR at the optimal laden speed than at the ballast speed since the impact of higher fuel prices at the decrease of optimal speed and the increase in fuel costs is more pronounced when a ship is laden than when it is not. Thus, fixed costs are higher at a lower optimal laden speed than at a lower optimal ballast speed, whereas the difference in fuel costs depends on the speed differential at each fuel price level.

The consideration of ship value and/or value of cargo carried on board leads to higher speeds and benefit shorter routes in general. When considering the ship value i.e. capital costs in the analysis, optimal laden speeds increase across all route alternatives. The economic explanation is that the frequency of voyages needs to be increased and/or shorter routes need to be used in order to cover the capital costs which are added in total costs. This is reflected in the optimal speed function, where the numerator increases when including capital costs. When considering the cargo value on board by including in-transit inventory costs in the analysis, optimal laden speeds become higher than optimal ballast speeds across all fuel and commodity prices, and route alternatives. This indicates that optimal laden speeds are more sensitive to the value of cargo than to fuel prices, depending on the interest rate, the price of the commodity and its price relationship with fuel prices. Not only are minimum RFR rates at laden speeds, including in-transit inventory, higher than those at ballast speeds but also they are higher than minimum RFR rates at laden speeds without in-transit inventory. Both fuel and fixed costs are higher at optimal laden than ballast speeds when moving towards high fuel and commodity price levels. On the one hand, a growing value of cargo on board influences fixed costs more than the lower operating and capital costs per fuel and commodity price level. On the other hand, fuel costs are higher due to both an increased speed differential and increased fuel consumption when a ship is loaded with cargo.

As regards ship speed through ice on NSR, this is primarily determined by sea ice conditions per month, navigation zone, voyage direction, season, and ice class notation of a ship. A lower speed on ice means a lower average speed for a whole voyage at a given month. Thus, the longer the time spent within ice, the longer the overall voyage transit time. Consequently, the minimum NSR RFR at a given transit gets higher when the speed on ice decreases, and vice versa. The section above provides a more detailed explanation of the impact of speed through ice on the economics of the NSR, which is based on the analysis of Chapter 6.

Generally, a lower optimal voyage speed on NSR than on other routes is the result of the lower speed on ice, given that optimal NSR speeds on open water legs are higher than those on other routes due to increased costs of ice class tankers. Yet, this also depends on fuel price levels and the consideration of certain cost factors, such as capital costs. Optimal NSR speed is higher than optimal SCR speed when capital costs are not considered in the analysis, as is the case for the period 2018-2020 analysed in Chapter 4. This is explained by the fact that the speed on ice influences more the average voyage speed than the optimal speed on open water, which is lower than the speed on ice when capital costs are not included in the analysis. Conversely, the optimal NSR speed is lower than the optimal SCR speed when capital costs are considered in the analysis, as is the case for the periods 2011-2014 and 2015-2017 analysed in Chapter 4. This is explained by the fact that the speed on ice influences more the average voyage speed than the optimal speed on open water, which is higher than the speed on ice when capital costs are included in the analysis.

Alternative fuel types and operational modes also affect optimal speeds across all route alternatives. A combination of fuel heating (calorific) values, fuel prices, and capital costs of a certain fuel type/operational mode and technology largely determines optimal speed per route alternative. The optimal speed tends to be higher than the design speed for low-priced fuels, such as HSFO and LNG, whereas it tends to be lower than the design speed for high-priced fuels such as VLSFO, depending on fuel price levels. Moreover, the effect of fuel prices outweighs any additional capital expenses of fuel technologies, such as those of scrubbers in the case of HSFO-Scrubber mode or those of fuel tanks and relevant costs in the case of dual-fuel Oil/LNG modes.

Optimal speeds also affect planning for seasonal operations, as shown in the analysis in Chapter 6. All else being equal, the impact of fuel and commodity prices in a speed optimisation context is evident. The choice of fuel and commodity affects optimal speeds, and therefore determines the number of round voyages per season, depending on OD pair distances. The choice of a cheap fuel leads to high optimal speeds and number of round voyages, and vice versa.

When comparing a shorter route with a longer route against the constant speed of 12 knots, such as NSR versus SCR and Cape, or SCR versus Cape, it is found that a shorter route is more competitive than a longer route. The reason is that transit times for a longer route increase more than those for a shorter route. On the one hand, a speed which is lower than the design or optimal speed results in higher fuel costs owing to the non-linear increase in fuel consumption. On the other hand, fixed costs increase significantly, especially in-transit inventory costs. This is the result of longer transit times since the speed of 12 knots is lower than the design or optimal speed. Yet, longer routes increase their competitiveness either at optimal or lower than optimal or fixed speeds, when in-transit inventory costs are not considered in the analysis.

A longer route is favoured at constant speeds, which are lower than optimal speeds, when assuming an increase in the use of a low-priced fuel and a simultaneous decrease in the use of a high-priced fuel, under a dual-fuel operational mode. Yet, this effect is also dependent on OD pair distances, fuel heating (calorific) values, and the price difference between the two fuels. This applies to the Cape route versus the SCR across all OD pairs at the base case and high fuel/commodity price scenarios of the LNG-VLSFO 1,600 m^3 mode under the constant speed regime of 12 knots. The reason is that the use of LNG increases with lower speeds and results in a higher LNG/VLSFO distance ratio in favour of the Cape route. As a result, the SCR-Cape RFR differentials are reduced at the constant speed regime compared to the RFR differentials under the optimal speed regime.

Research Question 5: *How do emissions regulations and alternative operational modes and fuel types affect the feasibility of the NSR compared to the traditional routes for oil product tankers?*

The analysis in Chapter 4 addresses current emissions reductions policies (Emission Control Areas: ECAs, IMO sulphur limit) by assuming the use of Marine Gasoil (MGO) and VLSFO. The analysis in Chapters 5 and 6 addresses current and future emissions reductions policies (ECAs, IMO sulphur limit, Initial IMO greenhouse gas (GHG) Strategy, future prohibition on the use of heavy fuels in the Arctic) by assuming the use of MGO, VLSFO, and dual-fuel Oil/LNG engine set-ups, based on current and future technologies with respect to LNG fuel tank capacity.

The analysis in Chapter 4 shows that the IMO regulation with respect to ECAs led to increased fuel costs and lower optimal speeds due to the use of MGO within ECAs regardless of route choice. The implementation of ECAs policy impacts the competitiveness of a route depending on the ECAs distance and the quantity of the fuel used for compliance. The SCR-NSR RFR differential on the Yeosu-Rotterdam pair would have been lower if MGO was used in ECAs prior to 2015. The reason is that the NSR ECAs leg is longer than the SCR ECAs leg against the Yeosu-Rotterdam pair. On the other hand, the SCR-NSR RFR differential on the Mongstad-Mizushima pair would have been higher due to a significantly shorter ECAs leg for the NSR compared to that for the SCR.

The IMO 2020 regulation with respect to global sulphur limit is addressed in Chapters 4, 5, and 6. The IMO 2020 sulphur limit can benefit the NSR, since VLSFO is a high-priced fuel compared to HSFO. Yet, this depends on the price differential between VLSFO and HSFO, as well as the adoption rate of scrubbers in order for a ship to be able to use the low-priced HSFO after 2020.

The impact of a future prohibition on the use of heavy fuel oils in the Arctic, such as VLSFO and HSFO, even with the use of a scrubber, largely depends on the fuel type or operational mode which could be adopted by a shipowner. The analysis in Chapters 5 and 6 shows that the use of MGO through ice by oil-powered tankers reduces the competitiveness of NSR compared to both Cape and SCR routes on the HSFO-Scrubber mode, especially when moving towards high fuel/commodity price scenarios. This impact is similar either at optimal or constant speed regimes and both with and without assuming icebreaking fees. This is the result of a wide price differential between HSFO and MGO. On the other hand, the difference is negligible on the VLSFO mode, where the VLSFO-MGO price differential is smaller, since the prices of the two fuels are closer than those between HSFO and MGO. However, the relative difference between each pair of fuels may vary and not be relatively stable.

Chapters 5 and 6 address the impact of the Initial IMO GHG strategy by assuming the use of dual-fuel Oil/LNG engine set-ups. Fuel price differentials determine the attractiveness of a fuel type and operational mode for a given route alternative. Moreover, the ranking of each fuel type or operational mode varies with respect to distance, fuel tank capacity, fuel prices, optimal speed levels and/or real speed levels.

The analysis in Chapter 5 shows that the competitiveness of the NSR increases under high-priced fuel types/operational modes, such as, VLSFO, LNG-VLSFO 1,700 m^3, and high relative LNG/VLSFO distance ratios, all else being equal. The use of the NSR is favoured at VLSFO and LNG-VLSFO 1,700 m^3, across all OD pairs and optimal speed regimes. The highest SCR-NSR and Cape-NSR RFR differentials at optimal speeds are found under the

VLSFO mode, followed by the LNG-VLSFO 1,700 m^3, HSFO-Scrubber, and LNG-VLSFO 3,600 m^3 modes, respectively. The highest SCR-NSR RFR differentials at constant speeds are found under the VLSFO mode, followed by HSFO-Scrubber, LNG-VLSFO 1,700 m^3 and 3,600 m^3 modes, respectively. The highest Cape-NSR RFR differentials are the same as those at the optimal speed regime. When including ice damage repairs, the LNG-VLSFO 1,700 m^3 mode comes first, followed by VLSFO, HSFO-Scrubber, and LNG-VLSFO 3,600 m^3 modes for both the SCR-NSR and Cape-NSR RFR differentials at optimal speeds, respectively. Yet, the order of modes for RFR differentials at constant speeds is the same as that when ice damage repairs are not included.

Similar observations can be made for seasonal navigation scenarios. The analysis in Chapter 6 shows that the choice of VLSFO, including MGO within ECAs, gives the highest SCR-NSR RFR differential across all individual voyages, whereas the choice of HSFO-Scrubber gives the lowest RFR differential. The RFR differential of individual voyages on the LNG-VLSFO 1,700 m^3 option is found in between those under the VLSFO and HSFO-Scrubber modes due to the combination of a low-priced fuel (LNG) with a high-priced fuel (VLSFO). Yet, LNG-VLSFO is slightly more competitive than VLSFO for seasonal navigation on the NSR. This is the result of using only the low-priced LNG fuel on the ballast voyages between the ports of Rotterdam and Ust-Luga. On the other hand, only the high-priced VLSFO is used on ballast voyages under the VLSFO mode.

The adoption of the dual-fuel LNG-VLSFO operational mode has various implications for route competitiveness, depending on distance, different technologies, sea ice conditions and speed through ice on NSR. The analysis in Chapter 6 shows that the LNG-VLSFO mode with LNG fuel tank capacity of 1,700 m^3, favours the use of the NSR. The reason is that low-priced LNG is used at longer distance legs compared to SCR and Cape. The relative competitiveness depends on the LNG/VLSFO distance ratio, OD pair distances and LNG tank capacity. Moreover, the LNG-VLSFO option can be an alternative to the use of MGO when assuming a prohibition on the use of heavy fuel oils in the Arctic.

The analysis in Chapter 5 shows that although a low-priced LNG favours the shorter NSR at LNG-VLSFO 1,700 m^3 mode, a larger LNG tank capacity reduces this benefit and results in higher capital costs, and an increasing LNG/VLSFO ratio for longer routes depending on OD pair distances. Moreover, a longer route increases its competitiveness or reduces its losses at constant speeds, which are lower than optimal speeds, when assuming an increase in the use of a low-priced fuel and a simultaneous decrease in the use of a high-priced fuel under a dual-fuel operational mode. Yet, this also depends on OD pair distances, fuel heating (calorific) values, and the price difference between the two fuels.

7.3 Contribution to knowledge

This Thesis provides the first systematic literature review on comparative studies between Arctic and traditional routes. An evaluation of the literature reporting results on economic and environmental assessments of the Arctic routes is attempted, based on journal articles published between 1980 and 2021. Further, the methodological characteristics of the reviewed papers are identified and analysed. Important factors are identified and discussed, concerning transport systems (bulk, liner, specialised shipping), cost premiums and related factors (crew, insurance, repairs and maintenance, capital costs, periodic maintenance, fuel consumption, speed on ice, icebreaking fees), revenue-related factors (speed on ice, ship size, ice class, deadweight utilisation/load factors, in-transit inventory costs, freight rates), navigational factors (route choice, navigation season, speed on ice), and environmental factors (emissions regulations, alternative fuel types, emissions assessment approaches).

This Thesis focuses on destination and transit voyages conducted on the NSR during 2011-2020. The first category refers to voyages that originated or terminated within or outside the Arctic. The second category refers to voyages conducted between the Atlantic and the Pacific Ocean through the Arctic. Historically, the share of oil tanker voyages and, to a lesser extent, that of dry bulk carrier, fluctuated considerably between 2011 and 2020. More specifically, the share of oil tanker destination and transit voyages was 53% in 2011, 54% in 2012, 47% in 2013, and 52% in 2014 of the total, whereas it comprised only an average 12% of the total between 2015 and 2020. Favourable sea ice conditions and distance savings explain only part of the surge in exploratory voyages through the NSR during the last ten years. Other factors, such as the nature of the transport system, geopolitical developments, cost and market factors, and commodity price developments, largely determine route choice. General cargo and heavy lift cargo ships are benefitted by using the NSR for voyages between east and west, and this is explained by the consistent use of the route during the last four years. Equally, the use of the NSR for cargoes originating from the Arctic considerably reduces distances for destinations in the Far East, depending on the nature of cargo.

However, commodity price developments, arbitrage opportunities, and geopolitics largely affect route choice for energy commodities along with cost factors, such as marine fuel prices.

The marked difference in the number of destination and transit tanker voyages through the NSR between the periods 2011-2014 and 2015-2020 reflects the volatility in commodity and fuel markets, as well as other developments that impacted oil products flows and ultimately route choice from a global perspective. Therefore, this Thesis is focused on the assessment of the NSR against the oil product tanker market, taking into account historic destination and transit traffic records, and developments in the global shipping and energy markets. This Thesis aims to explain the emergence of the NSR as an alternative route for oil product tankers during 2011-2020. Moreover, it aims to explain the economic, navigational and environmental factors which affect its use compared to traditional sea routes between Europe and Asia. It should be mentioned that only six papers examined the oil tanker market in the context of Arctic shipping as of 2021.

The factors considered in the analysis in Chapters 4, 5, and 6, are distance, fuel prices, ship speed through ice, seasonal navigation, icebreaking fees, ice damage repairs, ship size, capital and operating costs, commodity prices and in-transit inventory costs, as well as fuel types and operational modes, concerning commercial factors and environmental regulations.

The first modelling case in Chapter 4 examines the use of the NSR based on historic destination and transit voyages to explain its emergence since the 2010s. The analysis focuses on *distance*, *fuel prices*, *icebreaking fees*, and *ship size*. The feasibility of the NSR is assessed against the SCR route for single oil product tanker voyages between Europe, the Russian Arctic, and Northeast Asia at the tactical/operational level during the summer/autumn season. The choice of OD pairs reflects historic voyages conducted on the NSR, based on representative ports, distance savings, and tankers that were involved in the transport of major oil products during 2011-2020. Four oil product tanker sizes are considered to assess the impact of ship size on RFR and route choice. First, costs are assessed during 2011-2014 and 2015-2017, reflecting developments of major cost and market factors which affected route choice. Second, costs are assessed for the years 2018, 2019, and 2020, respectively. The analysis considers alternative fuel types to address current emissions reductions policies (ECAs, IMO sulphur limit).

The second modelling case in Chapter 5 assesses the feasibility of the NSR against the SCR and Cape of Good Hope routes. The analysis focuses on *commodity prices*, *in-transit inventory costs*, and *alternative operational modes* based on *current* and *future technologies*. The analysis in this chapter complements Chapter 4 by considering in-transit inventory costs and addressing market structure and route choice in the wider context of oil product tanker flows, drawing from AIS data of voyages conducted between the Far East and Europe in 2011-2020. The NSR is compared to the SCR and Cape of Good Hope routes for single oil product tanker voyages between Europe and Northeast Asia at the tactical/operational level during the summer/autumn season. The NSR is compared with both the SCR and Cape routes to explain route choice for oil product tanker trades between Northeast Asia and Europe, based on cost factors and market developments which favour longer or shorter routes. The analysis considers alternative fuel types and operational modes to address current and future emissions reductions policies (ECAs, IMO sulphur limit, Initial IMO GHG Strategy, future prohibition on the use of heavy fuel oils in the Arctic).

The third modelling case in Chapter 6 assesses the feasibility of the NSR against the SCR for seasonal navigation operations. The analysis considers *ship speed on ice* and *alternative operational modes and fuels* based on *current technologies*. The analysis in this chapter complements Chapter 4 and Chapter 5 by developing seasonal navigation scenarios and considering real hourly AIS speed data of historic tanker voyages conducted on NSR to determine the varying speed through ice on NSR. The analysis assesses seasonal navigation between ports located in the Baltic Sea, Northwest Europe and Northeast Asia during the summer/autumn season. The analysis is undertaken at the strategic level (choice of oil products/commodities and routes as an expert-based scenario). The analysis considers alternative fuel types and operational modes to address current and future emissions reductions policies (ECAs, IMO sulphur limit, Initial IMO GHG Strategy, future prohibition on the use of heavy fuel oils in the Arctic).

7.4 Contribution to methodology

The analysis in this Thesis is based on the Required Freight Rate that minimises the cost per tonne from the shipowner's perspective. The methodological approach has two objectives. First, the cost assessment is based on speed optimisation, which minimises the RFR of a route alternative. Second, the cost assessment is based on real speeds, drawing from AIS speed data.

On the one hand, the cost per tonne reaches its minimum when speed is optimised with respect to cost and market factors subject to engine technical boundaries. On the other hand, real ship speeds tend to depart from optimal points determined by market factors owing to organisational and technical constraints, ship, and voyage-specific variables, as well as weather factors amongst others. Moreover, speed through ice on the NSR is assumed to not vary with respect to cost and market factors. The reason is that speed through ice primarily depends on sea ice conditions and may not equal the optimal speed. Thus, it has to be approximated based on either physical factors, such as ice thickness, or on real speeds recorded on the NSR. The assumptions for ship speed through ice on NSR in this Thesis are informed by AIS speed data of historic oil product tanker voyages conducted on the NSR. The analysis in Chapter 4 and 6 is based on speed optimisation. The analysis in Chapter 5 is based on optimal speeds, and real speeds, drawing from AIS data. Moreover, the analysis in Chapters 4, 5, and 6, is informed by AIS speed data to determine speed on ice.

A fuel consumption function is employed in the RFR models which depends on speed, fuel type, operational mode and payload. Partial differentiation is carried out with respect to speed in order to obtain the optimal speed of a voyage or route alternative. This optimal speed depends on fixed costs, fuel prices, and payload. The relationship between laden speed, laden speed with in-transit inventory, and ballast speed is established. A novelty is the incorporation of dual-fuel Oil/LNG engine set-ups in the fuel consumption function to consider LNG and pilot fuel oil consumption, both of which vary with ship speed.

The RFR is a function of distance, fuel consumption, speed, total cost inputs and cargo carrying capacity of a tanker for a given voyage and route alternative. The RFR models include variables related to alternative operational modes. These operational modes and fuels refer to oil and gas-based fuels (HSFO, HSFO with scrubber, VLSFO, MGO, LNG), as well as current and future technologies, such as LNG fuel tank capacities based on current (1,700 m^3) and future (3,600 m^3) technologies. Moreover, the RFR models include in-transit inventory costs.

The purpose of using AIS data is fivefold. First, they are used to determine average ship speed through ice on NSR in the analysis in Chapters 4 and 5. Second, they are used to determine ship speed through ice on NSR per month, navigation zone and voyage direction in the analysis in Chapter 6. Third, they are used to determine real ship speeds in the analysis in Chapter 5. Fourth, they are used to identify route choice concerning oil product tanker voyages between Northeast Asia and Europe in the analysis in Chapter 5. Fifth, they are used in order to perform a valid analysis of all the voyages conducted on NSR during 2009-2020, based on voyage type, such as destination, transit, and intra-Arctic. This analysis is reported in Chapters 2 and 4.

The secondary data used in the RFR models are unique and up-to-date. This enables a valid and reliable methodological approach and analysis. Most importantly, unique primary data are used in the RFR models with respect to specific cost premiums for ice class tankers. The primary data significantly improved the accuracy and internal validity, measurement validity and ecological validity of the modelling research of this Thesis. The use of both primary and secondary data enabled the development of cost models which explain the use of the NSR, both historically and currently.

7.5 Contribution to practice

The findings of the systematic literature review of the Thesis serve as evidence to inform transport practitioners who operate or willing to operate on Arctic sea routes regarding cost, market, and navigational factors, as well as factors related to emissions regulations, alternative fuel types and operational modes, and emissions assessment approaches. The systematic review provides an understanding of the factors that promote or hinder the competitiveness of the Arctic routes, why and how.

This Thesis contributes to the literature by developing a cost analysis which aims to explain quantitatively why the NSR was a competitive alternative for oil product tankers during 2011-2014 and how cost and market factors affected its competitiveness during 2015-2017 and between 2018 and 2020. The analysis in Chapter 4 refers to the historic use of the NSR, and is based on both new tankers with incurring capital costs and tankers without incurring capital costs. This approach provides an understanding on how voyage cost structure and route competitiveness is affected by including or excluding certain cost factors in the analysis. Most importantly, the volatility of fuel prices is taken into account amongst others. The relationship between distance and ship size is also assessed.

The analysis in Chapter 5 considers commodity prices and in-transit inventory costs to address market structure and route choice in the wider context of oil product tanker flows, drawing from AIS data of voyages conducted between the Far East and Europe during 2011-2020. Not only is the NSR compared with SCR, but also the Cape of Good Hope route is included in the analysis to explain route choice for oil product tanker trades, based on cost factors and market developments which favour longer or shorter routes. The cost-based analysis explains route choice depending on two distinct states of the market. First, it explains the choice of shorter routes when cargo value is important, and fuel and commodity prices are high. Second, it explains the choice of longer routes when cargo value is not critical, and fuel and commodity prices are low.

The analysis of seasonal navigation operations in Chapter 6 is informed by real hourly AIS speed data of historic oil product tanker voyages conducted on NSR to determine the varying speed through ice on NSR. Thus, it provides an understanding on how sea ice conditions affect ship speed per month, navigation zone and voyage direction. The results explain how the competitiveness of the NSR is affected by varying speeds through ice and inform shipowners and operators who aim to use the NSR for seasonal operations during the summer/autumn season.

Another novelty is the consideration of alternative fuel types with reference to the IMO 2020 sulphur limit policy, the Initial IMO GHG Strategy, and a future prohibition on the use of heavy fuel oils in the Arctic. These operational modes and fuel types include the use of scrubber with HSFO, the new VLSFO, and dual-fuel Oil/LNG engine set-ups. Moreover, the use of MGO through ice is considered for oil-powered tankers, when assuming a future prohibition on the use of VLSFO and HSFO, including with the use of scrubbers, in the Arctic. The assumptions and scenarios on alternative fuel types and operational modes explain how the competitiveness of the NSR is affected with respect to specific fuel type and operational mode choices.

The factors of distance, USD/RUB exchange rates, capital and operating costs, capital cost premiums, fuel consumption for ice class tankers, icebreaking fees, Suez Canal Tolls, interest rates, and fuel and commodity prices, are all informed by relevant practices and up-to-date secondary data.

As regards icebreaking fees, the official tariff rates are considered, based on the inverse relationship between the USD/RUB exchange rate and fuel oil prices. Moreover, the analysis is informed from real practices by assuming relevant discounted fees and independent navigation scenarios. Moreover, ice damage repairs are factored in the analysis to better reflect the cost structure of voyages on NSR. The assumptions and data on fuel consumption at the design speed per tanker, fuel type and technology are derived from an on-line tool from MAN Energy Solutions. Moreover, assistance and clarifications on the tool were sought from marine engineers of MAN by means of email communication.

Moreover, unique primary data, such as ice class premiums (crew premium, insurance premiums, ice coating costs) and ice damage repairs costs were obtained from a shipowner who conducted a considerable number of destination and transit oil product tanker voyages on the Northern Sea Route in 2011-2020. These data are used in the RFR models to develop a valid analysis concerning the comparison between the NSR, SCR and Cape routes. The primary data improved the quality of the cost analysis and provide valuable insights to practitioners who own or operate ice class tankers and aim to use the NSR as an alternative route to the traditional sea routes and ship canals.

7.6 Reflection on the research design, methodology, and aspects of validity and reliability

Two distinctive research designs are adopted in this Thesis. A research design based on a systematic literature review and a multi-method quantitative research design. The first design refers to the systematic review of the literature. The second design refers to the development of cost models, and the use of optimisation techniques, secondary data sources, and email communication. The research findings are derived from a coherent and applied methodology, the uniqueness of the data employed, the validation procedures applied and the quality of the research design.

As regards cost modelling and optimisation techniques, the validity is considered by using the criteria of internal and external validity, ecological validity, face validity, content validity, and criterion validity (concurrent and predictive validity). Reliability is considered by addressing internal reliability and external reliability. Moreover, validation is considered by employing triangulation.

The Required Freight Rate approach is fundamental in voyage cost estimation and route comparisons. It offers a cost-based approach to freight estimation and establishes the break-even point of operations. The face validity is ensured by developing RFR models which are informed from both the academic and industry literature. The content validity is established by considering all variables included in a RFR model, that is, capital costs, operating costs, and voyage costs. Cargo value is also included in the RFR models by considering the in-transit inventory costs. The criterion validity is also addressed in the research design. The RFR models are used to assess costs for competing routes under various scenarios and assumptions drawing from the period between 2011 and 2020. The basic scenarios and sensitivity analyses in the analysis in Chapters 4, 5, and 6 provide outcomes in the past and present (concurrent validity) and predict outcomes in the future (predictive validity).

The highly structured nature of the research enquiry by means of employing mathematical models and logic, which are commonly used to address the problem under investigation in the area of maritime economics, establishes the internal validity and measurement validity of the modelling research of this Thesis. The research findings ensure the external validity, that is, the generalisability of the findings, to organisations of similar characteristics, given the global nature of shipping and the way market developments affect all market participants. Notwithstanding the small number of destination and transit tanker voyages conducted on the

NSR so far, the primary and secondary data obtained enhance the quality of the research design and establish the ecological validity of the findings of the research. More specifically, the findings from the analysis in Chapters 4, 5, and 6, are validated and confirmed in the 'Discussion and concluding remarks' Sections of the respective Chapters, as well as in this Chapter.

The internal reliability of the cost models and optimisation techniques is addressed in various ways. The use of the Microsoft Excel software ensures the consistency of calculations, which are repeated at different times to ensure that findings are correct. Moreover, the stability is promoted by writing detailed accounts of the methodological procedure. These accounts include both the main modelling approach reported in Chapters 4, 5, and 6, and supporting calculations and assumptions reported in Appendices L, M, N, O2, P, S1, S2, T, X1, X2, Y1, Y2. Similarly, the external reliability is addressed by replicating the calculations for all modelling cases and scenarios. This involved using the same methods, data analysis techniques and assumptions in order to compare the new findings with the initial ones.

As regards secondary data sources, the overall suitability is considered by addressing measurement validity and coverage. The precise suitability is considered by addressing validity and reliability, and measurement bias criteria. Moreover an evaluation of the costs and benefits of obtaining and using secondary data sources is provided.

The face validity is assumed since the secondary data are relevant and appear to reflect the content of the data variables. Moreover, the reputation of the organisations which provide the data further enhances face validity. The content validity is established, given that the data variables provided by secondary data sources enable the adequate coverage of the research questions. Moreover, several secondary data sources, including databases, websites, industry reports and articles, as well as academic and industry literature are used for supporting calculations related to the main modelling approach. These sources can be found in the analysis in Chapters 4, 5, and 6, and in Appendices L, M, N, O2, P, S1, S2, T, X1, X2, Y1, Y2. A summary of the data sources is provided in Table 3.5.

The criterion validity of secondary data sources is also addressed in the research design. The secondary sources provide a range of data variables and respective time series which enable the measurement of variables in the past and present (concurrent validity). As regards the consideration of predictive validity, this depends on the data analysis techniques, scenarios, and sensitivity analyses employed, which are informed by the data.

The internal validity of secondary data sources is assumed since the specific procedures which are used to collect, compile or analyse the data cannot be confirmed. Yet, the procedures and data analysis techniques are assumed to truly measure the concepts, given the reputation of the organisations which provide the data. As regards external validity, the data can be used for research purposes in order to generalise to organisations of similar characteristics. Besides, ecological validity is established since the secondary data are collected from natural occurring social settings. As regards coverage, a number of characteristics are ensured. First, the secondary data cover the population about which the data are needed. The time period varies for some of the data variables but not very significantly. More specifically, data of operating costs in Chapters 5 and 6 cover the period 2011-2018, whereas in Chapter 4 they cover the period 2011-2020. This is attributed to the unavailability of data for the period 2018-2020 when the modelling cases in Chapters 5 and 6 were developed. Similarly, data of newbuilding prices for LR2 tankers in Chapters 4, 5, and 6 cover the period after 2013, since Clarksons (2021) does not provide data of newbuilding prices for LR2 tankers before 2013. However, the lack of data for these years does not significantly affect the assumptions and research findings since both operating costs and newbuilding prices do not vary considerably in the time periods chosen for analysis. Second, the data variables enable answering the research questions. Third, the representativeness of the number of observations is not affected when excluding data which are not needed in the analysis.

Measurement bias criteria are addressed in the research design of this Thesis. The purpose for which the secondary data are collected and compiled by organisations, such as Clarksons, Refinitiv Eikon, Bloomberg, S&P Platts (Capital IQ), IHS Maritime, DNV, BDO, BP, IGU, the IEA, the IMF, the FED of St. Louis, the Bank of Russia, and OPEC is for use by researchers, market participants, policy makers, or academics in order to conduct further research and analysis.

There are a number of measurement biases which are difficult to detect. These include the deliberate distortion of data, changes in the way data are collected or measured, undocumented changes in the way data are collected or measured, and whether the data analysis techniques developed to collect, compile or analyse the data are able to truly measure the concepts.

There are various ways to address these issues. Triangulation with other secondary data sources is conducted to compare data from one database with same data from other databases to ensure validity. A high degree of confirmability is achieved across independent secondary data sources. Examples include data of newbuilding prices between Clarksons (2021) and several other shipbroking companies reporting such data, operating costs data between BDO (2021), Clarksons (2021) and the Baltic Exchange (2021), fuel and commodity prices data between Clarksons (2021), the IEA (2021c), OPEC (2021), and BP (2020), distance estimation between Dataloy (2021), Marine Traffic (2021), Sea Distances (2021), and Worldscale (2021), and estimation of the Suez Canal Tolls between calculators of Leth Agencies (Leth Agencies 2021b), the Suez Canal Authority (SCA 2021), and Wilhelmsen (2021). Should there be any wide discrepancies between two sources, then a third or even a fourth one is used to further compare the data. Examples include differences in LNG prices data in Asia between Clarksons (2021) and Refinitiv Eikon (2021). Data from the website Ship & Bunker (2021) were used to compare between the three sources. Data from Refinitiv Eikon (2021) were finally used since values are closer to data values from Ship & Bunker (2021) than those from Clarksons (2021). Similarly, speed data points from Bloomberg (2021) are richer than those from Refinitiv Eikon (2021), although both sources provide the same AIS data.

The use of the same source for the same data is consistent throughout the methodological process and calculations to ensure consistency and avoid discrepancies. Moreover, it is assumed that data analysis techniques employed truly measure the concepts, given the reputation of the organisations which provide the data. Finally, documented changes did not report any changes in the way data are collected or measured by the organisations which provide the data during the conduct of the research of this Thesis. Financial costs to obtain the data were low since most of the sources and databases which provide the data are available by the University. The only exception is the annual subscription paid to Dataloy to use its distance calculator. Equally, the time taken to locate and obtain the data from secondary sources was very short in all cases. Conversely, significant benefits were derived from obtaining and using the data as they enabled answering the research questions of the Thesis. Other benefits include the familiarity of the form in which the data files are available as well as the user-friendliness of the Microsoft Word and Microsoft Excel softwares.

The internal reliability of the secondary data is assumed since the procedures used by the organisations to collect, compile or analyse the data cannot be confirmed. These procedures are assumed to be rigid and accurate, given the reputation of the organisations which provide the data.

As regards the method of email communication, the validity is considered by using the criteria of face validity, content validity, and criterion validity (concurrent and predictive validity). Reliability is considered by using the ‘alternative form’. Moreover, validation is considered by addressing participant validation.

The face validity is assumed since the primary data are relevant and appear to reflect the content of the data variables. Moreover, the tanker owner who provided the primary data conducted a considerable number of destination and transit oil product tanker voyages on the Northern Sea Route in 2011-2020. This further enhances the face validity of the primary data collected.

The content validity is established, given that the list of the survey questions contain questions which enable the adequate coverage of the research questions of the Thesis. The survey questions are formulated based on careful definition of the research and drawing from both the academic and industry literature regarding factors and variables relevant to the concept measured. The criterion validity of primary sources is also addressed in the research design. The primary data source provided data which enabled the measurement of the concept in the past and present (concurrent validity). As in the case of secondary data sources, the predictive validity depends on the data analysis techniques, scenarios, and sensitivity analyses employed, which are informed by the data.

As regards reliability of the primary data collected, the ‘alternative form’ is used, where data collection is repeated at different time periods to confirm consistency. This is achieved by repeating questions which refer to the same data or by asking questions in alternative forms of the same question (Saunders et al. 2019). The tanker company which provided the primary data is one of the eight companies which used the NSR for exploratory transit or destination voyages in 2011-2020. This implies that the reliability and quality of the primary data obtained may be a concern due to a single source of information. On the one hand, the number of companies which conducted tanker voyages on the NSR during 2011-2020 is relatively small. On the other hand, a better measure of quality assurance should take into account the number of voyages conducted by each tanker company rather than relying on the number of companies per se. Although only one tanker company provided primary data, its tankers conducted a large number of voyages compared to the rest of the tanker companies. The exact number of voyages in absolute values or percentages cannot be provided due to confidential reasons.

Validation is used to further enhance validity. The multi-method quantitative research design adopted in this Thesis includes the development of cost models and the use of optimisation techniques, secondary data sources, and email communication. Authoritative sources from both the academic and industry literature are used to develop valid cost modelling approaches. Several secondary sources are used to confirm the validity of the data and comparisons are made across databases and other secondary sources. These data and assumptions refer to cost, market, and navigational factors. Moreover, the measurement validity is significantly improved by using unique primary data and insights from a tanker shipowner who conducted a considerable number of destination and transit oil product tanker voyages on the NSR in 2011-2020. Had the author of this Thesis relied only on secondary data sources to develop the modelling research, the findings could have been misleading. Participant validation is also employed to confirm that the primary data provided are correct. The data were sent to the informant for further validation and amendments were made in case inconsistent data were provided initially. This procedure was also followed in other settings, such as in email communication with informants related to secondary sources who assisted the author of this Thesis by providing further information and clarifications on the secondary data.

The RFR models comprise capital, in-transit inventory, operating, and voyage costs. The variation of any or all of these cost categories affects the RFR of a route and has a direct impact on its competitiveness. Capital cost calculations are based on tanker newbuilding prices, interest rates, and spreads which refer to specific years or an average of years in the analysis in Chapters 4, 5, and 6. The newbuilding prices of 2004 are assumed in the analysis in Chapter 4 since the aim is to explain the use of the NSR based on specific tankers which used the route in 2011-2018 (Appendix O2). Most of these tankers were ordered in 2004 and, to a lesser extent, in 2003 and 2005. Thus, the newbuilding prices and the London Interbank Offered Rate (LIBOR) interest rate in 2004 are used to estimate capital costs. Further, it is assumed, based on the statistical records of these tankers, that the time period between the order and delivery is three years, and that the bank loan is issued for 10 years. This enables route comparison between tankers which incur capital costs and tankers which do not incur capital costs. As regards capital cost estimation in the analysis in Chapters 5 and 6, this refers to the 2013-2019 average newbuilding prices of LR2 tankers in order to take into account the volatility of prices during that period. Similarly, the 2011-2019 average 12-month LIBOR rate is used in order to take into account the volatility of rates during that period. As regards the spread used over the LIBOR rate, this is assumed 1% in the analysis in Chapter 4, reflecting the period before the financial crisis in 2008-2009 (Giannakoulis 2016; Petrofin 2017). The spread used over the

LIBOR rate in the analysis in Chapters 5 and 6 is assumed 3% (Alizadeh and Nomikos 2009), reflecting an increase between 2% to 5.5% recently (Petrofin 2017).

Operating costs are assumed to vary annually during 2011-2020 in the analysis in Chapter 4, whereas the 2011-2018 average value of operating costs is used in the analysis in Chapters 5 and 6. Besides, annual operating costs did not vary significantly in 2011-2018 regardless of the tanker size, as can be seen in Table 4.9.

When it comes to voyage costs, these consist of fuel types and prices, transit fees and other voyage-related costs, such as ice damage repairs, and ice coating. The variability of all these factors is considered in the analysis in Chapters 4, 5, and 6. First, fuel prices are assumed to vary annually in the analysis in Chapter 4, and therefore fuel costs are representative for each year in 2011-2020. The same also holds true for the two average fuel price values assumed in the same Chapter, that is, the averages of 2011-2014 and 2015-2017. The reason is that annual fuel price values in 2011-2014 and 2015-2017 are close to the respective fuel price averages. Second, high, base case, and low fuel price scenarios are included in the sensitivity analyses conducted in Chapters 5 and 6. The fuel price scenarios refer to historic low, average, and high levels during 2011-2020. The aim is to take into account the volatility in fuel prices during that period, as well as to address the fact that prices in Rotterdam and Singapore may not be representative of the prices in other ports included in the analysis. Thus, a wide range between 150 US$/t to 600 US$/t for HSFO, 250 US$/t to 900 US$/t for MGO, 240 US$/t to 720 US$/t for VLSFO, and 150 US$/t to 350 US$/t for LNG is assumed for each fuel type to take into account the uncertainty regarding fuel prices both for Rotterdam and Singapore, as well as for other ports in their vicinity. Similarly, commodity prices are assumed to range from 228 US$/t to 747 US$/t in the analysis in Chapters 5 and 6, reflecting historically low and high price levels during 2011-2020. As regards icebreaking fees, both the official and discounted fees are used in the analysis in Chapters 4, 5, and 6, reflecting practice and policy of the Northern Sea Route Authority (NSRA) in 2011-2020. Moreover, the sensitivity analysis includes low, base case, and high levels of USD/RUB exchange rates drawing from historic values in 2011-2020.

When it comes to OD pair distances, the most representative ports are chosen for comparison in terms of historic voyages, major oil product flows, and distance savings between Asia and Europe in the analysis in Chapters 4, 5, and 6. The impact of ship size on costs and route choice is also considered by including four tanker sizes in the analysis in Chapter 4.

Insurance costs, including relevant premiums for both the NSR and SCR are considered, as well as other relevant costs, such as ice damage repairs costs and ice coating. Factors related to safety and pollution can also be included in the RFR analysis. More specifically, costs related to oil spills and/or cargo losses when operating on the NSR can be factored in the analysis. Yet, the insurance cost premiums for ice class tankers assumed in the analysis reflect these factors amonst others.

Port turnaround time and port dues are assumed the same for a given voyage. Thus, they are not considered in the RFR models. These assumptions stem from the fact that the time period a tanker spends in port, such as loading/unloading and/or waiting, is the same regardless of the route chosen to link an origin with a destination port. Most importantly, the RFR models are based on the *least cost speed* (LCS), which establishes the break-even point of operations and does not depend on the level of prevailing freight rates, port time, port-related costs, and potential delays. According to Alderton (1981), a cost-based approach, which establishes the RFR against competing route alternatives, is more appropriate for long-term planning than one which aims to maximise profit. On the other hand, a profit maximisation modelling approach, which is based on the *most profitable speed* (MPS), depends on port time and port-related costs, amongst others. Assessments of both profits and costs based on profit maximisation and cost minimisation, respectively, would provide a two-way approach to route comparison. However, the non-existence of a spot market for tanker trades via the NSR as of today, as well as the lack of freight rates or lumpsum rates data of voyages conducted in 2011-2019, prevents the use of profit-based comparisons.

Should port time and costs are factored in such a modelling approach, the effect of port time on a certain route would depend on several factors. When it comes to port efficiency issues or congestion in port or approaching lanes, these would result in delays, which could affect either route alternative equally. Moreover, market structure and arbitrage opportunities determine the route chosen, which may not always be the shorter, such as NSR versus SCR, or even SCR and NSR versus Cape. Thus, the effect of port turnaround time on costs should be considered within the wider perspective of operations and commercial practices in the oil tanker sector.

7.7 Future research directions

Future research could consider simulations of the Northwest Passage (NWP), the Transpolar Sea Route (TSR), alternative lanes of the NSR, land-based routes, such as the Trans-Siberian Railway and the New Eurasian Land Bridges, as well as other established or future trade routes

(Tavasszy et al. 2011; Yip and Wong 2016; Martinez et al. 2016; Zeng et al. 2017; Stevenson et al. 2019; Yuan et al. 2020; Zeng et al. 2020; Bennett et al. 2020).

As regards navigational factors, future research could take into account studies related to climate models and variations in the Arctic sea ice (Wang, Ren et al. 2018; Wang and Zhang 2019; Wang, Liu et al. 2021), the relationship between sea ice thickness, ship speed, and icebreaker assistance (Faury and Cariou 2016; Faury, Cheaitou et al. 2020; Cariou et al. 2021; Gleb and Jin 2021), the relationship between fuel consumption and sea ice (Xu et al. 2018), and the use of AIS data to obtain ship speeds on ice from voyages conducted on Arctic waters.

Ship speed optimisation and real speeds based on AIS data should be further investigated for other routes and across various shipping sectors, given that real speeds tend to depart from optimal points owing to organisational and technical constraints, ship, and voyage specific variables as well as weather factors amongst others. Future research should also consider the impact of delays and time lost due to deviation of a ship from its predefined navigational route in order to avoid difficult ice conditions, as well as the impact of a ship getting beset on ice.

Moreover, speed-dependent fuel consumption elasticities could be employed to address the fact that the cubic law between speed and fuel consumption does not hold at speeds lower than the design speed (Adland et al. 2020). This can have implications for certain traditional routes and OD pair distances, as well as for fuel consumption through ice on the NSR. Further, the impact of ice on fuel consumption should be further investigated, given the variability of ice conditions during the summer/autumn navigation season.

The global geography of trades, wider geographical implications on route choice, commodity prices, economies of scale, and cargo value can complement the transport cost analysis for oil product tankers or other shipping sectors, such as crude oil tankers, dry bulk carriers, general cargo ships, LNG tankers, Liquefied Petroleum Gas (LPG) tankers, refrigerated cargo ships, and future sectors and ship types, such as liquid hydrogen tankers.

Future research could focus on new technologies, fuel types and operational modes, and future emissions and environmental regulations. As regards fuel types, these could include LNG (Ding et al. 2020; Xu and Yang 2020; this Thesis), and other low or zero carbon fuels and energy systems, such as LPG, methanol, biofuels, ammonia, synthetic fuels, dual-fuel modes, batteries (Savard et al. 2020), hydrogen, solar and wind energy.

Fuel price differences, especially between HSFO and VLSFO could be further explored, given the volatility of the price differential between the two fuel types. Similarly, price differences between oil-based and gas-based fuels should be further examined, given the significantly higher LNG prices than oil-based fuels during 2021-2022. Moreover, the relationship between oil-based and gas-based marine fuels could be further investigated. Asian spot LNG prices seem to follow closely the global oil prices, whereas Title Transfer Facility (TTF) gas prices are less sensitive to oil price movements (Fulwood 2019). Yet, the decoupling of LNG prices in Asia from oil prices could mean a weaker relationship between LNG prices in Europe and Asia and global oil prices. This can have further implications for route comparison, depending on scenarios and assumptions.

Future research should also address the impact of pricing policies of ship canals or authorities controlling sea passages on route choice. Examples include the practice of the NSRA and Suez Canal Authority to offer discounts depending on market conditions (Falck 2012; Gritsenko and Kiiski 2016; Lloyd’s List 2020b). Moreover, future research could examine the impact of a shift in pricing policies from the Suez Canal Authority and the Panama Canal Authority as a response to emerging routes, such as the Arctic routes.

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Appendices

Appendix A. Searching procedure on Scopus and Web of Science

The search syntax presented below was used in Scopus to search for papers which are relevant to the Systematic Review Questions. The syntax was split in five search strings to better handle the search results in terms of volume and further screening and selection. The searches were carried out during March 2021.

1. {Northern Sea Route} OR {Northwest Passage} OR {Arctic shipping} OR {Cape Horn} OR {Magellan Strait} OR {Magellan Straits} OR {Cape of Good Hope} OR {Maritime canal} OR {Maritime canals} OR {Maritime corridor} OR {Maritime corridors}

2. {maritime lane} OR {maritime lanes} OR {Maritime passage} OR {Maritime passages} OR {Maritime route} OR {Maritime routes} OR {Maritime strait} OR {Maritime straits} or {Nicaragua Canal} OR {Nicaraguan Canal} OR {Northeast Passage} OR {Panama Canal}

3. {Sea canal} OR {Sea canals} OR {Sea corridor} OR {Sea corridors} OR {Sea lane} OR {Sea lanes} OR {Sea passage} OR {Sea passages} OR {Sea route} OR {Sea routes} OR {Sea strait} OR {Sea straits} OR {Ship* canal} OR {Ship* canals}

4. {Ship* corridor} OR {Ship* corridors} OR {Ship* lane} OR {Ship* lanes} OR {Ship* passage} OR {Ship* passages} OR {Ship* route} OR {Ship* routes} OR {Ship* strait} OR {Ship* straits} OR {Strait of Magellan} OR {Straits of Magellan}

5. {Suez Canal} OR {Transpolar Passage} OR {Transpolar Sea Route}

Once results were provided by Scopus, they were refined based on ‘Document Type’ (Article, Review). The remaining papers were selected and downloaded by choosing ‘CSV Export’ and selecting all information (Citation information, Bibliographical information, Abstract & keywords, Funding details, Other information). Scopus allows 2,000 papers per time to be downloaded. Thus, if more than 2,000 papers are retrieved, this procedure is repeated for the remaining papers. The results were downloaded in Microsoft Excel file format. Following the downloading of all papers, these were collated and saved in one single Excel spreadsheet.

The search syntax presented below was used in Web of Science to search for papers which are relevant to the Systematic Review Questions. The syntax was split in five search strings to better handle the search results in terms of volume and further screening and selection. The searches were carried out during March 2021.

1. "Northern Sea Route" OR "Northwest Passage" OR "Arctic shipping" OR "Cape Horn" OR "Magellan Strait" OR "Magellan Straits" OR "Cape of Good Hope" OR "Maritime canal" OR "Maritime canals" OR "Maritime corridor" OR "Maritime corridors"

2. "Maritime lane" OR "Maritime lanes" OR "Maritime passage" OR "Maritime passages" OR "Maritime route" OR "Maritime routes" OR "Maritime strait" OR "Maritime straits" or "Nicaragua Canal" OR "Nicaraguan Canal" OR "Northeast Passage" OR "Panama Canal"

3. "Sea canal" OR "Sea canals" OR "Sea corridor" OR "Sea corridors" OR "Sea lane" OR "Sea lanes" OR "Sea passage" OR "Sea passages" OR "Sea route" OR "Sea routes" OR "Sea strait" OR "Sea straits" OR "Ship* canal" OR "Ship* canals"

4. "Ship* corridor" OR "Ship* corridors" OR "Ship* lane" OR "Ship* lanes" OR "Ship* passage" OR "Ship* passages" OR "Ship* route" OR "Ship* routes" OR "Ship* strait" OR "Ship* straits" OR "Strait of Magellan" OR "Straits of Magellan"

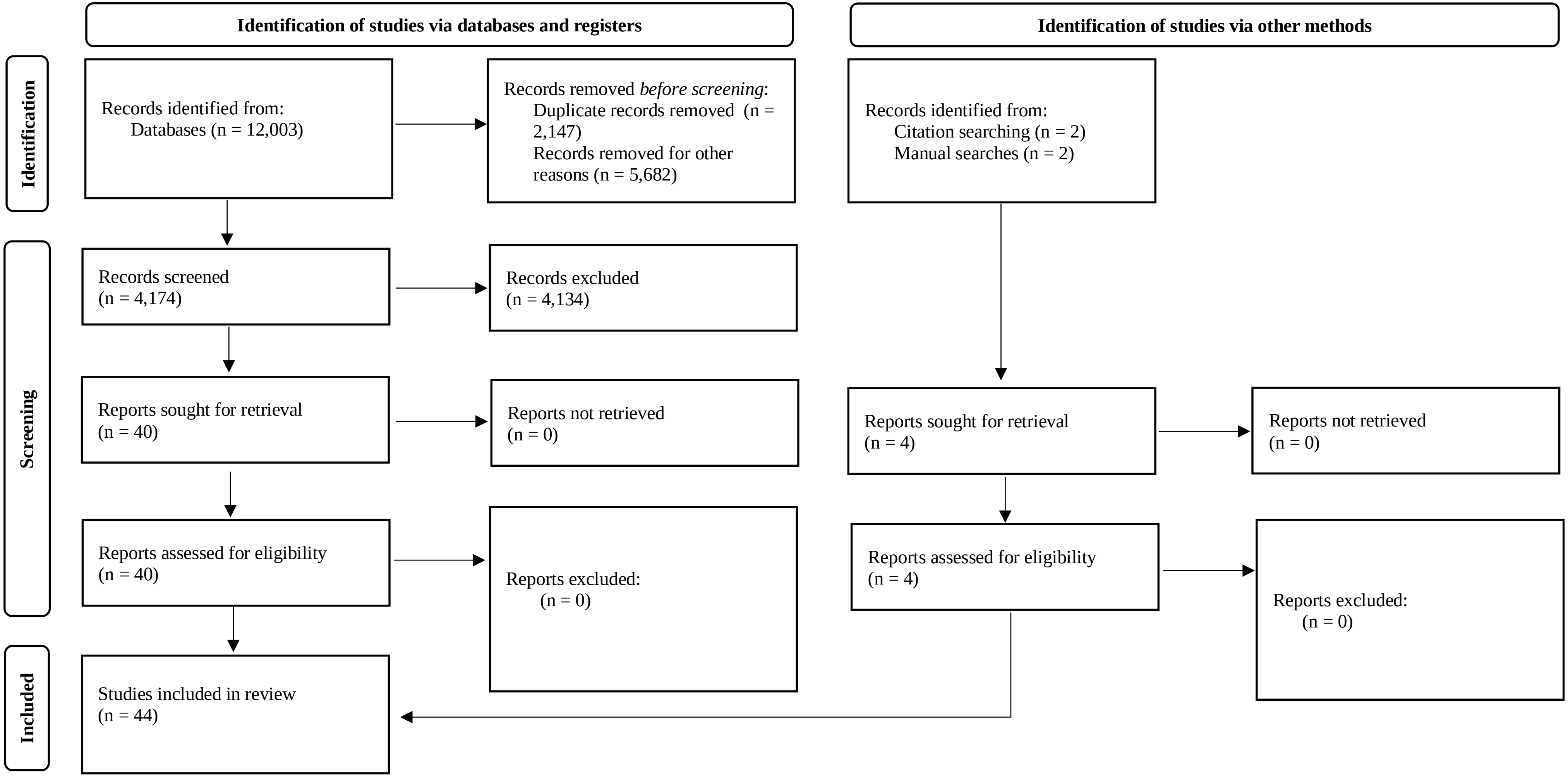
5. "Suez Canal" OR "Transpolar Passage" OR "Transpolar Sea Route"

Once results were provided by Web of Science, they were refined based on 'Document Types' (Articles, Review Articles). The remaining papers were selected and downloaded by choosing 'Export', 'Excel', and then 'Records from 1 to 1000', and Record Content: 'Full Record'.

Scopus allows 1,000 papers per time to be downloaded. Thus, if more than 1,000 papers are retrieved, this procedure is repeated for the remaining papers. The results were downloaded in Microsoft Excel file format. Following the downloading of all papers, these were collated and saved in one single Excel spreadsheet.

The two Excel spreadsheets containing the results from Scopus and Web of Science were then merged in one Excel spreadsheet to conduct screening and selection based on the inclusion and exclusion criteria described in Section '2.3.3.2 Inclusion and exclusion criteria', Chapter 2.

Appendix B. Prisma flow diagram



Sources: Prisma (2021), Page et al. (2021).

Appendix C. Quality assessment criteria of the reviewed studies

Quality assessment criteria					
Element	Level				
	0 Absence	1 Low	2 Medium	3 High	Not applicable
1. Theory robustness	The article does not provide enough information to assess this criterion	Poor awareness of existing literature and debates Under- or over-referenced Low validity of theory	Basic understanding of the issues around the topic being discussed The theory weakly is related to data	Deep and broad knowledge of relevant literature and theory relevant for addressing the research Good relation theory-data	This element is not applicable to the document or study
2. Implications for practice	The article does not provide enough information to assess this criterion	Very difficult to implement the concepts and ideas presented Not relevant for practitioners or professionals	There is a potential for implementing the proposed ideas, with minor revisions or adjustments	Significant benefit may be obtained if the ideas being discussed are put into practice	This element is not applicable to the document or study
3. Methodology, data, supporting arguments	The article does not provide enough information to assess this criterion	Data inaccuracy and not related to theory Flawed research design	Data are related to the arguments, though there are some gaps Research design may be improved	Data strongly supports arguments Besides, the research design is robust: sampling, data gathering, data analysis is rigorous	This element is not applicable to the document or study
4. Generalisability	The article does not provide enough information to assess this criterion	Only to the population studied	Generalisable to organisations of similar characteristics	High level of generalisability	This element is not applicable to the document or study
5. Contribution plus a short statement summarising the article's contribution	The article does not provide enough information to assess this criterion	Does not make an important contribution It is not clear the advances it makes	Although using others' ideas, builds upon the existing theory	Further develops existing knowledge, expanding the way the issue was explained so far	This element is not applicable to the document or study

Source: Pittaway et al. (2004).

Appendix D. Quality assessment of the reviewed studies

Author(s) and year	Theory Robustness	Implications for practice	Methodology, data, supporting arguments	Generalisability	Contribution plus a short statement summarising the article's contribution
Wergeland (1992)	3	3	3	2 to 3	3
Kondo and Takamasa (1999)	3	3	3	2	3
Guy (2006)	2	2	2	2 to 3	3
Somanathan et al. (2007)	3	3	2	2 to 3	3
Somanathan et al. (2009)	3	3	2	2 to 3	3
Verny and Grigentin (2009)	3	2	2	2 to 3	3
Liu and Kronbak (2010)	3	3	3	2 to 3	3
Schøyen and Bråthen (2011)	3	3	3	2 to 3	3
Xu et al. (2011)	2	1	1	1	1
Song and Zhang (2013)	1	1	1	0	1
Lasserre (2014)	3	3	3	2 to 3	3
Raza and Schøyen (2014)	3	3	3	2 to 3	3
Lu et al. (2014)	3	3	3	2 to 3	3
Lasserre (2015)	3	3	3	2 to 3	3
Furuichi and Otsuka (2015)	3	3	3	2 to 3	3
Chou et al. (2015)	1	1	1	0	1
Chang et al. (2015)	1	2	2	2 to 3	1
Cariou and Faury (2015)	3	3	3	2 to 3	3
Von Bock und Polach et al. (2015)	3	3	3	2 to 3	3
Lindstad et al. (2016)	3	3	2	2 to 3	3
Pruyn (2016)	3	3	3	2 to 3	3
Zhao et al. (2016)	3	3	3	2 to 3	3
Zhao and Hu (2016)	3	3	3	2 to 3	3
Zhang, Meng, Ng (2016)	3	3	3	2 to 3	3
Faury and Cariou (2016)	3	3	3	2 to 3	3
Wang et al. (2016)	3	3	3	2 to 3	3
Lin and Chang (2018)	3	3	3	2 to 3	3
Zhu et al. (2018)	3	3	3	2 to 3	3
Xu et al. (2018)	3	3	3	2 to 3	3
Wan et al. (2018)	3	3	3	2 to 3	3
Shibasaki et al. (2018)	3	3	3	2 to 3	3
Furuichi and Otsuka (2018)	3	3	3	2 to 3	3
Wang, Ren et al. (2018)	3	3	3	2 to 3	3
Wang and Zhang (2019)	3	3	3	2 to 3	3
Ding et al. (2020)	3	3	3	2 to 3	3
Faury, Cheaitou et al. (2020)	3	3	3	2 to 3	3
Keltto and Woo (2020)	3	3	3	2 to 3	3
Wang et al. (2020)	3	3	3	2 to 3	3
Xu and Yang (2020)	3	3	3	2 to 3	3
Tseng et al. (2021)	3	3	3	2 to 3	3
Cariou et al. (2021)	3	3	3	2 to 3	3
Gleb and Jin (2021)	3	3	3	2 to 3	3
Wang, Liu et al. (2021)	3	3	3	2 to 3	3
Wang, Silberman et al. (2021)	3	3	3	2 to 3	3

Appendix E. Methodological Characteristics

Research Methods			
Analytical Mathematical	Wergeland (1992)	Chang et al. (2015)	Wang, Ren et al. (2018)
	Kondo and Takamasa (1999)	Cariou and Faury (2015)	Wang and Zhang (2019)
	Guy (2006)	Von Bock und Polach et al. (2015)	Ding et al. (2020)
	Somanathan et al. (2007)	Lindstad et al. (2016)	Faury, Cheaitou et al. (2020)
	Somanathan et al. (2009)	Zhao et al. (2016)	Keltto and Woo (2020)
	Verny and Grigentin (2009)	Zhang, Meng, Ng (2016)	Wang et al. (2020)
	Liu and Kronbak (2010)	Faury and Cariou (2016)	Xu and Yang (2020)
	Schøyen and Bråthen (2011)	Wang et al. (2016)	Cariou et al. (2021)
	Xu et al. (2011)	Lin and Chang (2018)	Tseng et al. (2021)
	Song and Zhang (2013)	Zhu et al. (2018)	Gleb and Jin (2021)
	Lasserre (2014)	Xu et al. (2018)	Wang, Liu et al. (2021)
	Lasserre (2015)	Wan et al. (2018)	Wang, Silberman et al. (2021)
	Furuichi and Otsuka (2015)	Shibasaki et al. (2018)	
	Chou et al. (2015)	Furuichi and Otsuka (2018)	
Empirical Case Study	Raza and Schøyen (2014)	Zhao and Hu (2016)	
Empirical Statistical	Lu et al. (2014)	Pruyn (2016)	

Data Analysis Techniques			
Transport Cost Model	Wergeland (1992)	Lasserre (2014)	Xu et al. (2018)
	Kondo and Takamasa (1999)*	Lasserre (2015)	Shibasaki et al. (2018)
	Guy (2006)	Chou et al. (2015)	Furuichi and Otsuka (2018)
	Verny and Grigentin (2009)	Von Bock und Polach et al. (2015)	Ding et al. (2020)*
	Liu and Kronbak (2010)	Zhang, Meng, Ng (2016)	Faury, Cheaitou et al. (2020)
	Xu et al. (2011)	Faury and Cariou (2016)	Keltto and Woo (2020)
	Song and Zhang (2013)	Wang et al. (2016)	Gleb and Jin (2021)
Transport Cost Model & Emissions Model	Schøyen and Bråthen (2011)	Zhu et al. (2018)	Xu and Yang (2020)
	Furuichi and Otsuka (2015)	Wan et al. (2018)	Cariou et al. (2021)
	Lindstad et al. (2016)	Wang et al. (2020)	Wang, Silberman et al. (2021)
Transport Cost Model & Game Theory	Wang, Ren et al. (2018)	Wang and Zhang (2019)	Wang, Liu et al. (2021)
Transport Cost Model & Monte Carlo Simulation	Somanathan et al. (2007)	Somanathan et al. (2009)	
Transport Cost Model & Emissions Model & Interviews	Zhao and Hu (2016)		
Transport Cost Model & Interviews	Raza and Schøyen (2014)		
Transport Cost Model & GIS Simulation	Chang et al. (2015)		
Optimisation model	Cariou and Faury (2015)* Lin and Chang (2018)	Pruyn (2016)	Zhao et al. (2016)
Optimisation model & Emissions Model	Tseng et al. (2021)		
Regression	Lu et al. 2014		

* These papers include emissions taxes in their analysis.

Appendix F. Factors affecting ship revenues and costs

Author(s) and year	Crew premium	Insurance premium	Transit fees	Fuel consumption rate	Speed	Capital Cost Premium
Wergeland (1992)	Increased crew costs due to higher travel and repatriation costs, and higher provisions costs: +17.3%	H&M and P&I: +25% Cargo insurance: 0.2% per voyage	Official NSRA fees	N.A.	NSR: 12 knots Suez and Panama Canal: 13.5 knots	+35% per day
Kondo and Takamasa (1999)[40]	+147% per day	H&M: +275% per day P&I: 5% per day lower than Diesel ship on SCR Liability insurance for damage: + US$ 900,000 per year Contract indemnity for damage: + US$ 36,000 per year	N.A.	N.A.	NSR: 20 knots Suez Canal: 25, 30, 34.2 knots	+134% per day
Guy (2006)	Time Charter Rate premium: Containership: +15%, 50%, 200% per day Dry Bulk Carrier: 25% per day less for lower Ice Class ship	Time Charter Rate premium: Containership: +15%, 50%, 200% per day Dry Bulk Carrier: 25% per day less for lower Ice Class ship	Two scenarios: NWP Icebreaking fees equal to Suez Canal Tolls, No Fees	N.A.	Optimistic Scenario: 22 knots Pessimistic Scenario: 6 knots on ice via the NWP	Time Charter Rate premium: Containership: +15%, 50%, 200% per day Dry Bulk Carrier: 25% per day less for lower Ice Class ship

[40] The factors reported here refer to the benchmark scenario of a 6,000 TEU diesel ship (20-year life at a speed at 30 knots) compared to a cassette-type MRX ice-breaking 1,400 TEU ship (40-year life). Two cases are assumed: A 20-year life, where the MRX reactor is only used in one ship, and a 40-year life, where the reactor is transferred to a second ship for another 20 years.

Author(s) and year	Crew premium	Insurance premium	Transit fees	Fuel consumption rate	Speed	Capital Cost Premium
Somanathan et al. (2007)	Overall premium: 24-30% per day Additional second engineer: 150 US$ per day Additional engine room crew and two deckhands: 150 US$ per day	H&M: 50% per day P&I: 50-53% per day Sensitivity for both up to +100%	No Icebreaking Fees reported Icebreaking assistance is assumed depending on stochastically modelled speed and ice conditions Ice Navigator: 265 US$ per day (they include this cost element under crew costs)	Same Specific Fuel Oil Consumption (SFOC) Higher engine power: 114-122% kW when operating through ice	NWP: Open water: 11 and 20 knots Panama Canal: 11 and 20 knots Speed is also stochastically modelled for both open water and through ice, allowing for periods of the ship being beset and wating for icebreaker assistance	+30% per day Sensitivity: 110-200%
Somanathan et al. (2009)	+21.2% per day Additional costs due to Ice navigator, additional engineer, four additional crew, additional spares for second propulsion train	H&M: 50% per day P&I: 50% per day	No Icebreaking Fees reported Icebreaking assistance is assumed depending on stochastically modelled speed and ice conditions	Same Specific Fuel Oil Consumption (SFOC) New York-Yokohama: +50% tonnes per day when operating through ice St Johns, Newfoundland-Yokohama: +58% tonnes per day when operating through ice	NWP and Panama Canal initial speed: 20 knots Simulated speed: NWP: 18.4 knots (September) 18.2 knots (February) Speed is also stochastically modelled for both open water and through ice, allowing for periods of the ship being beset	+30% per day
Verny and Grigentin (2009)	N.A.	N.A.	Official NSRA fees? (Assumed to be 100% higher than Suez Canal Tolls)	N.A.	NSR: 17 knots on ice and 24 knots on open water, SCR: 24 knots	N.A.

Author(s) and year	Crew premium	Insurance premium	Transit fees	Fuel consumption rate	Speed	Capital Cost Premium
Liu and Kronbak (2010)	+10% per day	H&M: +100% per day P&I: +25% per day	Official NSRA fees and three variant scenarios: 50%, 85%, 100% discount	Same fuel consumption in tonnes per nautical mile on open water +67% tonnes per nautical mile when operating through ice	NSR: 10 knots on ice water, 18 knots on open water, SCR: 18 knots	+20% per day
Schøyen and Bråthen (2011)	Handymax Dry Bulk Carrier: Time Charter Rate premium: +20% per day	Handymax Dry Bulk Carrier: Time Charter Rate premium: +20% per day +US$ 125,000 per voyage for both H&M and P&I insurance	Official NSRA fees Assumed to be 100% higher than Suez Canal Tolls based on Verny and Grigentin (2009)	1. Porsgrunn-Shekou OD pair: NSR: – 49% and 78% tonnes per day than SCR and Cape of Good Hope, respectively 2. Narvik-Qingdao OD pair: NSR: – 84% tonnes per day than SCR (Based same scheduling in terms of transit times amongst all routes, with lower speeds on NSR and higher speeds on SCR and Cape)	1a. Porsgrunn – Shekou OD pair: NSR: 11.5 knots, SCR: 14.4 knots 1b. Porsgrunn – Shekou: NSR: 8.7 knots, Cape of Good Hope: 14.4 knots 2. Narvik – Qingdao OD pair: NSR: 8.3 knots, SCR: 14.4 knots	+20% per day, based on Liu and Kronbak (2010)
Xu et al. (2011)	N.A.	N.A.	No fees	N.A.	Speed is variable depending on weekly scheduling Lowest speed: 11.7 knots Highest speed : 25.8 knots	No premium (Non-ice class ship)

Author(s) and year	Crew premium	Insurance premium	Transit fees	Fuel consumption rate	Speed	Capital Cost Premium
Song and Zhang (2013)	+28% per day	+5% per day (H&M and P&I not reported explicitly)	N.A.	+7% tonnes per day	NSR: Simulated based on AIRSS rules, SCR: 14.5 knots	+5% per day
Lasserre (2014)	+10% per day	H&M and P&I: NSR: +50% per day NWP: +65% per day (higher risk on NWP than on NSR)	Official NSR fees Discounted NSR fees: 7.44 US$ per tonne NWP: No fees (No icebreaking assistance)	**First Scenario: Rotterdam – Shanghai:** NSR: – 21% tonnes per day than SCR **Rotterdam-Yokohama:** NSR: – 25% tonnes per day than SCR **Second Scenario: Rotterdam-Shanghai:** NWP: – 21% tonnes per day than SCR **Rotterdam-Yokohama:** NWP: – 24% tonnes per day than SCR (Lower fuel consumption on NSR and NWP results from adjustment owing to lower speeds than SCR)	**First Scenario (IAS): Rotterdam-Shanghai:** NSR on ice: 14 knots, open water: 20 knots, Average NSR Speed: 17.71 knots SCR: 20 knots **Rotterdam Yokohama:** NSR on ice: 14 knots, open water: 20 knots, Average NSR Speed: 16.95 knots SCR: 20 knots **Second Scenario (IAS): Rotterdam-Shanghai:** NWP on ice: 13 knots, open water: 20 knots, Average NWP Speed: 16.94 knots SCR: 20 knots **Rotterdam Yokohama:** NWP on ice: 13 knots, open water: 20 knots, Average NWP Speed: 16.6 knots SCR: 20 knots	+20 per day

Author(s) and year	Crew premium	Insurance premium	Transit fees	Fuel consumption rate	Speed	Capital Cost Premium
Raza and Schøyen (2014)	N.A.	H&M premium: +281,250 US$ per round voyage Increased Values: +20,250 US$ per round voyage	NSR: 6.8 US$/t laden, 3 US$/t ballast SCR: 158,294US$ per round voyage (piracy premium)	N.A.	NSR: 12 knots on ice & 19.5 knots on open water SCR: 19.5 knots	No premium
Lu et al. (2014)	N.A.	N.A.	5 US$/t	N.A.	NWP: 10 knots on ice	N.A.

Author(s) and year	Crew premium	Insurance premium	Transit fees	Fuel consumption rate	Speed	Capital Cost Premium
Lasserre (2015)	**First and Second Scenarios:** +10% per day **Third Scenario:** NWP: +15% per day owing to winter operations **Fourth Scenario:** NSR: +15% per day owing to winter operations	**First and Second Scenarios:** H&M and P&I: NSR: +50% per day NWP: +65% per day (higher risk on NWP than on NSR) **Third Scenario:** NWP: +80% per day (Higher risk for year-round operations on NWP) **Fourth Scenario:** NSR: 65% per day (Higher risk for year-round operations than on summer operations only on NSR)	**First and Second Scenarios:** Official NSR fees: 34 US$ per tonne Discounted NSR fees: 8.2 US$ per tonne NWP: No fees (No icebreaking assistance) **Third Scenario:** NWP: No fees (No icebreaking assistance) **Fourth Scenario:** Discounted NSR fees: 8.2 US$ per tonne	**First Scenario (IAS): Rotterdam-Shanghai:** NSR: – 21% tonnes per day than SCR **Rotterdam-Yokohama:** NSR: – 25% tonnes per day than SCR **Second Scenario (IAS): Rotterdam-Shanghai:** NWP: – 21% tonnes per day than SCR **Rotterdam-Yokohama:** NWP: – 24% tonnes per day than SCR (Lower fuel consumption on NSR or NWP results from adjustments owing to a combination of lower speeds in either route than SCR and increased fuel consumption through sea ice)	**First Scenario (IAS): Rotterdam-Shanghai:** NSR on ice: 14 knots, open water: 20 knots, Average NSR Speed: 17.71 knots SCR: 20 knots **Rotterdam Yokohama:** NSR on ice: 14 knots, open water: 20 knots, Average NSR Speed: 16.95 knots SCR: 20 knots **Second Scenario (IAS): Rotterdam-Shanghai:** NWP on ice: 13 knots, open water: 20 knots, Average NWP Speed: 16.94 knots SCR: 20 knots **Rotterdam Yokohama:** NWP on ice: 13 knots, open water: 20 knots, Average NWP Speed: 16.6 knots SCR: 20 knots	**First and Second Scenarios:** NSR & NWP: +20% per day (IAS Ice Class) **Third Scenario:** NWP: +30% per day (PC4 Ice-class) **Fourth Scenario:** NSR: +20% per day (IAS Ice-class)

Author(s) and year	Crew premium	Insurance premium	Transit fees	Fuel consumption rate	Speed	Capital Cost Premium
Lasserre (2015) **(Continued)**				**Third Scenario (PC4): Rotterdam-Yokohama** **Summer:** NWP: – 19% tonnes per day than SCR **Winter:** NWP: +26% tonnes per day than SCR **Fourth Scenario (IAS): Rotterdam-Yokohama** **Summer:** NSR: – 25% tonnes per day than SCR **Winter:** NSR: – 32% tonnes per day than SCR (Lower/Higher fuel consumption on NSR or NWP results from adjustments owing to a combination of lower speeds in either route than SCR and increased fuel consumption through sea ice)	**Third Scenario (PC4): Rotterdam-Yokohama, Summer:** NWP on ice: 13 knots, open water: 20 knots, Average NWP Speed: 16.6 knots SCR: 20 knots **Rotterdam Yokohama, Winter:** NWP on ice: 7 knots, open water: 20 knots, Average NWP Speed: 11.72 knots SCR: 20 knots **Fourth Scenario (IAS): Rotterdam-Yokohama, Summer:** NSR on ice: 14 knots, open water: 20 knots, Average NWP Speed: 16.95 knots SCR: 20 knots **Rotterdam Yokohama, Winter:** NSR on ice: 7 knots, open water: 20 knots, Average NWP Speed: 11.23 knots SCR: 20 knots	

Author(s) and year	Crew premium	Insurance premium	Transit fees	Fuel consumption rate	Speed	Capital Cost Premium
Furuichi and Otsuka (2015)	N.A.	10 US$ per GT per year Piracy Premium (SCR): 40 US$ per TEU	5 US$ per GT	+10% SFOC for an ice-class ship (additional weight)	NSR: 13-14 knots on ice 20 knots on open water	+10% per day
Chou et al. (2015)	N.A.	N.A.	N.A.	N.A.	12 knots for all routes and cases	N.A.
Chang et al. (2015)	N.A.	N.A.	Official NSRA fees?	NSR: – 26% tonnes than SCR on average	NSR: 14 knots on open water, 6-12 knots on ice	N.A.
Cariou and Faury (2015)	+9.5% daily premium in Operating Costs	+62.5% per day	Official NSRA fees	NSR: +5% tonnes per day than SCR	NSR: 6.4-12.8 knots SCR: 8-16 knots	N.A.
Von Bock und Polach et al. (2015)	N.A.	N.A.	5 US$ per GT	Laden: +56% tonnes per day than SCR Ballast: +3% tonnes per day than SCR	SCR: 15.6 knots NSR: 13.5 knots NSR: 5-10 knots on ice	1A: +35% 1AS (DAS): +38%
Lindstad et al. (2016)	N.A.	N.A.	N.A.	N.A.	NSR and SCR: 10-11 knots	N.A.
Pruyn (2016)	N.A.	P&I: +100% per GT per year H&M: +200% per GT per year Piracy Premium: 18 US$ per GT per year	Ice 0: No fees Ice 1,2: 4 US$ per tonne Reg-1: 5 US$ per tonne Reg-2: 19 US$ per tonne below 40,000 DWT and 16 US$ per tonne above 40,000 DWT	NSR: Ice 0,1,2: +5% Reg-1, Reg-2: same as SCR	NSR: Ice 0: 14.3 knots Ice 1,2: 11 knots Reg-1,2: 9 knots SCR: 14.3 knots	Ice 0,1,2: +5% Reg-1,2: same as a non-ice class ship

Author(s) and year	Crew premium	Insurance premium	Transit fees	Fuel consumption rate	Speed	Capital Cost Premium
Zhao et al. (2016)	+10% per day	H&M : +100% per day P&I: +25% per day	Three hypothetical scenarios	Same fuel consumption in tonnes per nautical mile on open water +67% tonnes per nautical mile when operating through ice	N.A.	+20%
Zhao and Hu (2016)	+9% per year	+19% per year	Official NSRA fees	Same in both NSR and SCR	NSR and SCR: 12.5 knots	N.A.
Zhang, Meng, Ng (2016)	**Containerships:** +10% per day **Oil Tankers:** +20% daily premium in Operating Costs	**Containerships:** H&M: 50% per day, P&I: 25% per day **Oil Tankers:** +20% daily premium in Operating Costs	5 US$ per GT	+30% daily fuel consumption for both Containerships and Oil Tankers	**Containerships:** NSR: 12 knots on ice SCR: 14.4-17.7 knots **Tankers:** NSR: 9.4 knots on ice SCR: 15-15.5 knots	+30% per day for both Containerships and Oil Tankers
Faury and Cariou (2016)	+20% daily premium in Operating Costs	+20% daily premium in Operating Costs	Official NSRA fees Independent navigation during September, October & November	+5.1% tonnes per day	SCR: 14.5 knots NSR (Depending on the month and zone)	N.A.
Wang et al. (2016)	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Lin and Chang (2018)	N.A.	N.A.	Official NSRA fees	NSR: – 22% tonnes per day than SCR	N.A.	N.A.
Zhu et al. (2018)	+10% per day	+20% per day	Official NSRA fees	NSR: – 73.7% tonnes per day than SCR	NSR: 17.71 knots (14 knots on ice, 20 knots on open water) SCR: 23 knots	+24% per day
Xu et al. (2018)	N.A.	No premium	Six hypothetical NSR/SCR Transit Fees ratios: 1, 0.8, 0.6, 0.4, 0.2, or 0	+10% per day	3, 4, 5 knots on ice water	+10% per day

Author(s) and year	Crew premium	Insurance premium	Transit fees	Fuel consumption rate	Speed	Capital Cost Premium
Wan et al. (2018)	+10% per day Administration premium: +10% per day	SCR: P&I and H&M: 50% NSR: +50%	Official NSRA fees Discounted Fees: 20%	+8% tonnes per day	NSR: 14 knots on ice SCR and NSR on open water: 20 knots	Owned: +20% per day Chartered: + 20% per day
Shibasaki et al. (2018)	N.A.	+100% in GT per year	Official NSRA fees Discounted Fees: 50%	+10% SFOC for an ice-class ship	All routes and NSR on open water: 18 knots NSR on ice: 6-15 knots depending on navigation zone and season	Arc4: +20% per day Arc7: +50% per day
Furuichi and Otsuka (2018)	N.A.	Annual premium for both H&M and P&I: 0.343% of Capital costs NSR premium: 10 US$ per GT per year Piracy Premium (SCR): 40 US$ per TEU	5 US$/GT	N.A.	NSR: 12.8-14.1 knots on ice SCR and NSR on open water: 20 knots	N.A.
Wang, Ren et al. (2018)	+46% daily premium in Operating Costs	+46% daily premium in Operating Costs	N.A.	SCR: 0.3 tonnes per nautical miles NSR (on ice): 0.5 tonnes per nautical mile	SCR: 16.7-17 knots NSR: 9.3-9.4 knots on ice water NSR: 15.9-16.2 knots on open water	+20% per day
Wang and Zhang (2019)	+46% daily premium in Operating Costs	+46% daily premium in Operating Costs	N.A.	N.A.	SCR: 11.25, 12.75, 17 knots, NSR: 8.41, 8.97, 10.54 knots at fuel price of 350, 700, and 900 US$/t respectively	+20% per day

Author(s) and year	Crew premium	Insurance premium	Transit fees	Fuel consumption rate	Speed	Capital Cost Premium
Ding et al. (2020)	+25% daily premium in Operating Costs	+25% daily premium in Operating Costs	Official NSRA fees	+30% daily fuel consumption	SCR: 16.47 knots NSR: 12 knots on ice water NSR: 17.73 knots on open water	+10% per day
Faury, Cheaitou et al. (2020)	+5% and +6% daily premium in Operating Costs for 1A and 1AS, respectively	+5% and +6% daily premium in Operating Costs for 1A and 1AS, respectively	Official NSRA fees	+14% and +60% tonnes per day for 1A and 1AS, respectively	SCR and NSR: 15.3-16 knots Minimum speed on ice: 3-8 knots	N.A.
Keltto and Woo (2020)	+16.6% ice and +5% Scrubber daily premiums in Operating Costs	+16.6% ice and +5% Scrubber daily premiums in Operating Costs	7.5 US$ per GT	Higher engine load through sea ice +2% fuel consumption due to Scrubber use	SCR & NSR: 14.5 knots at 80% load ECA: 12 knots at 65% load Speed on ice: 9.37 knots at 70% load	+20% per day + 3 M. US$ for Scrubber installation
Wang et al. (2020)	+20% per day	+20% per day	Official NSRA fees	Depends on the speed-ice dependency	SCR and NSR: 15 knots NSR on ice: 7.84-12.73 knots	+20% per day
Xu and Yang (2020)	+20% daily premium in Operating Costs	N.A.	Independent navigation during summer/autumn season	+10% per day	N.A.	+10% per day +20% per day for all LNG-powered ships compared to oil-powered ships
Cariou et al. (2021)	N.A.	N.A.	Official NSRA fees	N.A.	SCR and NSR: 19 knots NSR on ice: It depends on the model	N.A.

Author(s) and year	Crew premium	Insurance premium	Transit fees	Fuel consumption rate	Speed	Capital Cost Premium
Tseng et al. (2021)	+8% daily premium in Operating Costs	+8% daily premium in Operating Costs	Hypothetical scenarios From 100,000 to 1,000,000 US$ per voyage	NSR: – 22.2% Tonnes per day than SCR	SCR: 20 knots NSR: 18 knots	N.A.
Gleb and Jin (2021)	+10% daily premium for both ice class and non-ice class ships	+50% daily premium for both ice class and non-ice class ships	Official NSRA fees	Ice 1 (II): 1% Ice 2 (1C): 2.5% Ice 3 (1B): 3.4% Arc 4 (1A): 5.1% Arc 5 (1AS): 6.3% Arc 6 (PC5 IACS): 7.6% (All rates in tonnes per day)	SCR and NSR on open water for all scenarios: 18 knots NSR on ice water: 12 knots	Ice 1 (II): 1.2% Ice 2 (1C): 4.8% Ice 3 (1B): 10.8% Arc 4 (1A): 19.2% Arc 5 (1AS): 30% Arc 6 (PC5 IACS): 43.2% (All rates per day)
Wang, Liu et al. (2021)	+14% daily premium in Operating Costs	+14% daily premium in Operating Costs	Official NSRA fees	+4% tonnes per day on ice	SCR and NSR on open water for all scenarios: 18 knots 2020: August-November: 13.87-14.45 knots 2025: August-November: 14.06-14.53 knots 2030: July-December: 13.55-14.57 knots	N.A.
Wang, Silberman et al. (2021)	+20% daily premium in Operating Costs	+20% daily premium in Operating Costs	5 US$ per GT	+20% SFOC for an ice-class ship		+20% per day

Author(s) and year	Maintenance premium[41]	Load Factor	Type of ship	Ice Class	Transport Costs[42]	Impact of Ice on Fuel Consumption
Wergeland (1992)	+23.6%	75% in all scenarios	20,000 DWT Norilsk type Multi-purpose ship	ULA (PC4/PC5, IACS Classification)[43]	Shipowner's & Cargo Owner's perspective	Yes
Kondo and Takamasa (1999)	+50% per day	100% in all scenarios	1,400 TEU Nuclear-powered Containership 4,000 TEU, 6,000 TEU, 8,000 TEU Diesel-powered Containerships	Cassette-type MRX Nuclear-powered Ice-breaking ship	Shipowner's & Shipper's perspective	N.A.
Guy (2006)	Time Charter Rate premium: Containership: +15%, 50%, 200% per day Dry Bulk Carrier: 25% per day less for lower Ice Class ship	N.A.	Panamax Containership, Panamax Dry Bulk Carrier	N.A.	Shipowner's/Industrial Producer's & Charterer's perspective	N.A.
Somanathan et al. (2007)	Additional spares and repairs for the second engine: 650 US$ per day (they include this cost element under crew costs) Periodic Maintenance (Dry Docking): +150% per year Steel Repairs per year for the Ice Class ship: 180-360,000 US$	100% in all scenarios	4,500 TEU Containership	CAC 3 (PC3, IACS Classification)	Shipowner's perspective	Yes Second engine on operation when operating through ice on NWP Higher engine power: 114-122% kW when operating through ice

[41] Increased costs for repairs or relevant premiums are reported where these are discerned from the reviewed studies.
[42] Transport costs are distinguished between "Shipowner's" and "Charterer's" unless otherwise stated.
[43] The ice class in the parenthesis is the Finnish-Swedish equivalent where applicable. IACS classification is used otherwise.

Author(s) and year	Maintenance premium	Load Factor	Type of ship	Ice Class	Transport Costs	Impact of Ice on Fuel Consumption
Somanathan et al. (2009)	Periodic Maintenance (Dry Docking): +150% per year Steel Repairs per year for the Ice Class ship: 262,500 US$	100% in all scenarios?	4,500 TEU Containership?	CAC 3 (PC3, IACS Classification)	Shipowner's perspective	Yes Second engine on operation when operating through ice on NWP New York-Yokohama: +50% tonnes per day when operating through ice St Johns, Newfoundland-Yokohama: +58% tonnes per day when operating through ice
Verny and Grigentin (2009)	+100% per day	Westbound: 100%[44] Eastbound: 30%	4,000 TEU/51,870 DWT Containership	N.A.	Shipowner's perspective	N.A.
Liu and Kronbak (2010)	+100% per day	60% in all scenarios	4,300 TEU Containership	1B (IB)	Shipowner's perspective	Yes Increased fuel consumption when operating through ice on NSR +67% tonnes per nautical mile when operating through ice
Schøyen and Bråthen (2011)	Handymax Dry Bulk Carrier: Time Charter Rate premium: +20% per day	Handymax Dry Bulk Carrier: 100% Panamax Dry Bulk Carrier: 74%	40,000 DWT Handymax and 50-68,000 DWT Panamax Dry Bulk Carriers	GL E3 (IA)	Charterer's perspective	N.A.

[44] It is also assumed that when a container is loaded up to 14 tonnes of weight, then the ship can only carry 2,800 TEU.

Author(s) and year	Maintenance premium	Load Factor	Type of ship	Ice Class	Transport Costs	Impact of Ice on Fuel Consumption
Xu et al. (2011)	N.A.	N.A.	10,000 TEU Containership	No ice-class	Shipowner's perspective	N.A.
Song and Zhang (2013)	+26% per day (Unclear whether it is Repairs and Maintenance or Periodic Maintenance)	100%	120,000 DWT Aframax tanker	1A (IA)	Shipowner's perspective	Yes Increased engine power
Lasserre (2014)	NSR and NWP: Periodic Maintenance: +20% per season/day	**First Scenario:** Rotterdam – Shanghai/Yokohama: NSR: Eastbound: 45%, Westbound: 70% SCR: Eastbound: 60%, Westbound: 87% **Second Scenario:** Rotterdam – Shanghai/Yokohama: NWP: Eastbound: 45%, Westbound: 70% SCR: Eastbound: 60%, Westbound: 87%	4,500 TEU Containership	1AS (IAS)	Shipowner's perspective	Yes Increased fuel consumption by 8% per day owing to ice-class No overconsumption for friction with loose ice Considered Also for NWP: Fuel consumption of 39 tonnes per day at a speed of 13 knots
Raza and Schøyen (2014)	N.A.	Eastbound: NSR & SCR: 90%	150,000 cm/84,682 DWT LNG Tanker	Lloyd's 1A (IA)	Charterer's Perspective	N.A.
Lu et al. (2014)	N.A.	100% in all scenarios?	4,500 –15,000 TEU Containership	N.A.	Charterer's Perspective	N.A.

Author(s) and year	Maintenance premium	Load Factor	Type of ship	Ice Class	Transport Costs	Impact of Ice on Fuel Consumption
Lasserre (2015)	**First and Second Scenarios:** NSR and NWP: Periodic Maintenance: +20% per season/day **Third Scenario:** NWP: Periodic Maintenance: +150% per year/day (based on Somanathan et al. 2009) **Fourth Scenario:** **NSR:** Periodic Maintenance: +25% per winter operations	**First Scenario:** Rotterdam – Shanghai/Yokohama: NSR: Eastbound: 50%, Westbound: 70% SCR: Eastbound: 75%, Westbound: 85% **Second Scenario:** Rotterdam – Shanghai/Yokohama: NWP: Eastbound: 50%, Westbound: 70% SCR: Eastbound: 75%, Westbound: 85% **Third Scenario:** Rotterdam – Yokohama: NWP: Eastbound: 50%, Westbound: 70% SCR: Eastbound: 75%, Westbound: 85% **Fourth Scenario:** Rotterdam – Yokohama: NSR: Eastbound: 50%, Westbound: 70% SCR: Eastbound: 75%, Westbound: 85%	4,500 TEU Containership	First, Second, Fourth Scenarios: 1AS (IAS) Third Scenario: PC4 Ice Class	Shipowner's Perspective	Yes **First and Second Scenarios (IAS):** Increased fuel consumption by 8% per day owing to ice-class No overconsumption for friction with loose ice considered Also for NWP: Fuel consumption of 39 tonnes per day at a speed of 13 knots **Third Scenario (PC4):** **Summer:** Fuel Consumption of 39 tonnes per day at a speed of 13 knots Increased fuel consumption rate by 15% per day owing to increased power and double shaft propulsion No overconsumption for friction with loose ice Considered

Author(s) and year	Maintenance premium	Load Factor	Type of ship	Ice Class	Transport Costs	Impact of Ice on Fuel Consumption
Lasserre (2015) **(Continued)**						**Third Scenario (PC4):** **Winter:** **Winter:** Fuel Consumption of 120 tonnes per day at a speed of 7 knots when navigating in heavy ice Increased fuel consumption by 12% per day owing to increased power and double shaft propulsion **Fourth Scenario (IAS):** **Summer:** Fuel Consumption of 40 tonnes per day at a speed of 14 knots Increased consumption by 8% per day owing to ice class No overconsumption for friction with loose ice considered **Winter:** Fuel Consumption of 45 tonnes per day at a speed of 7 knots when navigating in heavy broken ice

Author(s) and year	Maintenance premium	Load Factor	Type of ship	Ice Class	Transport Costs	Impact of Ice on Fuel Consumption
Furuichi and Otsuka (2015)	N.A.	Eastbound and Westbound: 70%	4,000 TEU – 15,000 TEU Containership	N.A.	Shipowner's Perspective	Exponent of 2 instead of 3 i.e. cube law
Chou et al. (2015)	N.A.	N.A.	60,000 DWT Panamax Bulk Carrier	N.A.	Charterer's Perspective	N.A.
Chang et al. (2015)	N.A.	N.A.	N.A.	N.A.	Charterer's Perspective	N.A.
Cariou and Faury (2015)	+9.5% daily premium in Operating Costs	NSR and SCR: 80%	40,000 DWT Handymax Bulk Carrier	1A (IAS)	Shipowner's Perspective	N.A.
Von Bock und Polach et al. (2015)	+25% per year 1A: +16 to 19% premium per voyage in Operating Costs 1AS (DAS): +9 to 11% premium per voyage in Operating Costs	Design payload: -7% for both 1A and IAS (DAS)	Aframax Ice-class Aframax Double-Acting Ship (DAS)	1A; 1AS (DAS)	Shipowner's Perspective	Yes Higher engine load through sea ice
Lindstad et al. (2016)	N.A.	100%?	Capesize and Panamax Bulk Carriers	N.A.	Charterer's Perspective	Yes Higher engine load through sea ice
Pruyn (2016)	N.A.	100%?	11 Bulk Carrier sizes (17,000-289,000 DWT)	Ice 0, 1, 2, Reg-1, 2 (Hypothetical)	Shipowner's and Charterer's perspective	Yes Independent navigation: fuel consumption equal to that at design speed when operating on ice
Zhao et al. (2016)	+100% per day	Real data based on COSCO's Asia-N. Europe Service	4,800 TEU Containership	N.A.	Shipowner's Perspective	Yes Increased fuel consumption when operating through ice on NSR
Zhao and Hu (2016)	+17% per year	N.A.	19,461 DWT Multi-purpose/general cargo ship	1A (IA)	Shipowner's Perspective	N.A.

Author(s) and year	Maintenance premium	Load Factor	Type of ship	Ice Class	Transport Costs	Impact of Ice on Fuel Consumption
Zhang, Meng, Ng (2016)	**Containerships:** +20% per day **Oil Tankers:** +20% daily premium in Operating Costs	**Containerships:** Different levels of demand (TEUs) on each port **Oil Tankers:** 100% for oil tankers	New Panamax and Panamax, Containerships VLCC and Aframax Oil Tankers	1A (IA)?	Shipowner's Perspective	Yes Increased resistance on ice, heavier weight, higher engine power through sea ice
Faury and Cariou (2016)	+20% daily premium in Operating Costs	100%	74,997 DWT Panamax Oil Tanker	1A (IA)	Shipowner's Perspective	N.A.
Wang et al. (2016)	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Lin and Chang (2018)	N.A.	N.A.	SCR: 14,000 TEU NSR: 4,500 TEU	N.A.	Shipowner's Perspective	N.A.
Zhu et al. (2018)	+24% per day	Eastbound: NSR: 45%, SCR: 70%, Westbound: NSR: 60%, SCR: 87%	SCR: 15,000 TEU NSR: 4,500 TEU	1AS (Arc5)	Shipowner's Perspective	N.A.
Xu et al. (2018)	N.A.	Eastbound: NSR and SCR: 50% Westbound: NSR & SCR: 100%	Both SCR and NSR: 8,000/10,000/12,000/ 14,000/16,000 TEU	1A (Arc4)	Shipowner's Perspective	Yes Higher engine power through sea ice
Wan et al. (2018)	+20% per day	Eastbound: NSR: 45%, SCR: 70%, Westbound: NSR: 60%, SCR: 87%	SCR and NSR: 5,089 TEU	1A?	Shipowner's Perspective	Yes Increased fuel consumption when operating through ice on NSR
Shibasaki et al. (2018)	N.A.	90% due to boil-off gas	Non-ice class, and Arc 4: 147,500 m^3 Arc7: 172,000 m^3	Arc4 and Arc7	Charterer's Perspective	Exponent of 2 instead of 3 i.e. cube law
Furuichi and Otsuka (2018)	N.A.	Eastbound and Westbound: 70%	NSR: 4,000 TEU SCR: 4/6/8/11/15/20,000 TEU	N.A.	Shipowner's Perspective	Exponent of 2 instead of 3 i.e. cube law

Author(s) and year	Maintenance premium	Load Factor	Type of ship	Ice Class	Transport Costs	Impact of Ice on Fuel Consumption
Wang, Ren et al. (2018)	+46% daily premium in Operating Costs	N.A.	4,300 TEU ice class ship in both SCR and NSR	N.A.	Shipowner's Perspective Charterer's Perspective	N.A.
Wang and Zhang (2019)	+46% daily premium in Operating Costs	N.A.	4,300 TEU ice class ship in both in SCR and NSR	1B (IB)?	Shipowner's Perspective Charterer's Perspective	N.A.
Ding et al. (2020)	+25% daily premium in Operating Costs	100%	5,089/6,606/8,501/ 9,572/10,062/ 13,114/14,074/ 18,982/21,237 TEU	1A	Shipowner's Perspective	Yes Increased resistance on ice, heavier weight, higher engine power through sea ice
Faury, Cheaitou et al. (2020)	+5% and +6% daily premium in Operating Costs for 1A and 1AS, respectively	90%	Non-ice class: 73,400 DWT, 1A: 73,434 DWT, 1AS: 70,053 DWT Ice class ships are used in both SCR and NSR	Non-ice class 1A, 1AS	Shipowner's Perspective Charterer's Perspective	N.A.
Keltto and Woo (2020)	+16.6% ice and +5% Scrubber daily premiums in Operating Costs		Handymax/MR	1A	Shipowner's Perspective	Higher engine load through sea ice
Wang et al. (2020)	+20% per day	90%	Non-ice class: 75,000 DWT Panamax, 115,000 DWT Aframax, 150,000 DWT Suezmax, 300,000 DWT VLCC Ice class: Aframax 115,000 DWT	1A	Shipowner's Perspective	N.A.
Xu and Yang (2020)	N.A.	NSR: 85% Eastbound: NSR and SCR: 50%	NSR: 4,000/6,000/8,000/ 10,000/12,000/ 14,000/16,000 DWT SCR: Only 16,000 DWT	1A (IA)	Shipowner's Perspective	

Author(s) and year	Maintenance premium	Load Factor	Type of ship	Ice Class	Transport Costs	Impact of Ice on Fuel Consumption
Cariou et al. (2021)	N.A.	All routes: Eastbound: 60% Westbound: 87%	3,600 TEU	1A	Shipowner's Perspective	Engine load lower than 70-80% when ice thickness is greater than 0.30 cm
Tseng et al. (2021)	+8% daily premium in Operating Costs	N.A.	SCR: 8,000 TEU SCR/NSR: 4,000 TEU (ice class)	N.A.	Shipowner's Perspective	N.A.
Gleb and Jin (2021)	+20% per year (Periodic Maintenance) for both ice class and non-ice class ships	100% Load factors that give equal costs between SCR and SCR/NSR for an ice class Ice1 Handysize ship at HSFO price 250 US$/t: Yokohama – Rotterdam: 74% Shanghai – Rotterdam: 84% Shenzhen – Rotterdam: 93%	Handysize 38,000 DWT Multipurpose/ General Cargo ship	Non-ice class Ice 1 (II) Ice 2 (1C) Ice 3 (1B) Arc 4 (1A) Arc 5 (1AS) Arc 6 (PC5 IACS)	Shipowner's Perspective	N.A.
Wang, Liu et al. (2021)	+14% daily premium in Operating Costs	Eastbound: NSR and SCR: 60%, Westbound: NSR & SCR: 87%	SCR: 18,000 TEU SCR/NSR: 3,600 TEU ice class ship used in both SCR and NSR	1A	Shipowner's Perspective Charterer's Perspective	N.A.
Wang, Silberman et al. (2021)	+20% daily premium in Operating Costs	N.A.	Global Containership Fleet	All?	Shipowner's Perspective	N.A.

Appendix G. Results of the reviewed papers in terms of cost assessments

Economic assessments

Liner Shipping			
Time Frame	**Competitive**	**Not Competitive**	**Competitive in specific trades/scenarios**
Annual		Verny and Grigentin (2009)	Kondo and Takamasa (1999)
		Lasserre (2015)	Somanathan et al. (2007)
		Zhao et al. (2016)	Somanathan et al. (2009)
Combined Use of NSR/SCR (Annual)	Xu et al. (2011)	Liu and Kronbak (2010)	Furuichi and Otsuka (2018)
	Furuichi and Otsuka (2015)	Lin and Chang (2018)	Xu et al. (2018)
	Wang, Ren et al. (2018)		Wang and Zhang (2019)
			Xu and Yang (2020)
			Gleb and Jin (2021) (Multipurpose/General Cargo)
			Wang, Liu et al. (2021)
Seasonal	Wang et al. (2016)	Zhu et al. (2018)	Lasserre (2014)
		Wan et al. (2018)	Lasserre (2015)
			Cariou et al. (2021)
Single/round voyage	Wergeland (1992) (Multipurpose/General Cargo)	Zhang et al. (2016) (Liner)	Guy (2006) (Liner)
	Lu et al. (2014)		Tseng et al. (2021) (Combined Use of NSR/Traditional Routes)
	Zhao and Hu (2016) (Multipurpose/General Cargo)		Wang, Silberman et al. (2021) (Combined Use of NSR/Traditional Routes)
	Ding et al. (2020)		

Oil Tanker Shipping			
Time Frame	**Competitive**	**Not Competitive**	**Competitive in specific trades/scenarios**
Annual			Faury and Cariou (2016)
Combined Use of NSR/SCR (Annual)		Von Bock und Polach et al. (2015)	Faury, Cheaitou et al. (2020)
			Keltto and Woo (2020)
Seasonal	Song and Zhang (2013)		
Single/round voyage		Zhang et al. (2016) (Oil Tanker)	Wang et al. (2020)

LNG Tanker Shipping			
Time Frame	**Competitive**	**Not Competitive**	**Competitive in specific trades/scenarios**
Combined Use of NSR/SCR (Annual)			Shibasaki et al. (2018)
Single/round voyage	Raza and Schøyen (2014)		

Dry Bulk Shipping			
Time Frame	**Competitive**	**Not Competitive**	**Competitive in specific trades/scenarios**
Annual		Pruyn (2016)	
Single/round voyage	Schøyen and Bråthen (2011)		Guy (2006) (Dry Bulk Carrier)
	Chou et al. (2015)		
	Chang et al. (2015)		
	Cariou and Faury (2015)		
Unspecified time frame	Lindstad et al. (2016)		

Appendix H. Results of the reviewed papers in terms of emissions assessments

Environmental assessments

Lower Emissions	Lower/Higher Emissions depending on scenario	Air pollution	Emissions Tax
Schøyen and Bråthen (2011)	Lindstad et al. (2016)	Zhu et al. (2018)	Kondo and Takamasa (1999)
	Zhu et al. (2018)	Wang et al. (2020)	Cariou and Faury (2015)
Furuichi and Otsuka (2015)	Wang et al. (2020)		Ding et al. (2020)
Zhao and Hu (2016) (Multipurpose/General Cargo)	Wang, Silberman et al. (2021)		Wang, Silberman et al. (2021) (ETS)
Wan et al. (2018)	Tseng et al. (2021)		
Xu and Yang (2020)	Cariou et al. (2021)		

Appendix I. Consent form of informant from tanker company

CARDIFF BUSINESS SCHOOL
RESEARCH ETHICS

Consent Form –

This research project aims to investigate the feasibility of the Northeast Passage/Northern Sea Route compared to the traditional routes and oceanic canals. Primary data will be obtained from stakeholders of the wider maritime transport sector (e.g. shipowners, shipbrokers, analysts), such as additional operating, capital and other costs, or premiums regarding the organisation of Arctic maritime operations. The primary data will complement secondary data obtained from other sources, such as databases, websites and the literature in order to be used as inputs in cost models with the aim to compare various maritime routes. A quantitative modelling research design will be applied in this project and primary data (numerical data) will be used along with secondary data (numerical data) to be used as inputs in operational research models and techniques.

I understand that my participation in this project will involve providing certain cost data regarding the organisation of Arctic maritime operations via email communication.

I understand that participation in this study is entirely voluntary and that I can withdraw from the study at any time without giving a reason.

I understand that I am free to ask any questions at any time. If for any reason I have second thoughts about my participation in this project, I am free to withdraw or discuss my concerns with the researcher's supervisory team: Dr. Vasco Sanchez Rodrigues, Professor Stephen Pettit, and Dr. Jane Haider.

I understand that the information provided by me will be held confidentially and securely, such that only the researcher can trace this information back to me individually. The information will be anonymised, deleted or destroyed after the completion of the research. I understand that if I withdraw my consent I can ask for the information I have provided to be anonymised/deleted/destroyed in accordance with the Data Protection Act 1998.

I, consent to participate in the study conducted by Dimitrios Theocharis, TheocharisD@cardiff.ac.uk, PhD Student of Cardiff Business School, Cardiff University, under the supervision of Dr. Vasco Sanchez Rodrigues, Professor Stephen Pettit, and Dr. Jane Haider.

Signed:

Date: 14 May 2019

Appendix J. Calculations on marginal cost, average variable cost, average total cost, and optimal ship speeds – Chapter 3

Solutions for functions and calculations of Section '3.6.2 Marginal cost and the optimal speed':

Following Evans and Marlow (1990), the Variable Cost function, VC, is defined as:

$$VC = \left(\frac{D}{S}\right) \cdot \left(C_o + P_F \cdot F_d \cdot \left(\frac{S}{S_d}\right)^a\right)$$

$$VC = C_o \cdot \left(\frac{D}{S}\right) + P_F \cdot F_d \cdot \left(\frac{S}{S_d}\right)^a \cdot \left(\frac{D}{S}\right)$$

Let $k = \frac{D}{S}$ and $a = 3$

$$VC = C_o \cdot k + P_F \cdot F_d \cdot \left(\frac{S}{S_d}\right)^3 \cdot k$$

$$VC = C_o \cdot k + P_F \cdot F_d \cdot \frac{S^3}{S_d^3} \cdot k$$

But $S = \frac{D}{k}$:

$$VC = C_o \cdot k + P_F \cdot \frac{F_d}{S_d^3} \cdot \frac{D^3}{k^3} \cdot k$$

$$VC = C_o \cdot k + P_F \cdot \frac{F_d}{S_d^3} \cdot \frac{D^3}{k^2}$$

By differentiating the VC function with respect to distance, D, the marginal cost, MC, is obtained, which is the rate of change of the variable cost, VC, with respect to distance, D.

$$MC = \frac{dVC}{dD}$$

$$= 3 \cdot P_F \cdot \frac{F_d}{S_d^3} \cdot \frac{D^2}{k^2}$$

But $S^2 = \frac{D^2}{k^2}$:

$$\boldsymbol{MC = 3 \cdot P_F \cdot \frac{F_d}{S_d^3} \cdot S^2}$$

It is assumed that ship-mile is the output of transport service for one day (Evans and Marlow 1990). The average variable cost, AVC, is defined as the summation of operating and voyage costs divided by the output, in which case is the ship speed S:

$$AVC = \frac{C_o}{S} + P_F \cdot \frac{F_d \cdot \left(\frac{S}{S_d}\right)^3}{S}$$

$$AVC = \frac{C_o}{S} + P_F \cdot \frac{F_d \cdot S^3}{S \cdot S_d^3}$$

$$\boldsymbol{AVC = \frac{C_o}{S} + P_F \cdot \frac{F_d \cdot S^2}{S_d^3}}$$

The optimal speed at which the cost per unit of output is minimised, is found when:

$$\boldsymbol{AVC = MC}$$

$$\frac{C_o}{S} + P_F \cdot \frac{F_d \cdot S^2}{S_d^3} = 3 \cdot P_F \cdot \frac{F_d}{S_d^3} \cdot S^2$$

$$3 \cdot P_F \cdot \frac{F_d}{S_d^3} \cdot S^2 - P_F \cdot \frac{F_d \cdot S^2}{S_d^3} = \frac{C_o}{S}$$

$$2 \cdot P_F \cdot \frac{F_d}{S_d^3} \cdot S^2 = \frac{C_o}{S}$$

$$2 \cdot P_F \cdot F_d \cdot S^2 \cdot S = C_o \cdot S_d^3$$

$$S^3 = \frac{C_o \cdot S_d^3}{2 \cdot P_F \cdot F_d}$$

$$\boldsymbol{S = \left(\frac{C_o \cdot S_d^3}{2 \cdot P_F \cdot F_d}\right)^{1/3}}$$

And:

$$\boldsymbol{MC = 3 \cdot P_F \cdot \frac{F_d}{S_d^3} \cdot \left(\left(\frac{C_o \cdot S_d^3}{2 \cdot P_F \cdot F_d}\right)^{1/3}\right)^2}$$

Following the same process for the Total Cost function, TC, as in the case of the Variable Cost function, VC:

$$TC = \left(\frac{D}{S}\right) \cdot \left(C_o + C_c + P_F \cdot F_d \cdot \left(\frac{S}{S_d}\right)^a\right)$$

$$TC = C_o \cdot \left(\frac{D}{S}\right) + C_c \cdot \left(\frac{D}{S}\right) + P_F \cdot F_d \cdot \left(\frac{S}{S_d}\right)^a \cdot \left(\frac{D}{S}\right)$$

Let $k = \frac{D}{S}$ and $a = 3$

$$TC = C_o \cdot k + C_c \cdot k + P_F \cdot F_d \cdot \left(\frac{S}{S_d}\right)^3 \cdot k$$

$$TC = C_o \cdot k + C_c \cdot k + P_F \cdot F_d \cdot \frac{S^3}{S_d^3} \cdot k$$

But $S = \frac{D}{k}$:

$$TC = C_o \cdot k + C_c \cdot k + P_F \cdot \frac{F_d}{S_d^3} \cdot \frac{D^3}{k^3} \cdot k$$

$$TC = C_o \cdot k + C_c \cdot k + P_F \cdot \frac{F_d}{S_d^3} \cdot \frac{D^3}{k^2}$$

By differentiating the TC function with respect to distance, D, the marginal cost, MC, is obtained, which is the rate of change of the total cost, TC, with respect to distance, D.

$$MC = \frac{dTC}{dD}$$

$$= 3 \cdot P_F \cdot \frac{F_d}{S_d^3} \cdot \frac{D^2}{k^2}$$

But $S^2 = \frac{D^2}{k^2}$:

$$\boldsymbol{MC = 3 \cdot P_F \cdot \frac{F_d}{S_d^3} \cdot S^2}$$

It is assumed that ship-mile is the output of transport service for one day (Evans and Marlow 1990). The average total cost, $ATC,$ is defined as the summation of all costs, divided by the output, in which case is the ship speed S:

$$ATC = \frac{C_o}{S} + \frac{C_c}{S} + P_F \cdot \frac{F_d \cdot \left(\frac{S}{S_d}\right)^3}{S}$$

$$ATC = \frac{C_o}{S} + \frac{C_c}{S} + P_F \cdot \frac{F_d \cdot S^3}{S \cdot S_d^3}$$

$$\boldsymbol{ATC = \frac{C_o}{S} + \frac{C_c}{S} + P_F \cdot \frac{F_d \cdot S^2}{S_d^3}}$$

The optimal speed at which the cost per unit of output is minimised, is found when:

$$\boldsymbol{ATC = MC}$$

$$\frac{C_o}{S} + \frac{C_c}{S} + P_F \cdot \frac{F_d \cdot S^2}{S_d^3} = 3 \cdot P_F \cdot \frac{F_d}{S_d^3} \cdot S^2$$

$$3 \cdot P_F \cdot \frac{F_d}{S_d^3} \cdot S^2 - P_F \cdot \frac{F_d \cdot S^2}{S_d^3} = \frac{C_o}{S} + \frac{C_c}{S}$$

$$2 \cdot P_F \cdot \frac{F_d}{S_d^3} \cdot S^2 = \frac{C_o + C_c}{S}$$

$$2 \cdot P_F \cdot F_d \cdot S^2 \cdot S = (C_o + C_c) \cdot S_d^3$$

$$S^3 = \frac{(C_o + C_c) \cdot S_d^3}{2 \cdot P_F \cdot F_d}$$

$$\boldsymbol{S = \left(\frac{(C_o + C_c) \cdot S_d^3}{2 \cdot P_F \cdot F_d}\right)^{1/3}}$$

And:

$$\boldsymbol{MC = 3 \cdot P_F \cdot \frac{F_d}{S_d^3} \cdot \left(\left(\frac{(C_o + C_c) \cdot S_d^3}{2 \cdot P_F \cdot F_d}\right)^{1/3}\right)^2}$$

Solutions for functions and calculations of Section '3.6.3 Approaches to speed optimisation':

The optimal speed at which the profit per day is maximised (Equation (21)) is found when:

$$\pi = \frac{FR \cdot W - C_T}{\left(\frac{D}{S \cdot 24}\right)} - C_o - F(S, \nabla) \cdot P_F \qquad \text{Equation (19)}$$

Assuming a cubic fuel consumption function of the form:

$$F(S, \nabla) = F_d \cdot \left(\frac{S}{S_d}\right)^3 \cdot \left(\frac{P+L}{\nabla}\right)^{2/3} \qquad \text{Equation (18)}$$

The only decision variable is the optimal speed, S, the rest being data inputs to the problem.

$$\pi = \frac{FR \cdot W - C_T}{\left(\frac{D}{S \cdot 24}\right)} - C_o - F_d \cdot \left(\frac{S}{S_d}\right)^3 \cdot \left(\frac{P+L}{\nabla}\right)^{2/3} \cdot P_F$$

$$= \frac{24 \cdot (FR \cdot W - C_T) \cdot S}{D} - C_o - \frac{F_d \cdot S^3}{{S_d}^3} \cdot \left(\frac{P+L}{\nabla}\right)^{\frac{2}{3}} \cdot P_F$$

$$= \frac{24 \cdot (FR \cdot W - C_T)}{D} \cdot S - C_o - \frac{F_d \cdot (P+L)^{2/3}}{{S_d}^3 \cdot \nabla^{2/3}} \cdot P_F \cdot S^3$$

1st order derivative to obtain the optimal speed, S, which maximises the profit, π:

$$\frac{\partial \pi}{\partial S} = \frac{24 \cdot (FR \cdot W - C_T)}{D} - 3 \cdot \frac{F_d \cdot (P+L)^{2/3}}{{S_d}^3 \cdot \nabla^{2/3}} \cdot P_F \cdot S^2 = 0$$

$$3 \cdot \frac{F_d \cdot (P+L)^{2/3}}{{S_d}^3 \cdot \nabla^{2/3}} \cdot P_F \cdot S^2 = \frac{24 \cdot (FR \cdot W - C_T)}{D}$$

$$3 \cdot D \cdot F_d \cdot (P+L)^{2/3} \cdot P_F \cdot S^2 = 24 \cdot (FR \cdot W - C_T) \cdot {S_d}^3 \cdot \nabla^{2/3}$$

And:

$$S_{\pi}^{*\,2} = \frac{24 \cdot (FR \cdot W - C_T) \cdot S_d{}^3 \cdot \nabla^{2/3}}{3 \cdot D \cdot F_d \cdot P_F \cdot (P+L)^{2/3}} \qquad \text{or} \qquad S_{\pi}^{*} = \left(\frac{24 \cdot (FR \cdot W - C_T) \cdot S_d{}^3 \cdot \nabla^{2/3}}{3 \cdot D \cdot F_d \cdot P_F \cdot (P+L)^{2/3}}\right)^{1/2}$$

The optimal speed at which the cost per unit of output is minimised (Equation (24)) is found when:

$$C = \frac{1}{W} \cdot \left[\left(\frac{D}{S \cdot 24}\right) \cdot \left((F(S, \nabla) \cdot P_F) + (C_o + C_c)\right) + C_T\right] \qquad \text{Equation (22)}$$

Assuming a cubic fuel consumption function of the form:

$$F(S, \nabla) = F_d \cdot \left(\frac{S}{S_d}\right)^3 \cdot \left(\frac{P+L}{\nabla}\right)^{2/3} \qquad \text{Equation (18)}$$

The only decision variable is the optimal speed, S, the rest being data inputs to the problem.

$$C = \frac{1}{W} \cdot \left[\left(\frac{D}{S \cdot 24}\right) \cdot \left(\left(F_d \cdot \left(\frac{S}{S_d}\right)^3 \cdot \left(\frac{P+L}{\nabla}\right)^{2/3} \cdot P_F\right) + (C_o + C_c)\right) + C_T\right]$$

$$= \frac{D}{W \cdot S \cdot 24} \cdot \frac{F_d \cdot S^3}{S_d{}^3} \cdot \left(\frac{P+L}{\nabla}\right)^{\frac{2}{3}} \cdot P_F + (C_o + C_c) \cdot \frac{D}{W \cdot S \cdot 24} + \frac{C_T}{W}$$

$$= \frac{D \cdot F_d \cdot S^3 \cdot \left(\frac{P+L}{\nabla}\right)^{\frac{2}{3}} \cdot P_F}{W \cdot S \cdot 24 \cdot S_d{}^3} + \frac{(C_o + C_c) \cdot D}{W \cdot S \cdot 24} + \frac{C_T}{W}$$

$$= \frac{D \cdot F_d \cdot P_F \cdot S^2 \cdot (P+L)^{\frac{2}{3}}}{W \cdot 24 \cdot S_d{}^3 \cdot \nabla^{\frac{2}{3}}} + \frac{(C_o + C_c) \cdot D}{W \cdot 24} \cdot \frac{1}{S} + \frac{C_T}{W}$$

1st order derivative to obtain the optimal speed, S, which minimises the cost, C:

$$\frac{\partial C}{\partial_S} = \frac{2 \cdot D \cdot F_d \cdot P_F \cdot (P+L)^{\frac{2}{3}}}{W \cdot 24 \cdot {S_d}^3 \cdot \nabla^{\frac{2}{3}}} \cdot S - \frac{(C_o + C_c) \cdot D}{W \cdot 24} \cdot \frac{1}{S^2} = 0$$

$$\frac{2 \cdot D \cdot F_d \cdot P_F \cdot (P+L)^{\frac{2}{3}}}{W \cdot 24 \cdot {S_d}^3 \cdot \nabla^{\frac{2}{3}}} \cdot S = \frac{(C_o + C_c) \cdot D}{W \cdot 24 \cdot S^2}$$

$$\frac{2 \cdot F_d \cdot P_F \cdot (P+L)^{\frac{2}{3}}}{{S_d}^3 \cdot \nabla^{\frac{2}{3}}} \cdot S = \frac{(C_o + C_c)}{S^2}$$

$$2 \cdot F_d \cdot P_F \cdot (P+L)^{\frac{2}{3}} \cdot S \cdot S^2 = (C_o + C_c) \cdot {S_d}^3 \cdot \nabla^{\frac{2}{3}}$$

$$2 \cdot F_d \cdot P_F \cdot (P+L)^{\frac{2}{3}} \cdot S^{(1+2)} = (C_o + C_c) \cdot {S_d}^3 \cdot \nabla^{\frac{2}{3}}$$

$$2 \cdot F_d \cdot P_F \cdot (P+L)^{\frac{2}{3}} \cdot S^3 = (C_o + C_c) \cdot {S_d}^3 \cdot \nabla^{\frac{2}{3}}$$

And:

$${S_C^*}^3 = \frac{(C_o + C_c) \cdot {S_d}^3 \cdot \nabla^{\frac{2}{3}}}{2 \cdot F_d \cdot P_F \cdot (P+L)^{\frac{2}{3}}} \qquad \text{or} \qquad S_C^* = \left(\frac{(C_o + C_c) \cdot {S_d}^3 \cdot \nabla^{\frac{2}{3}}}{2 \cdot F_d \cdot P_F \cdot (P+L)^{\frac{2}{3}}} \right)^{1/3}$$

The cost minimising speed when including in-transit inventory costs (Equation (28)), is found in the same way, by using Equation (26) instead of Equation (22).

Appendix K. Calculations of optimal speeds – Chapter 4

When a tanker operates on either HSFO or VLSFO mode (Equation (3), Section '4.3.1 Modelling approach', Chapter 4):

$$RFR = \frac{1}{W} \cdot \left[\left(\frac{D_{SCR,NSR}}{S_{FO}^{*} \cdot 24} \right) \cdot \left(\left(F_{FO}(S_{FO}^{*}) \cdot P_{FO} \right) + (C_o + C_c) \right) + C_{TI} \right]$$

Assuming a fuel consumption function of the form:

$$F_{FO}(S^{*}, \nabla) = F_{FO\,d} \cdot \left(\frac{S_{FO}^{*}}{S_d} \right)^{a} \cdot \left(\frac{P + L}{\nabla} \right)^{2/3}$$

The only decision variable is the optimal speed, S_{FO}^{*}, the rest being data inputs to the problem.

$$RFR = \frac{1}{W} \cdot \left[\left(\frac{D_{SCR,NSR}}{S_{FO}^{*} \cdot 24} \right) \cdot \left(\left(F_{FO\,d} \cdot \left(\frac{S_{FO}^{*}}{S_d} \right)^{a} \cdot \left(\frac{P + L}{\nabla} \right)^{2/3} \cdot P_{FO} \right) + (C_o + C_c) \right) + C_{TI} \right]$$

$$= \frac{D_{SCR,NSR}}{W \cdot S_{FO}^{*} \cdot 24} \cdot \frac{F_{FO\,d} \cdot {S_{FO}^{*}}^{a}}{{S_d}^{a}} \cdot \left(\frac{P + L}{\nabla} \right)^{\frac{2}{3}} \cdot P_{FO} + (C_o + C_c) \cdot \frac{D_{SCR,NSR}}{W \cdot S_{FO}^{*} \cdot 24} + \frac{C_{TI}}{W}$$

$$= \frac{D_{SCR,NSR} \cdot F_{FO\,d} \cdot {S_{FO}^{*}}^{a} \cdot \left(\frac{P + L}{\nabla} \right)^{\frac{2}{3}} \cdot P_{FO}}{W \cdot S_{FO}^{*} \cdot 24 \cdot {S_d}^{a}} + \frac{(C_o + C_c) \cdot D_{SCR,NSR}}{W \cdot S_{FO}^{*} \cdot 24} + \frac{C_{TI}}{W}$$

$$= \frac{D_{SCR,NSR} \cdot F_{FO\,d} \cdot P_{FO} \cdot {S_{FO}^{*}}^{(a-1)} \cdot (P + L)^{\frac{2}{3}}}{W \cdot 24 \cdot {S_d}^{a} \cdot \nabla^{\frac{2}{3}}} + \frac{(C_o + C_c) \cdot D_{SCR,NSR}}{W \cdot 24} \cdot \frac{1}{S_{FO}^{*}} + \frac{C_{TI}}{W}$$

1st order derivative to obtain the optimal speed, S_{FO}^{*} , which minimises the RFR:

$$\frac{\partial RFR}{\partial_{S_{FO}^{*}}} = \frac{(a-1)\cdot D_{SCR,NSR}\cdot F_{FO\,d}\cdot P_{FO}\cdot(P+L)^{\frac{2}{3}}}{W\cdot 24\cdot {S_d}^{a}\cdot \nabla^{\frac{2}{3}}} \cdot {S_{FO}^{*}}^{(a-2)} - \frac{(C_o+C_c)\cdot D_{SCR,NSR}}{W\cdot 24} \cdot \frac{1}{{S_{FO}^{*}}^{2}} = 0$$

$$\frac{(a-1)\cdot D_{SCR,NSR}\cdot F_{FO\,d}\cdot P_{FO}\cdot(P+L)^{\frac{2}{3}}}{W\cdot 24\cdot {S_d}^{a}\cdot \nabla^{\frac{2}{3}}} \cdot {S_{FO}^{*}}^{(a-2)} = \frac{(C_o+C_c)\cdot D_{SCR,NSR}}{W\cdot 24\cdot {S_{FO}^{*}}^{2}}$$

$$\frac{(a-1)\cdot F_{FO\,d}\cdot P_{FO}\cdot(P+L)^{\frac{2}{3}}}{{S_d}^{a}\cdot \nabla^{\frac{2}{3}}} \cdot {S_{FO}^{*}}^{(a-2)} = \frac{(C_o+C_c)}{{S_{FO}^{*}}^{2}}$$

$$(a-1)\cdot F_{FO\,d}\cdot P_{FO}\cdot(P+L)^{\frac{2}{3}}\cdot {S_{FO}^{*}}^{(a-2)}\cdot {S_{FO}^{*}}^{2} = (C_o+C_c)\cdot {S_d}^{a}\cdot \nabla^{\frac{2}{3}}$$

$$(a-1)\cdot F_{FO\,d}\cdot P_{FO}\cdot(P+L)^{\frac{2}{3}}\cdot {S_{FO}^{*}}^{(a-2+2)} = (C_o+C_c)\cdot {S_d}^{a}\cdot \nabla^{\frac{2}{3}}$$

$$(a-1)\cdot F_{FO\,d}\cdot P_{FO}\cdot(P+L)^{\frac{2}{3}}\cdot {S_{FO}^{*}}^{a} = (C_o+C_c)\cdot {S_d}^{a}\cdot \nabla^{\frac{2}{3}}$$

And:

$${S_{FO}^{*}}^{a} = \frac{(C_o+C_c)\cdot {S_d}^{a}\cdot \nabla^{\frac{2}{3}}}{(a-1)\cdot(F_{FO\,d}\cdot P_{FO})\cdot(P+L)^{\frac{2}{3}}} \quad \text{or} \quad S_{FO}^{*} = \sqrt[a]{\frac{(C_o+C_c)\cdot {S_d}^{a}\cdot \nabla^{\frac{2}{3}}}{(a-1)\cdot(F_{FO\,d}\cdot P_{FO})\cdot(P+L)^{\frac{2}{3}}}}$$

The optimal speed when a tanker operates in ballast (Equation (7), Section ‘4.3.1 Modelling approach’) is found in the same way as above. The 2nd order derivative results in a positive value, which ensures that the solution is a minimum. Moreover, the solution is unique and is a global minimum in the range of 0-16 i.e. between the lowest and highest speed values. The only exception is in cases where the speed is constrained, such as on ice legs within NSR.

Appendix L. OD pairs of destination and transit tanker voyages in 2011-2018 – Chapter 4

Year	Tanker Size (dwt)	Ice Class	Tanker Name	Origin Port	Origin Country	Origin Region	Destination Port	Destination Country	Destination Region	Cargo Type	SCR Distance (n.m.)	NSR Distance (n.m.)	Distance Difference %
2013	MR (47,187)	IA	SCF Yenisei	Vitino	Russia	Arctic Russia	Iwakuni	Japan	Far East	Naphtha	13,085	6,191	-53
2012	LR1 (74,450)	IA	Palva	Murmansk	Russia	Arctic Russia	Daesan	South Korea	Far East	Condensate	12,476	6,183	-50
2011	LR1 (74,450)	IA	Stena Poseidon	Vitino	Russia	Arctic Russia	Incheon	South Korea	Far East	Condensate	13,023 (125)	6,459	-50
2011	LR1 (74,450)	IA	Mariann	Vitino	Russia	Arctic Russia	Incheon	South Korea	Far East	Condensate	13,023 (125)	6,459	-50
2012	LR1 (74,450)	IA	Marilee	Vitino	Russia	Arctic Russia	Incheon	South Korea	Far East	Condensate	13,023 (125)	6,459	-50
2012	LR1 (73,965)	IA	Two Million Ways	Vitino	Russia	Arctic Russia	Incheon	South Korea	Far East	Condensate	13,023 (125)	6,459	-50
2012	LR1 (74,450)	IA	Marika	Vitino	Russia	Arctic Russia	Incheon	South Korea	Far East	Condensate	13,023 (125)	6,459	-50
2012	LR1 (74,450)	IA	Marinor	Vitino	Russia	Arctic Russia	Daesan	South Korea	Far East	Condensate	12,943	6,487	-50
2012	LR1 (74,450)	IA	Stena Poseidon	Vitino	Russia	Arctic Russia	Daesan	South Korea	Far East	Condensate	12,943	6,487	-50
2012	LR1 (74,998)	IA	Maribel	Vitino	Russia	Arctic Russia	Daesan	South Korea	Far East	Condensate	12,943	6,487	-50
2013	LR1 (74,450)	IA	Marinor	Vitino	Russia	Arctic Russia	Daesan	South Korea	Far East	Condensate	12,943	6,487	-50
2011	LR1 (73,788)	IA	Perseverance	Vitino	Russia	Arctic Russia	Zhoushan	China	Far East	Condensate	12,474 (71)	6,580 (124)	-47
2013	LR2 (117,055)	IA	Propontis	Mongstad	Norway	Europe	Mizushima	Japan	Far East	Naphtha	11,605 (912)	6,668 (84)	-43

Sources: NSRA (2016), CHNL (2021a), Bloomberg (2021), Refinitiv Eikon (2021), Clarksons (2021), distances were calculated on Dataloy Distance Table (Dataloy 2021). ECAs distances are included in the parentheses.

Year	Tanker Size	Ice Class	Tanker Name	Origin Port	Origin Country	Origin Region	Destination Port	Destination Country	Destination Region	Cargo Type	SCR Distance (n.m.)	NSR Distance (n.m.)	Distance Difference %
2011	LR1 (74,450)	IA	Marilee	Vitino	Russia	Arctic Russia	Huizhou	China	Far East	Condensate	11,934 (87)	7,174 (119)	-40
2011	LR1 (74,450)	IA	Palva	Vitino	Russia	Arctic Russia	Huizhou	China	Far East	Condensate	11934 (87)	7,174 (119)	-40
2011	LR1 (73,293)	IA	Affinity	Vitino	Russia	Arctic Russia	Huizhou	China	Far East	Condensate	11,934 (87)	7,174 (119)	-40
2011	LR1 (73,788)	IA	Perseverance	Vitino	Russia	Arctic Russia	Huizhou	China	Far East	Condensate	11,934 (87)	7,174 (119)	-40
2012	LR1 (73,919)	IA	STI Harmony	Vitino	Russia	Arctic Russia	Zhanjiang	China	Far East	Condensate	11,817 (112)	7,426 (453)	-37
2013	LR2 (117,055)	IA	Propontis	Ulsan	South Korea	Far East	Amsterdam	Netherlands	Europe	Gasoil/Diesel	11,038 (440)	7,052 (588)	-36
2012	LR1 (74,450)	IA	Stena Poseidon	Yeosu	South Korea	Far East	Porvoo	Finland	Europe	Jet Fuel/ Kerosene	12,228 (1,689)	7,857 (1,271)	-36
2012	LR1 (74,450)	IA	Marika	Yeosu	South Korea	Far East	Porvoo	Finland	Europe	Jet Fuel/ Kerosene	12,228 (1,689)	7,857 (1,271)	-36
2012	LR1 (74,450)	IA	Palva	Yeosu	South Korea	Far East	Porvoo	Finland	Europe	Jet Fuel/ Kerosene	12,228 (1,689)	7,857 (1,271)	-36
2013	LR1 (65,125)	IA	Stena Polaris	Ust-Luga	Russia	Baltic Russia	Yeosu	South Korea	Far East	Naphtha	12,316 (1,777)	7,944 (1,358)	-35
2013	LR2 (104,532)	IC	Zaliv Baikal	Ust-Luga	Russia	Baltic Russia	Yeosu	South Korea	Far East	Naphtha	12,316 (1,777)	7,944 (1,358)	-35
2013	LR2 (104,542)	IC	Zaliv Amurskiy	Ulsan	South Korea	Far East	Antwerp	Netherlands	Europe	Gasoil/Diesel	11,006 (408)	7,165 (701)	-35
2013	LR2 (118,105)	IB	Viktor Bakaev	Yeosu	South Korea	Far East	Rotterdam	Netherlands	Europe	Jet Fuel/ Kerosene	10,954 (415)	7,207 (621)	-34
2011	LR1 (73,788)	IA	Perseverance	Yeosu	South Korea	Far East	Antwerp	Netherlands	Europe	Jet Fuel/ Kerosene	10,947 (408)	7,287 (701)	-33

Sources: NSRA (2016), CHNL (2021a), Bloomberg (2021), Refinitiv Eikon (2021), Clarksons (2021), distances were calculated on Dataloy Distance Table (Dataloy 2021). ECAs distances are included in the parentheses.

Year	Tanker Size (dwt)	Ice Class	Tanker Name	Origin Port	Origin Country	Origin Region	Destination Port	Destination Country	Destination Region	Cargo Type	SCR Distance (n.m.)	NSR Distance (n.m.)	Distance Difference %
2018	Aframax (113,226)	IA/B	Lomonosov Prospect	Yeosu	South Korea	Far East	Rotterdam	Netherlands	Europe	Jet Fuel/ Kerosene	10,872 (413)	7,276 (629)	-33
2013	LR1 (73,434)	IA	Mari Ugland	Mongstad	Norway	Europe	Mailiao	Taiwan	Far East	Naphtha	10,586 (912)	7,444 (84)	-30
2011	LR1 (73,956)	IA	STI Heritage	Vitino	Russia	Arctic Russia	Map Ta Phut	Thailand	Southeast Asia	Condensate	11,218	8,516	-24
2011	LR3/Suezmax (162,362)	IA	Vladimir Tikhonov	Honningsvåg	Norway	Arctic Europe	Map Ta Phut	Thailand	Southeast Asia	Condensate	10,599 (966)	8,217	-22
2013	LR1 (73,965)	IA	Two Million Ways	Vitino	Russia	Arctic Russia	Sungai Udang	Malaysia	Southeast Asia	Condensate	10,354	8,677	-16

Sources: NSRA (2016), CHNL (2021a), Bloomberg (2021), Refinitiv Eikon (2021), Clarksons (2021), distances were calculated on Dataloy Distance Table (Dataloy 2021). ECAs distances are included in the parentheses.

Notes:

The OD pairs presented in the tables above refer to tankers of 47-162,000 dwt which operated on NSR during the summer/autumn seasons of 2011-2018. The OD pair distance differences are arranged in descending order.

The Vitino-Daesan pair is considered a representative short-haul, given that all OD pair distances listed prior to this one (Vitino-Iwakuni, Murmansk-Daesan, Vitino-Incheon) result in same distance savings. The Yeosu-Rotterdam pair is considered a representative long-haul. OD pairs listed after this OD pair include ports that have already considered in other hauls (e.g. Mongstad, Vitino). Besides, distance differences below 30% offer limited distance savings for the NSR. The Mongstad-Mizushima pair lies somewhere in the middle of observations and include transport of naphtha cargo, one of the representative commodities. The choice of OD pairs is a combination of representative distance savings, representative number of voyages per commodity and port characteristics which can accommodate the tanker sizes assumed in the modelling case in Chapter 4.

Appendix M. Port characteristics – Chapter 4

Port	Tanker Terminals	Berths	Max DWT (tonnes)	Max LOA (metres)	Max draught (metres)
Yeosu	GS Galtex Crude Oil Terminal	No. 1 (Crude oil and Clean Products)	255,000	330	20.50
	GS Galtex Product Terminal	No. 3/5	35,000/50,000	183/195	11.30/120
	LPG & E-1 Gas Terminal	LPG Terminal (LPG, Chemicals and Clean Products)	65,200	249.8	12.60
	Sapo Terminal No. 1	Tank Terminal Quay	100,000	280	N.A.
	KNOC Terminal	No. 1/2/3	80,000/120,000/320,000	340/380/440	13.90/15.50/17.70
Rotterdam*	20 Terminals		50,000 – 355,000	185 – 366	11.00 – 16.10
Mongstad	Mongstad Refinery (Equinor, former Statoil)	Crude Oil Jetty No.1 (Crude oil and Clean Products)	380,000	350	23.00
		Jetty No. 14 (STS)	440,000	380	25.00
	Product Jetty	No. 2/8/9	90,000/60,000/50,802	240/235/235	14.50/16.40/16.40
Mizushima	Nippon Petroleum	No. 5/6	114,106/314,026	250/340	16.00
	Japan Energy	No. 1	114,106	250	N.A.
Vitino	Vitino Terminal	No. 3/4	116,000/80,000	249/230	15.40/10.90
Daesan	Seetec Terminal	MDH-21/23/ MDK-15/16	100,000/50,000/ 100,000/45,000	280/219/ 280/200	12.50/12.70/ 14.90/12.00
		Samsung Petrochemical MDS-31	100,000	270	14.00
		KNOC	325,000	330	23.00

Sources: IHS Maritime (2015). *20 terminals/berths were identified which explicitly refer to clean oil products.

Appendix N. Calculations for fuel consumption at design speed – Chapter 4

The tables below present data and assumptions on the fuel consumption at design speed for ordinary (non-ice class) and ice class tankers. The first table presents the assumptions for non-ice class tankers, whilst the second table presents the assumptions for ice class tankers. The assumptions for LR1 tankers are based on average values of tankers with a design speed of 14.9-15.1 knots (listed below).

Assumptions for ice class tankers

Tanker Size (dwt)	Tanker Name	Design Speed (knots)	Fuel Consumption (tonnes/day)	Draught (metres)	Tonnes per Centimetre Immersion (TPC)	Ballast Capacity (tonnes)
LR3/Suezmax (162,362)	**Vladimir Tikhonov**	**15.0**	**67.0**	**16.3**	**N.A.**	**57,301**
LR2 (117,055)	**Propontis**	**14.9**	**50.5**	**15.42**	**98.0**	**N.A.**
LR1 (73,956)	STI Heritage	15.0	42.1	14.37	67.0	27,230
LR1 (73,293)	Affinity	15.1	43.6	14.20	68.2	30,416
LR1 (73,919)	STI Harmony	15.0	42.1	14.37	67.0	39,699
LR1 (73,965)	Two Million Ways	14.9	42.2	14.37	67.0	39,699
LR1 (74,158)	**Average**	**15.0**	**42.5**	**14.30**	**67.3**	**28,026**
MR (47,842)	**Anichkov Bridge**	**14.9**	**34.4**	**12.51**	**52.1**	**22,218**

Source: Clarksons (2021). The characteristics presented in this table refer to tankers with a design speed of 14.9-15.1 knots.

Assumptions for non-ice class tankers

Tanker Size (dwt)	Design Speed (knots)	Fuel Consumption (tonnes/day)
LR3 Tanker	15.0	62.2
LR2Tanker	14.9	47.1
LR1 Tanker	15.0	42.3
MR Tanker	14.9	33.9

Source: Clarksons (2021). MR Tanker: averages of 2003-2007, LR1 Tanker: averages of 2005-2010, LR2 Tanker: 2006 values, LR3 Tanker: 2005 values. These averages reflect the years that the respective ice class tankers were built and operated on NSR.

The table below presents data and assumptions for the tank capacity of marine fuel oils.

Tanker Size (dwt)	HSFO (tonnes)	VLSFO (tonnes)*
LR3 Tanker	3,150	3,150
LR2 Tanker	2,415	2,415
LR1Tanker	2,130	2,130
MR Tanker	1,616	1,616

Source: Clarksons (2021). *Assumed to be the same as HSFO.

The process of calculating the draught when a tanker is loaded with cargo is presented below.

The Tonnes per Centimetre Immersion (TPC) is used to calculate the actual draught difference between the maximum dwt tonnage and payload, which depends on the cargo weight on board. The TPC is the change in draught by one centimetre resulting from the addition or removal of a particular mass (Wärtsilä 2021). The values in "Draught when loaded" reported in Table 4.11 are calculated by using the data presented in this Appendix (first table).

The "draught when loaded" is determined by the following equation:

$$Draught = D_D - \Big(\big((DWT - P)/TPC\big)/100\Big)$$

Where, D_D, is the draught, DWT, the deadweight (payload), TPC, the tonnes per centimetre immersion, and, P, the payload, is the weight of cargo, fresh water, fuel, lubricating oil, stores, water ballast, crew and effects, and baggage and passengers, and is measured in metric tonnes (Barrass 2005; Stopford 2009). The values presented in the first table of this Appendix are used to calculate the "draught when loaded".

When the ship operates in ballast, the payload includes all these elements except for cargo. According to Stopford (2009), the weight of fresh water, fuel, lubricating oil, stores, crew and effects, and baggage and passengers is approximated by using the function: $P = 0.05 \cdot DWT$.

Appendix O1. Capital cost estimation method

The function below describes an annuity factor, which is the present value of a stream of payments to be made in the future, discounted by an interest rate, i, to take into account the future payments (annuities) from year 1 to year n (Evans and Marlow 1990).

$$\frac{(1-(1+i)^{-n})}{i}$$

Which can be rewritten as:

$$\frac{(1+i)^n-1}{i\cdot(1+i)^n}$$

The annual repayment of a loan can then be found by using a capital recovery factor (CRF) (Evans and Marlow 1990). The CRF is the ratio that determines the present value of a stream of annual payments.

Diving 1 by the annuity factor:

$$\frac{1}{\frac{(1+i)^n-1}{i\cdot(1+i)^n}}$$

The CRF is then:

$$\frac{i\cdot(1+i)^n}{(1+i)^n-1}$$

The annual instalment, A, is found by multiplying the loan amount (principal), P_r , with the CRF:

$$A=P_r\cdot\frac{i\cdot(1+i)^n}{(1+i)^n-1}$$

And the daily capital cost, C_c, is found by dividing A with 365:

$$C_c=\frac{A}{365}$$

Appendix O2. Capital cost estimation assumptions – Chapters 4, 5, 6

Capital cost estimation assumptions – Chapter 4

Tanker Size (dwt)	Ice Class	Tanker Name	Year of Order	Assumed Year of Order	Year of Delivery	Lead time (years)	Newbuilding Price (M. US$)	Average Newbuilding Price of non-ice class tanker (M. US$)
LR3/Suezmax (162,362)	IA	Vladimir Tikhonov	2003		2006		58.0	
LR2 (117,055)	IA	Propontis		2003	2006			
LR1 (73,788)	IA	Perseverance		2002	2005			
LR1 (73,293)	IA	Affinity		2002	2005			
LR1 (74,450)	IA	Marilee	2004		2006	2	42.0	41.0
LR1 (74,450)	IA	Stena Poseidon	2004		2007	3	46.2	42.5
LR1 (74,450)	IA	Palva	2004		2007	3	46.2	42.5
LR1 (74,998)	IA	Maribel	2004		2007	3	42.0	42.5
LR1 (73,919)	IA	STI Harmony		2004	2007			
LR1 (74,450)	IA	Mariann	2005		2008	3	42.0	50.0
LR1 (73,434)	IA	Mari Ugland	2005		2008	3	42.0	50.0
LR1 (73,965)	IA	Two Million Ways		2005	2008			
LR1 (74,450)	IA	Marika		2005	2008			
LR1 (74,450)	IA	Marinor		2005	2008			
LR1 (73,956)	IA	STI Heritage		2005	2008			
LR1 (65,125)	IA	Stena Polaris		2007	2010			
MR (47,842)	IA	Anichkov Bridge		2000	2003			
MR (47,125)	IA	SCF Neva		2003	2006			
MR (47,095)	IA	SCF Amur		2004	2007			
MR (47,187)	IA	SCF Yenisei		2004	2007			
MR (47,218)	IA	SCF Pechora		2004	2007			

Source: Clarksons (2021).

Notes:

Most of the ice class tankers which operated on the NSR during 2011-2019 were ordered in 2004 and, to a lesser extent, in 2005 and 2003, and were delivered in 2007-2008, based on the data presented in the table above. The lead time, which is the difference between the year of order and year of delivery of a tanker, is three years most of the times. Moreover, the years 2007 and 2008 are reported as years of delivery for tankers where the year of order is not reported. It is assumed that the lead time for those tankers is also three years. Thus, the year 2004 is assumed as the year of order for all tankers and used as a basis to calculate capital costs. Average newbuilding prices of tankers from Clarksons (2021) and ice class premiums from

Solakivi et al. (2018) are used to calculate capital costs since the data for newbuilding prices of ice class tankers presented in the table above are neither representative of all tanker sizes nor sufficient to compare with newbuilding prices of ordinary (non-ice class) tankers. The average newbuilding prices of 2004 are used to estimate capital costs for each tanker size, which are assumed to be repaid in 10 years from the date of delivery i.e. 2017 (Section '4.3.2.2 Cost and navigational factors', Table 4.7, Chapter 4).

The tables below show newbuilding tanker prices in 2004 used to estimate capital costs for ordinary and ice class tankers, respectively. The prices for the assumed coated Suezmax (LR3) and Aframax (LR2) tankers are increased by 10% based on historic price differences between coated and uncoated tankers, since prices for product tankers of these sizes are not reported for 2004 in Clarksons (2021).

Tanker newbuilding prices in 2004 (Million USD).

156-158,000 DWT Suezmax Tanker	113-115,000 DWT Aframax Tanker	73-75,000 DWT LR1 Tanker	47-51,000 DWT MR Tanker
71	59	48	40

Source: Clarksons (2021).

Oil product tanker newbuilding prices in 2004, used for capital cost estimation of ordinary tankers (Million USD).

156-158,000 DWT LR3 Tanker	113-115,000 DWT LR2 Tanker	73-75,000 DWT LR1 Tanker	47-51,000 DWT MR Tanker
74.6	62	48	40

Source: Calculations based on Clarksons (2021).

As regards ice class tankers, a premium of 30.4% is assumed for ice class IA notation (Solakivi et al. 2018).

Capital cost estimation – Chapter 5

The table below shows newbuilding prices of Aframax and LR2 tankers. It can be seen that LR2 tankers i.e. coated Aframax tankers cost 2-2.25 million US$ more than Aframax tankers between 2013 and 2019. The 2013-2019 average newbuilding price of LR2 tankers is used to calculate capital costs in order to take into account the volatility of prices during that period.

Newbuilding Prices in million US$ for oil product tankers in 2013-2019.

Year	113-115,000 DWT Aframax Tanker	113-115,000 DWT LR2 Tanker
2013	52.25	54.50
2014	54.00	56.00
2015	52.00	54.00
2016	44.50	46.50
2017	44.00	46.00
2018	48.00	50.00
2019	48.50	50.50
Average	49.31	51.07

Source: Clarksons (2021).

Assumptions for ordinary and ice class dual-fuel Oil/LNG-powered LR2 tankers with LNG tank capacity of 1,700 m^3:

Sovcomflot ordered a series of dual-fuel Oil/LNG-powered ice class IA/B Aframax tankers at 60 million US$ (M. US$) in 2017 (Sovcomflot 2018).

The price for LR2 tankers equivalent to Sovcomflot's Aframax tankers would have been 60 M. US$ + 2 M. US$ (tank coating premium) = 62 M. US$. An ordinary LR2 tanker cost 46 M. US$ in 2017. Thus, the premium for ice class IA/B and dual fuel set-up is 34.78% in 2017.

Assuming that 30.4% is the premium for ice class IA (Solakivi et al. 2018), there remains a 4.38% premium for the dual fuel set-up.

Applying the dual fuel set-up premium of 4.38% to the 2013-2019 LR2 tanker average price, 51.07 M. US$, gives a price of 53.31 M. US$ for an ordinary (non-ice class) dual-fuel Oil/LNG-powered LR2 tanker.

Applying the ice class IA/B and dual fuel set-up premium of 34.78% to the 2013-2019 LR2 tanker average price, 51.07 M. US$, gives a price of 68.83 M. US$ for an ice class dual-fuel Oil/LNG-powered LR2 tanker.

Assumptions for ordinary and ice class dual-fuel Oil/LNG-powered LR2 tankers with LNG tank capacity of 3,600 m^3:

Shell and Hafnia/Viken Shipping ordered dual-fuel Oil/LNG-powered LR2 tankers with LNG tank capacity of 3,400 m^3 and 3,600 m^3, respectively in 2020 (Riviera 2020; The Motorship 2020b). These orders cost 54.17 M. US$ and 60 M. US$, respectively (Clarksons 2021). The average of the two values is 57.1 M. US$. This value implies a dual fuel set-up premium of 12% on top of the average LR2 tanker price of 2013-2019. This price is used for an ordinary (non-ice class) dual-fuel Oil/LNG-powered LR2 tanker with LNG tank capacity of 3,600 m^3.

Applying the ice class IA premium of 30.4% to the 57.1 M. US$ price, gives a price of 74.44 M. US$ for an ice clas dual-fuel Oil/LNG-powered LR2 tanker with LNG tank capacity of 3,600 m^3.

Capital cost estimation – Chapter 6

Assumptions for ordinary and ice class dual-fuel Oil/LNG-powered LR2 tankers with LNG tank capacity of 1,700 m^3: Same as above.

LIBOR rates, Spread and Gearing – Chapters 4, 5, and 6

The annual capital costs for all modelling cases in Chapters 4, 5, and 6, are calculated by using a capital recovery factor (CRF) and are converted to daily values in USD. This calculation process is presented in Appendix O1. Bank financing is assumed, with the interest rate referring to the 12-month London Interbank Offered Rate (LIBOR). The LIBOR rate is obtained by the website of FED of St. Louis (FED of St. Louis 2021). The 12-month LIBOR rate in 2004 is assumed in the analysis in Chapter 4, whereas the average 12-month LIBOR rate of 2011-2019 is assumed in the analysis in Chapters 5 and 6 in order to take into account of the volatility of rates during that period.

The table below presents the annual LIBOR rates in 2004 and between 2011 and 2019.

Date	LIBOR rate in %
2004-01-01	2.12
2011-01-01	0.83
2012-01-01	1.01
2013-01-01	0.68
2014-01-01	0.56
2015-01-01	0.79
2016-01-01	1.38
2017-01-01	1.79
2018-01-01	2.76
2019-01-01	2.37

Source: FED of St. Louis (2021).

The LIBOR rates are increased by applying a spread depending on the period and reflecting prevailing market conditions. The 12-month LIBOR rate of 2004 is increased by 1% , that is, 100 basis points over LIBOR, reflecting the period before the financial crisis in 2008-2009 (Giannakoulis 2016; Petrofin 2017). The average 2011-2019 12-month LIBOR rate is increased by 3%, that is, 300 basis points over LIBOR (Alizadeh and Nomikos 2009), reflecting an increase during recent years between 200 to 550 basis points (Petrofin 2017). The term loan is assumed 10 years and the gearing 70% (gearing: amount of debt relative to equity i.e. ratio of debt to equity).

Appendix P. Calculations for transit fees – Chapters 4, 5, 6

Suez Canal Tolls for MR – LR3 Tankers (Chapter 4)

The tables below present data and assumptions used for the calculation of Suez Canal Tolls.

MR – LR3 Tanker technical characteristics.*

Ship Type	DWT (tonnes)[a]	SCNT[a]	GT[a]	Draught (metres)[a]	Beam (metres)[a]
LR3 Tanker	162,362	78,647	87,146	16.30	50.00
LR2 Tanker	117,055	68,838	66,919	15.42	44.06
LR1 Tanker	74,158	39,485	41,285	14.30	32.00
MR Tanker	47,842	25,199	27,829	12.51	32.20

Sources: [a]Clarksons (2021). *All values are taken from the table below. The assumptions for LR1 tankers are based on average values of tankers with a design speed of 15 knots (listed below).

Technical characteristics of tankers which operated on NSR in 2011-2014.

Tanker Size (dwt)	Tanker Name	SCNT	GT	Draught (metres)	Beam (metres)
LR3/Suezmax (162,362)	**Vladimir Tikhonov**	**78,647**	**87,146**	**16.30**	**50.00**
LR2 (117,055)	**Propontis**	**68,838**	**66,919**	**15.42**	**44.06**
LR1 (73,956)	STI Heritage	39,699	40,865	14.37	32.23
LR1 (73,293)	Affinity	38,841	42,611	14.20	32.24
LR1 (73,919)	STI Harmony	39,699	40,800	14.37	32.23
LR1 (73,965)	Two Million Ways	39,699	40,865	14.37	32.24
LR1 (74,158)	**Average**	**39,485**	**41,285**	**14.30**	**32.00**
MR (47,842)	**Anichkov Bridge**	**25,199**	**27,829**	**12.51**	**32.20**

Source: Clarksons (2021). The characteristics presented in this table refer to tankers with a design speed of 14.9-15.1 knots

Suez Canal Tolls calculations for MR – LR3 Tankers during 2011-2014.

	Canal Tolls								Other Canal-related costs					
SCNT per Tariff Rate*	First 5,000	Next 5,000	Next 10,000	Next 20,000	Next 30,000	Next 50,000	Total	SDR Exchange Rate**	Canal Tolls (US$)	Tugs (US$)	Mooring (US$)	Pilotage (US$)	Disbursements (US$)	Total (US$)
Tariff Rate (SDR/SCNT)	7.80	5.11	4.05	2.44	2.39	2.28								
LR3 Tanker														
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(20,000)	(30,000)	(8,647)								
Southbound	39,017	25,533	40,467	48,733	71,600	19,744	245,094	1.53	375,940	14,757	2,309	396	15,742	409,143
Northbound	39,017	25,533	40,467	48,733	71,600	19,744	245,094	1.53	375,940	14,757	2,588	635	15,842	409,761
LR2 Tanker														
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(20,000)	(28,838)									
Southbound	39,017	25,533	40,467	48,733	68,827		222,577	1.53	341,401	14,757	2,309	341	11,819	370,626
Northbound	39,017	25,533	40,467	48,733	68,827		222,577	1.53	341,401	14,757	2,588	544	11,919	371,208
LR1 Tanker														
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(19,485)										
Southbound	39,017	25,533	40,467	47,478			152,495	1.53	233,906		2,309	212	8,948	245,374
Northbound	39,017	25,533	40,467	47,478			152,495	1.53	233,906		2,588	390	9,048	245,931
MR Tanker														
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(5,199)										
Southbound	39,017	25,533	40,467	12,668			117,685	1.53	180,512		2,309	209	7,021	190,050
Northbound	39,017	25,533	40,467	12,668			117,685	1.53	180,512		2,588	263	7,121	190,484

Sources for Canal Tolls and Other Canal-related costs: Leth Agencies (2021a), Leth Agencies (2021b). *The values in the parentheses show the SCNT units for each tanker size, which are multiplied by the respective tariff rates. **The SDR rates did not vary significantly between July-November 2011 and July-November 2014 (IMF 2021a). The average SDR rate of the July-November 2011-2014 periods are used to reflect the NSR navigation season for comparison with SCR transits during the same periods (IMF 2021a).

Suez Canal Tolls calculations for MR – LR3 Tankers during 2015-2017.

	Canal Tolls								Other Canal-related costs					
SCNT per Tariff Rate*	First 5,000	Next 5,000	Next 10,000	Next 20,000	Next 30,000	Next 50,000	Total	SDR Exchange Rate**	Canal Tolls (US$)	Tugs (US$)	Mooring (US$)	Pilotage (US$)	Disbursements (US$)	Total (US$)
Tariff Rate (SDR/SCNT)	7.88	5.58	4.22	2.80	2.74	2.47								
LR3 Tanker														
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(20,000)	(30,000)	(8,647)								
Southbound	39,400	27,900	42,200	56,000	82,200	21,358	269,058	1.40	376,211	13,952	2,309	396	15,742	408,609
Northbound	39,400	27,900	42,200	56,000	82,200	21,358	269,058	1.40	376,211	13,952	2,588	635	15,842	409,227
LR2 Tanker														
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(20,000)	(28,838)									
Southbound	39,400	27,900	42,200	56,000	79,016		244,516	1.40	341,895	13,952	2,309	341	11,819	370,315
Northbound	39,400	27,900	42,200	56,000	79,016		244,516	1.40	341,895	13,952	2,588	544	11,919	370,897
LR1 Tanker														
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(19,485)										
Southbound	39,400	27,900	42,200	54,558			164,058	1.40	229,394		2,309	212	8,948	240,862
Northbound	39,400	27,900	42,200	54,558			164,058	1.40	229,394		2,588	390	9,048	241,419
MR Tanker														
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(5,199)										
Southbound	39,400	27,900	42,200	14,557			124,057	1.40	173,463		2,309	209	7,021	183,001
Northbound	39,400	27,900	42,200	14,557			124,057	1.40	173,463		2,588	263	7,121	183,435

Sources for Canal Tolls and Other Canal-related costs: Leth Agencies (2021a), Leth Agencies (2021b). *The values in the parentheses show the SCNT units for each tanker size, which are multiplied by the respective tariff rates. **The SDR rates did not vary significantly between July-November 2015 and July-November 2017 (IMF 2021a). The average SDR rate of the July-November 2015-2017 periods are used to reflect the NSR navigation season for comparison with SCR transits during the same periods (IMF 2021a).

Suez Canal Tolls calculations for MR – LR3 Tankers during 2018.

	Canal Tolls									Other Canal-related costs				
SCNT per Tariff Rate*	First 5,000	Next 5,000	Next 10,000	Next 20,000	Next 30,000	Next 50,000	Total	SDR Exchange Rate**	Canal Tolls (US$)	Tugs (US$)	Mooring (US$)	Pilotage (US$)	Disbursements (US$)	Total (US$)
Tariff Rate (SDR/SCNT)	7.88	5.58	4.22	2.80	2.74	2.47								
LR3 Tanker														
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(20,000)	(30,000)	(8,647)								
Southbound	39,400	27,900	42,200	56,000	82,200	21,358	269,058	1.40	375,401	13,952	2,309	396	15,742	407,799
Northbound	39,400	27,900	42,200	56,000	82,200	21,358	269,058	1.40	375,401	13,952	2,588	635	15,842	408,418
LR2 Tanker														
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(20,000)	(28,838)									
Southbound	39,400	27,900	42,200	56,000	79,016		244,516	1.40	341,159	13,952	2,309	341	11,819	369,579
Northbound	39,400	27,900	42,200	56,000	79,016		244,516	1.40	341,159	13,952	2,588	544	11,919	370,161
LR1 Tanker														
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(19,485)										
Southbound	39,400	27,900	42,200	54,558			164,058	1.40	228,901		2,309	212	8,948	240,369
Northbound	39,400	27,900	42,200	54,558			164,058	1.40	228,901		2,588	390	9,048	240,926
MR Tanker														
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(5,199)										
Southbound	39,400	27,900	42,200	14,557			124,057	1.40	173,090		2,309	209	7,021	182,628
Northbound	39,400	27,900	42,200	14,557			124,057	1.40	173,090		2,588	263	7,121	183,062

Sources for Canal Tolls and Other Canal-related costs: Leth Agencies (2021a), Leth Agencies (2021b). *The values in the parentheses show the SCNT units for each tanker size, which are multiplied by the respective tariff rates. **The average SDR rate between July-November 2018 is used to reflect the NSR navigation season for comparison with SCR transits during the same period (IMF 2021a).

Suez Canal Tolls calculations for MR – LR3 Tankers during 2019.

	Canal Tolls								Other Canal-related costs					
SCNT per Tariff Rate*	First 5,000	Next 5,000	Next 10,000	Next 20,000	Next 30,000	Next 50,000	Total	SDR Exchange Rate**	Canal Tolls (US$)	Tugs (US$)	Mooring (US$)	Pilotage (US$)	Disbursements (US$)	Total (US$)
Tariff Rate (SDR/SCNT)	7.88	5.58	4.22	2.80	2.74	2.47								
LR3 Tanker														
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(20,000)	(30,000)	(8,647)								
Southbound	39,400	27,900	42,200	56,000	82,200	21,358	269,058	1.37	369,664	13,700	2,309	396	15,233	401,301
Northbound	39,400	27,900	42,200	56,000	82,200	21,358	269,058	1.37	369,664	13,700	2,588	2,588	15,333	403,872
LR2 Tanker														
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(20,000)	(28,838)									
Southbound	39,400	27,900	42,200	56,000	79,016		244,516	1.37	335,945	13,700	2,309	341	12,181	364,476
Northbound	39,400	27,900	42,200	56,000	79,016		244,516	1.37	335,945	13,700	2,588	544	12,281	365,058
LR1 Tanker														
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(19,485)										
Southbound	39,400	27,900	42,200	54,558			164,058	1.37	225,402		2,309	212	9,051	236,974
Northbound	39,400	27,900	42,200	54,558			164,058	1.37	225,402		2,588	390	9,151	237,531
MR Tanker														
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(5,199)										
Southbound	39,400	27,900	42,200	14,557			124,057	1.37	170,445		2,309	209	7,158	180,119
Northbound	39,400	27,900	42,200	14,557			124,057	1.37	170,445		2,588	263	7,258	180,553

Sources for Canal Tolls and Other Canal-related costs: Leth Agencies (2021a), Leth Agencies (2021b). *The values in the parentheses show the SCNT units for each tanker size, which are multiplied by the respective tariff rates. **The average SDR rate between July-November 2019 is used to reflect the NSR navigation season for comparison with SCR transits during the same period (IMF 2021a).

Suez Canal Tolls calculations for MR – LR3 Tankers during 2020.

	Canal Tolls								Other Canal-related costs					
SCNT per Tariff Rate*	First 5,000	Next 5,000	Next 10,000	Next 20,000	Next 30,000	Next 50,000	Total	SDR Exchange Rate**	Canal Tolls (US$)	Tugs (US$)	Mooring (US$)	Pilotage (US$)	Disbursements (US$)	Total (US$)
Tariff Rate (SDR/SCNT)	7.88	5.58	4.22	2.80	2.74	2.47								
							LR3 Tanker							
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(20,000)	(30,000)	(8,647)								
Southbound	39,400	27,900	42,200	56,000	82,200	21,358	269,058	1.41	379,462	14,100	2,309	396	15,712	411,979
Northbound	39,400	27,900	42,200	56,000	82,200	21,358	269,058	1.41	379,462	14,100	2,588	635	15,812	412,597
							LR2 Tanker							
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(20,000)	(28,838)									
Southbound	39,400	27,900	42,200	56,000	79,016		244,516	1.41	344,850	14,100	2,309	396	13,922	375,576
Northbound	39,400	27,900	42,200	56,000	79,016		244,516	1.41	344,850	14,100	2,588	635	14,022	376,195
							LR1 Tanker							
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(19,485)										
Southbound	39,400	27,900	42,200	54,558			164,058	1.41	231,377		2,309	212	9,312	243,210
Northbound	39,400	27,900	42,200	54,558			164,058	1.41	231,377		2,588	390	9,412	243,767
							MR Tanker							
SCNT per Tariff Rate	(5,000)	(5,000)	(10,000)	(5,199)										
Southbound	39,400	27,900	42,200	14,557			124,057	1.41	174,962		2,309	209	7,184	184,663
Northbound	39,400	27,900	42,200	14,557			124,057	1.41	174,962		2,588	263	7,284	185,097

Sources for Canal Tolls and Other Canal-related costs: Leth Agencies (2021a), Leth Agencies (2021b). *The values in the parentheses show the SCNT units for each tanker size, which are multiplied by the respective tariff rates. **The average SDR rate between July-November 2020 is used to reflect the NSR navigation season for comparison with SCR transits during the same period (IMF 2021a).

The Suez Canal Tolls are calculated as follows: The total Suez Canal Net Tonnage (SCNT) of a ship is split in “First 5,000”, “Next 5,000” and so on, up to “Next 50,000” for large ships. Each SCNT tonnage unit is multiplied by the respective tariff rate until the total tonnage of the ship is fully priced. For a LR2 tanker with a SCNT value of 68,838, it means that the SCNT units are split in 5,000, 5,000, 10,000, 20,000, and 28,838 units. The summation equals the total SCNT of the ship. This total is then multiplied by the Special Drawing Rights (SDR) rate to estimate the Canal Tolls. The total cost for the Suez Canal Tolls is the summation of the Canal Tolls, and the costs for Tugs, Mooring, Pilotage, and Disbursements. The same logic applies to other tanker sizes and across all periods and OD pairs. The Tolls for southbound transits apply to the Vitino – Daesan pair and to the Mongstad – Mizushima pair, whereas the northbound transits apply to the Yeosu – Rotterdam pair. The Suez Canal Toll calculator provided on the website of Leth Agencies (Leth Agencies 2021b) allows one to calculate the Suez Canal Tolls by using the tariff rates for a specific ship type, and its SCNT, Gross Tonnage (GT), Draught, Beam, and choosing whether it is a laden or ballast voyage and a southbound or northbound transit. This online calculator calculates Tolls based on the latest tariff rates. Previous tariff rates should be used in order to estimate Canal Tolls for previous years. The ‘Other Canal-related costs’ might have also been different in previous years as well.

Suez Canal Tolls for LR2 Tankers during 2019 (Chapters 5 and 6)

The tables below present data and assumptions used for the calculation of Suez Canal Tolls.

LR2 Tanker technical characteristics

Ship Type	DWT (tonnes)[a]	SCNT[b]	GT[c]	Draught (metres)[a]	Beam (metres)[a]
LR2 Tanker	115,000	57,500	63,250	15.00	44.00

Sources: [a]MAN Diesel and Turbo (2013b), [b]the SCNT is roughly half the DWT of the ship (Leth Agencies 2021c), [c]the GT is estimated at 0.55·DWT based on LR2 tankers of the same DWT (Clarksons 2021).

Suez Canal Tolls calculations for LR2 Tankers during 2019.

	Canal Tolls								Other Canal-related costs				
SCNT per Tariff Rate*	First 5,000 (5,000)	Next 5,000 (5,000)	Next 10,000 (10,000)	Next 20,000 (20,000)	Next 30,000 (17,500)	Total	SDR Exchange Rate**	Canal Tolls (US$)	Tugs (US$)	Mooring (US$)	Pilotage (US$)	Disbursements (US$)	Total (US$)
Tariff Rate (SDR/SCNT)	7.88	5.58	4.22	2.80	2.74								
Southbound	39,400	27,900	42,200	56,000	47,950	213,450	1.37	292,427	13,700	2,309	341	12,181	320,957
Northbound	39,400	27,900	42,200	56,000	47,950	213,450	1.37	292,427	13,700	2,588	544	12,281	321,539

Sources for Canal Tolls and Other Canal-related costs: Leth Agencies (2021a), Leth Agencies (2021b). *The values in the parentheses show the SCNT units of the LR2 Tanker, which are multiplied by the respective tariff rates. **The average SDR rate between July-November 2019 is used to reflect the NSR navigation season for comparison with SCR transits during the same period (IMF 2021a).

The Suez Canal Tolls are calculated as follows: The total Suez Canal Net Tonnage (SCNT) of a ship is split in “First 5,000”, “Next 5,000” and so on, up to “Next 50,000” for large ships. Each SCNT tonnage unit is multiplied by the respective tariff rate until the total tonnage of the ship is fully priced. For a LR2 tanker with a SCNT value of 57,500, it means that the SCNT units are split in 5,000, 5,000, 10,000, 20,000, and 17,500 units. The summation equals the total SCNT of the ship. This total is then multiplied by the Special Drawing Rights (SDR) rate to estimate the Canal Tolls. The total cost for the Suez Canal Tolls is the summation of the Canal Tolls, and the costs for Tugs, Mooring, Pilotage, and Disbursements. The Tolls for southbound transits apply to the Ust-Luga – Ulsan pair (Chapter 6), whereas the northbound transits apply to the Chiba – Coryton pair (Chapter 6), Ulsan – Rotterdam pair (Chapters 5 and 6), and Ulsan – Bilbao pair (Chapter 5). The Suez Canal Toll calculator provided on the website of Leth Agencies (Leth Agencies 2021b) allows one to calculate the Suez Canal Tolls by using the tariff rates for a specific ship type, and its SCNT, Gross Tonnage (GT), Draught, Beam, and choosing whether it is a laden or ballast voyage and a southbound or northbound transit. This online calculator calculates the Tolls based on the latest tariff rates. Previous tariff rates should be used in order to estimate Canal Tolls for previous years. The ‘Other Canal-related costs’ might have also been different in previous years as well.

Icebreaking fees for LR2 Tankers (Chapters 4, 5, and 6)

Icebreaking fees depend on the ice class of a ship, Gross Tonnage (GT), number of escorting (navigation) zones, and period of navigation (summer/autumn: July-November, winter/spring: December-June), and are determined by the US Dollar – Russian Rouble (USD/RUB) currency exchange rates (NSRA 2014; Bank of Russia 2021). The icebreaking fees are calculated as follows: The tariff rate is divided by the USD/RUB exchange rate to convert it in USD. Then, the result is multiplied by the GT of the ship to obtain the icebreaking fees. For example, the icebreaking fees for a LR2 tanker of 63,250 GT at a tariff rate of 446.8 Roubles and a USD/RUB exchange rate of 64.41 are calculated as follows:

$$(446.8/64.41) \cdot 63{,}250 = 438{,}793 \text{ USD}$$

The rates presented in Table 4.13, Section '4.3.2.4 Transit fees and icebreaking assitance' refer to 6/7 zones of navigation during summer/autumn (July-November) for an ice class Arc4 ship (NSRA 2014), which is equivalent to ice class IA (Trafi 2017b). The same tariff rate is used for LR1, LR2, and LR3 tankers, since their GT ranges between 40,001 and 100,000, whereas a different rate is used for MR tankers, since their GT ranges between 20,001 and 40,000 (NSRA 2014). It should be noted that the discounted fee of 5 US$ per tonne is multiplied by the cargo weight, and not by the GT of a ship (Falck 2012; Tanker Company 2018). The tariff rate of 530 Roubles per GT in 2011-2013 refers to icebreaking tariff rates before 2014 (ARCTIS 2021c; Table 4.13).

The same calculation process is followed in the analysis in Chapter 5, with rates and assumptions presented in Section '5.4.4 Transit fees and icebreaking assistance' and Table 5.5, as well as in the analysis in Chapter 6, with rates and assumptions presented in Section '6.3.4 Transit fees and icebreaking assistance' and Table 6.5.

Appendix Q. Cost analysis – Chapter 4

Total cost analysis for Vitino – Daesan pair in US$ per tonne during 2011-2013.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	STS Transfer Cost	RFR	Repairs	RFR incl. repairs
					SCR					
MR	11.6	46	10.9	5.3	11.8	11.7		39.8		
LR1	11.2	48	7.7	4.0	7.7	8.7		28.1		
LR2	11.4	47	6.0	4.3	5.2	7.6		23.1		
LR3	11.1	49	5.3	3.4	4.3	6.8	1.6	21.4		
					NSR					
MR	11.5	24	5.6	17.3	7.4	7.7		37.9	4.6	42.5
LR1	11.2	24	4.0	17.1	4.7	5.6		31.4	2.8	34.2
LR2	11.3	24	3.2	17.0	3.2	5.0		28.5	2.1	30.6
LR3	11.0	25	2.9	17.0	2.6	4.5	1.6	28.5	1.6	30.1

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for Vitino – Daesan pair in US$ per tonne during 2014, assuming Official Icebreaking Fees.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	STS Transfer Cost	RFR	Repairs	RFR incl. repairs
					SCR					
MR	11.6	46	10.9	5.3	11.8	11.7		39.8		
LR1	11.2	48	7.7	4.0	7.7	8.7		28.1		
LR2	11.4	47	6.0	4.3	5.2	7.6		23.1		
LR3	11.1	49	5.3	3.4	4.3	6.8	1.6	21.4		
					NSR					
MR	11.5	24	5.6	11.1	7.4	7.7		31.8	4.6	36.4
LR1	11.2	24	4.0	8.2	4.7	5.6		22.4	2.8	25.3
LR2	11.3	24	3.2	8.6	3.2	5.0		20.0	2.1	22.1
LR3	11.0	25	2.9	8.6	2.6	4.5	1.6	20.1	1.6	21.7

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for Vitino – Daesan pair in US$ per tonne during 2011-2014.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	STS Transfer Cost	RFR	Repairs	RFR incl. repairs
					SCR					
MR	11.6	46	10.9	5.3	11.8	11.7		39.8		
LR1	11.2	48	7.7	4.0	7.7	8.7		28.1		
LR2	11.4	47	6.0	4.3	5.2	7.6		23.1		
LR3	11.1	49	5.3	3.4	4.3	6.8	1.6	21.4		
					NSR					
MR	11.5	24	5.6	5.4	7.4	7.7		26.1	4.6	30.7
LR1	11.2	24	4.0	5.2	4.7	5.6		19.5	2.8	22.3
LR2	11.2	24	3.2	5.2	3.2	5.0		16.6	2.1	18.7
LR3	11.0	25	2.9	5.1	2.6	4.5	1.6	16.6	1.6	18.2

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Daesan to a repair yard at Qushan, China, in US$ per tonne during 2011-2014.*

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
MR	13.2	2	0.4	0.3	0.5	1.3	3.3	4.6
LR1	13.0	2	0.3	0.2	0.4	0.9	2.0	2.8
LR2	12.8	2	0.2	0.2	0.3	0.7	1.4	2.1
LR3	12.4	2	0.2	0.1	0.3	0.6	1.0	1.6

*The cost analysis refers to the ‘2011-2013’, ‘during 2014 assuming Official Icebreaking Fees’, and ‘2011-2014’ scenarios.

Total cost analysis for Vitino – Daesan pair in US$ per tonne during 2015-2017.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	STS Transfer Cost	RFR	Repairs	RFR incl. repairs
					SCR					
MR	15.1	36	8.3	5.1	8.2	9.0		30.6		
LR1	14.5	37	5.8	4.0	5.3	6.7		21.8		
LR2	14.8	36	4.6	4.2	3.5	5.9		18.2		
LR3	14.4	38	4.0	3.4	3.0	5.2	1.6	17.2		
					NSR					
MR	13.5	20	3.7	7.2	6.4	6.6		23.9	4.3	28.1
LR1	13.3	20	2.7	5.2	4.0	4.8		16.6	2.6	19.3
LR2	13.3	20	2.1	5.5	2.7	4.3		14.6	1.9	16.5
LR3	13.1	21	1.9	5.4	2.2	3.8	1.6	14.9	1.5	16.4

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Daesan to a repair yard at Qushan, China, in US$ per tonne during 2015-2017.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
MR	16.0	1	0.3	0.3	0.4	1.0	3.3	4.3
LR1	16.0	1	0.2	0.2	0.3	0.7	2.0	2.6
LR2	16.0	1	0.2	0.1	0.3	0.5	1.4	1.9
LR3	16.0	1	0.2	0.1	0.2	0.5	1.0	1.5

Total cost analysis for Vitino – Daesan pair in US$ per tonne during 2018.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	STS Transfer Cost	RFR	Repairs	RFR incl. repairs
					SCR				
MR	9.8	54	5.5	5.1	11.3		21.9		
LR1	9.4	58	3.7	4.0	7.6		15.3		
LR2	9.0	60	2.6	4.2	5.2		12.0		
LR3	8.7	62	2.3	3.4	4.6	1.6	11.8		
					NSR				
MR	10.2	27	2.9	6.8	7.6		17.3	3.9	21.2
LR1	9.8	28	2.0	5.0	4.9		11.9	2.4	14.2
LR2	9.3	29	1.5	5.2	3.4		10.0	1.7	11.7
LR3	9.2	30	1.3	5.1	2.9	1.6	10.9	1.2	12.1

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Daesan to a repair yard at Qushan, China, in US$ per tonne during 2018.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	RFR	Repairs	Total Repairs
MR	11.0	2	0.2	0.4	0.6	3.3	3.9
LR1	10.6	2	0.1	0.3	0.4	2.0	2.4
LR2	9.7	2	0.1	0.2	0.3	1.4	1.7
LR3	9.4	2	0.1	0.2	0.2	1.0	1.2

Total cost analysis for Vitino – Daesan pair in US$ per tonne during 2019.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	STS Transfer Cost	RFR	Repairs	RFR incl. repairs
					SCR				
MR	10.0	54	5.3	5.0	10.9		21.2		
LR1	9.5	57	3.6	3.9	7.4		14.9		
LR2	9.0	60	2.5	4.2	5.0		11.7		
LR3	8.8	61	2.2	3.3	4.4	1.6	11.5		
					NSR				
MR	10.3	26	2.8	6.9	7.4		17.1	3.9	21.0
LR1	9.9	27	1.9	5.1	4.8		11.8	2.4	14.2
LR2	9.4	29	1.4	5.3	3.3		10.0	1.6	11.6
LR3	9.2	29	1.3	5.2	2.8	1.6	10.9	1.2	12.1

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Daesan to a repair yard at Qushan, China, in US$ per tonne during 2019.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	RFR	Repairs	Total Repairs
MR	11.1	2	0.2	0.4	0.6	3.3	3.9
LR1	10.7	2	0.1	0.3	0.4	2.0	2.4
LR2	9.8	2	0.1	0.2	0.3	1.4	1.6
LR3	9.5	2	0.1	0.2	0.2	1.0	1.2

Total cost analysis for Vitino – Daesan pair in US$ per tonne during 2020.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	STS Transfer Cost	RFR	Repairs	RFR incl. repairs
					SCR				
MR	10.5	51	5.1	5.1	10.6		20.8		
LR1	10	54	3.5	4.0	7.2		14.7		
LR2	9.5	57	2.4	4.3	4.9		11.6		
LR3	9.2	58	2.1	3.4	4.3	1.6	11.4		
					NSR				
MR	10.6	26	2.6	6.0	7.4		16.0	3.9	19.9
LR1	10.2	26	1.8	4.4	4.8		11.0	2.3	13.3
LR2	9.7	28	1.3	4.6	3.3		9.2	1.6	10.8
LR3	9.5	28	1.2	4.5	2.7	1.6	10.0	1.2	11.3

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Daesan to a repair yard at Qushan, China, in US$ per tonne during 2020.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	RFR	Repairs	Total Repairs
MR	11.5	2	0.2	0.4	0.5	3.3	3.9
LR1	11.2	2	0.1	0.2	0.4	2.0	2.3
LR2	10.2	2	0.1	0.2	0.3	1.4	1.6
LR3	9.9	2	0.1	0.2	0.2	1.0	1.2

Total cost analysis for Mongstad – Mizushima pair in US$ per tonne during 2011-2013.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	RFR	Repairs	RFR incl. repairs
					SCR				
MR	11.6	42	9.8	5.3	10.8	10.5	36.4		
LR1	11.2	43	6.9	4.0	7.0	7.8	25.7		
LR2	11.4	42	5.4	4.3	4.7	6.8	21.2		
LR3	11.1	44	4.8	3.4	3.9	6.1	18.2		
					NSR				
MR	11.5	24	5.7	17.3	7.5	7.9	38.5	5.2	43.6
LR1	11.2	25	4.1	17.1	4.8	5.8	31.7	3.3	35.0
LR2	11.3	25	3.3	17.0	3.3	5.2	28.8	2.4	31.2
LR3	11.0	25	3.0	17.0	2.7	4.6	27.2	1.8	29.0

*Transit fees refer to Suez Canal Tolls or icebreaking fees and relevant costs.

Total cost analysis for Mongstad – Mizushima pair in US$ per tonne during 2014, assuming Official Icebreaking Fees.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	RFR	Repairs	RFR incl. repairs
					SCR				
MR	11.6	42	9.8	5.3	10.8	10.5	36.4		
LR1	11.2	43	6.9	4.0	7.0	7.8	25.7		
LR2	11.4	42	5.4	4.3	4.7	6.8	21.2		
LR3	11.1	44	4.8	3.4	3.9	6.1	18.2		
					NSR				
MR	11.5	24	5.7	11.1	7.5	7.9	32.4	5.2	37.5
LR1	11.2	25	4.1	8.2	4.8	5.8	22.8	3.3	26.1
LR2	11.3	25	3.3	8.6	3.3	5.2	20.3	2.4	22.7
LR3	11.0	25	3.0	8.6	2.7	4.6	18.7	1.8	20.5

*Transit fees refer to Suez Canal Tolls or icebreaking fees and relevant costs.

Total cost analysis for Mongstad – Mizushima pair in US$ per tonne during 2011-2014.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	RFR	Repairs	RFR incl. repairs
					SCR				
MR	11.6	42	9.8	5.3	10.8	10.5	36.4		
LR1	11.2	43	6.9	4.0	7.0	7.8	25.7		
LR2	11.4	42	5.4	4.3	4.7	6.8	21.2		
LR3	11.1	44	4.8	3.4	3.9	6.1	18.2		
					NSR				
MR	11.5	24	5.7	5.4	7.5	7.9	26.6	5.2	31.8
LR1	11.2	25	4.1	5.2	4.8	5.8	19.8	3.3	23.1
LR2	11.3	25	3.3	5.2	3.3	5.2	16.9	2.4	19.3
LR3	11.0	25	3.0	5.1	2.7	4.6	15.3	1.8	17.1

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Mizushima to a repair yard at Qushan, China (MR and LR1 tankers), and Ulsan, South Korea (LR2 and LR3 tankers), in US$ per tonne during 2011-2014.*

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
MR	13.2	2	0.6	0.5	0.7	1.8	3.3	5.2
LR1	13.0	2	0.4	0.3	0.5	1.3	2.0	3.3
LR2	12.8	1	0.1	0.1	0.2	0.4	1.9	2.4
LR3	12.4	1	0.1	0.1	0.2	0.4	1.4	1.8

*The cost analysis refers to the ‘2011-2013’, ‘during 2014 assuming Official Icebreaking Fees’, and ‘2011-2014’ scenarios.

Total cost analysis for Mongstad – Mizushima pair in US$ per tonne during 2015-2017.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	RFR	Repairs	RFR incl. repairs
	SCR								
MR	15.0	32	7.4	5.1	7.5	8.1	28.1		
LR1	14.5	33	5.2	4.0	4.8	6.0	20.0		
LR2	14.8	33	4.1	4.2	3.2	5.3	16.8		
LR3	14.4	34	3.6	3.4	2.7	4.7	14.4		
	NSR								
MR	13.5	21	3.9	7.2	6.5	6.7	24.3	4.7	29.0
LR1	13.3	21	2.7	5.2	4.1	4.9	16.9	2.9	19.9
LR2	13.3	21	2.2	5.5	2.8	4.4	14.8	2.2	17.0
LR3	13.1	21	2.0	5.4	2.3	3.9	13.5	1.7	15.2

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Mizushima to a repair yard at Qushan, China (MR, LR1, LR2 tankers), and Ulsan, South Korea (LR3 tankers), in US$ per tonne during 2015-2017.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
MR	16.0	2	0.4	0.4	0.6	1.4	3.3	4.7
LR1	16.0	2	0.3	0.3	0.4	1.0	2.0	2.9
LR2	16.0	2	0.2	0.2	0.4	0.8	1.4	2.2
LR3	16.0	1	0.1	0.1	0.1	0.3	1.4	1.7

Total cost analysis for Mongstad – Mizushima pair in US$ per tonne during 2018.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	RFR	Repairs	RFR incl. repairs
	SCR							
MR	9.9	49	4.9	5.1	10.2	20.2		
LR1	9.4	52	3.3	4.0	6.9	14.2		
LR2	8.9	54	2.3	4.2	4.7	11.2		
LR3	8.7	56	2.0	3.4	4.1	9.5		
	NSR							
MR	10.2	27	2.9	6.8	7.8	17.5	4.2	21.7
LR1	9.8	28	2.1	5.0	5.0	12.0	2.5	14.6
LR2	9.3	30	1.5	5.2	3.5	10.2	1.8	11.9
LR3	9.1	30	1.4	5.1	2.9	9.4	1.3	10.8

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Mizushima to a repair yard at Qushan, China, in US$ per tonne during 2018.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	RFR	Repairs	Total Repairs
MR	11.0	3	0.3	0.6	0.9	3.3	4.2
LR1	10.6	3	0.2	0.4	0.6	2.0	2.5
LR2	9.7	3	0.1	0.3	0.4	1.4	1.8
LR3	9.4	3	0.1	0.2	0.4	1.0	1.3

Total cost analysis for Mongstad – Mizushima pair in US$ per tonne during 2019.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	RFR	Repairs	RFR incl. repairs
				SCR				
MR	10.0	48	4.8	5.0	9.8	19.6		
LR1	9.5	51	3.2	3.9	6.7	13.8		
LR2	9.0	54	2.2	4.2	4.5	10.9		
LR3	8.8	55	1.9	3.3	4.0	9.3		
				NSR				
MR	10.2	27	2.8	6.9	7.6	17.3	4.2	21.5
LR1	9.9	28	2.0	5.1	4.9	12.0	2.5	14.5
LR2	9.4	30	1.5	5.3	3.4	10.1	1.8	11.9
LR3	9.2	30	1.3	5.2	2.8	9.4	1.3	10.7

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Mizushima to a repair yard at Qushan, China, in US$ per tonne during 2019.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	RFR	Repairs	Total Repairs
MR	11.1	3	0.3	0.6	0.8	3.3	4.2
LR1	10.7	3	0.2	0.4	0.6	2.0	2.5
LR2	9.8	3	0.1	0.3	0.4	1.4	1.8
LR3	9.5	3	0.1	0.2	0.3	1.0	1.3

Total cost analysis for Mongstad – Mizushima pair in US$ per tonne during 2020.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	RFR	Repairs	RFR incl. repairs
				SCR				
MR	10.5	46	4.6	5.1	9.5	19.3		
LR1	10.0	48	3.1	4.0	6.5	13.6		
LR2	9.5	51	2.1	4.3	4.4	10.8		
LR3	9.2	52	1.9	3.4	3.9	9.2		
				NSR				
MR	10.6	26	2.7	6.0	7.5	16.2	4.1	20.4
LR1	10.2	27	1.9	4.4	4.9	11.2	2.5	13.7
LR2	9.7	29	1.4	4.6	3.3	9.3	1.8	11.0
LR3	9.5	29	1.2	4.5	2.8	8.6	1.3	9.9

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Mizushima to a repair yard at Qushan, China, in US$ per tonne during 2020.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	RFR	Repairs	Total Repairs
MR	11.5	3	0.3	0.5	0.8	3.3	4.1
LR1	11.2	3	0.2	0.4	0.5	2.0	2.5
LR2	10.2	3	0.1	0.3	0.4	1.4	1.8
LR3	9.9	3	0.1	0.2	0.3	1.0	1.3

Total cost analysis for Yeosu – Rotterdam pair in US$ per tonne during 2011-2013.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	RFR	Repairs	RFR incl. repairs
					SCR				
MR	11.6	39	9.2	5.3	10.2	9.8	34.5		
LR1	11.2	41	6.4	4.1	6.6	7.3	24.4		
LR2	11.4	40	5.1	4.3	4.5	6.4	20.2		
LR3	11.1	41	4.5	3.4	3.7	5.7	17.3		
					NSR				
MR	11.5	26	6.3	17.3	8.0	8.6	40.2	6.7	46.9
LR1	11.3	27	4.5	17.1	5.1	6.3	32.9	4.1	37.1
LR2	11.3	27	3.6	17.0	3.5	5.6	29.8	3.0	32.8
LR3	11.1	27	3.3	17.0	2.8	5.0	28.1	2.3	30.4

*Transit fees refer to Suez Canal Tolls or icebreaking fees and relevant costs.

Total cost analysis for Yeosu – Rotterdam pair in US$ per tonne during 2014, assuming Official Icebreaking Fees.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	RFR	Repairs	RFR incl. repairs
					SCR				
MR	11.6	39	9.2	5.3	10.2	9.8	34.5		
LR1	11.2	41	6.4	4.1	6.6	7.3	24.4		
LR2	11.4	40	5.1	4.3	4.5	6.4	20.2		
LR3	11.1	41	4.5	3.4	3.7	5.7	17.3		
					NSR				
MR	11.5	26	6.3	11.1	8.0	8.6	34.1	6.7	40.8
LR1	11.3	27	4.5	8.2	5.1	6.3	24.0	4.1	28.2
LR2	11.3	27	3.6	8.6	3.5	5.6	21.3	3.0	24.4
LR3	11.1	27	3.3	8.6	2.8	5.0	19.6	2.3	21.2

*Transit fees refer to Suez Canal Tolls or icebreaking fees and relevant costs.

Total cost analysis for Yeosu – Rotterdam pair in US$ per tonne during 2011-2014.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	RFR	Repairs	RFR incl. repairs
					SCR				
MR	11.6	39	9.2	5.3	10.2	9.8	34.5		
LR1	11.2	41	6.4	4.1	6.6	7.3	24.4		
LR2	11.4	40	5.1	4.3	4.5	6.4	20.2		
LR3	11.1	41	4.5	3.4	3.7	5.7	17.3		
					NSR				
MR	11.5	26	6.3	5.4	8.0	8.6	28.3	6.7	35.0
LR1	11.3	27	4.5	5.2	5.1	6.3	21.1	4.1	25.2
LR2	11.3	27	3.6	5.2	3.5	5.6	17.9	3.0	20.9
LR3	11.1	27	3.3	5.1	2.8	5.0	16.2	2.3	18.5

*Transit fees refer to Suez Canal Tolls or icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Rotterdam to a repair yard at Odense, Denmark, in US$ per tonne during 2011-2014.*

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
MR	13.2	2	0.6	0.5	0.7	1.7	5.0	6.7
LR1	13.0	2	0.4	0.3	0.5	1.2	3.0	4.1
LR2	12.8	2	0.3	0.2	0.4	1.0	2.1	3.0
LR3	12.4	2	0.3	0.2	0.4	0.8	1.5	2.3

*The cost analysis refers to the '2011-2013', 'during 2014 assuming Official Icebreaking Fees', and '2011-2014' scenarios.

Total cost analysis for Yeosu – Rotterdam pair in US$ per tonne during 2015-2017.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operatin g cost	Capital cost	RFR	Repairs	RFR incl. repairs
					SCR				
MR	15.1	30	6.9	5.1	7.0	7.5	26.5		
LR1	14.6	31	4.8	4.0	4.5	5.6	18.9		
LR2	14.9	30	3.8	4.3	3.0	4.9	16.0		
LR3	14.5	31	3.4	3.4	2.5	4.4	13.7		
					NSR				
MR	13.6	22	4.4	7.2	6.9	7.3	25.8	6.5	32.3
LR1	13.3	23	3.1	5.2	4.3	5.3	18.0	4.0	22.0
LR2	13.3	23	2.5	5.5	2.9	4.8	15.7	2.9	18.6
LR3	13.1	23	2.2	5.4	2.4	4.2	14.3	2.2	16.5

*Transit fees refer to Suez Canal Tolls or icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Rotterdam to a repair yard at Odense, Denmark, in US$ per tonne during 2015-2017.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
MR	14.8	2	0.5	0.4	0.6	1.5	5.0	6.5
LR1	14.3	2	0.3	0.3	0.4	1.0	3.0	4.0
LR2	14.2	2	0.3	0.2	0.4	0.9	2.1	2.9
LR3	13.9	2	0.2	0.2	0.3	0.7	1.5	2.2

Total cost analysis for Yeosu – Rotterdam pair in US$ per tonne during 2018.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	RFR	Repairs	RFR incl. repairs
					SCR			
MR	10.0	45	4.6	5.1	9.5	19.2		
LR1	9.4	48	3.1	4.0	6.4	13.5		
LR2	9.0	50	2.1	4.2	4.4	10.8		
LR3	8.8	52	1.9	3.4	3.9	9.1		
					NSR			
MR	10.1	30	3.2	6.8	8.4	18.4	5.9	24.3
LR1	9.7	31	2.3	5.0	5.4	12.7	3.6	16.2
LR2	9.2	33	1.6	5.2	3.8	10.6	2.5	13.1
LR3	9.0	34	1.5	5.1	3.2	9.8	1.9	11.7

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Rotterdam to a repair yard at Odense, Denmark, in US$ per tonne during 2018.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	RFR	Repairs	Total Repairs
MR	9.6	3	0.3	0.6	0.9	5.0	5.9
LR1	9.2	3	0.2	0.4	0.6	3.0	3.6
LR2	8.4	3	0.1	0.3	0.4	2.1	2.5
LR3	8.3	3	0.1	0.2	0.4	1.5	1.9

Total cost analysis for Yeosu – Rotterdam pair in US$ per tonne during 2019.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	RFR	Repairs	RFR incl. repairs
	SCR							
MR	10.1	45	4.4	5.0	9.2	18.6		
LR1	9.5	48	3.0	3.9	6.2	13.2		
LR2	9.1	50	2.1	4.2	4.2	10.5		
LR3	8.8	51	1.8	3.3	3.7	8.9		
	NSR							
MR	10.1	30	3.1	6.9	8.2	18.2	5.9	24.1
LR1	9.8	31	2.2	5.1	5.3	12.6	3.5	16.1
LR2	9.3	33	1.6	5.3	3.6	10.5	2.5	13.0
LR3	9.1	33	1.4	5.2	3.1	9.7	1.8	11.6

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Rotterdam to a repair yard at Odense, Denmark, in US$ per tonne during 2019.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	RFR	Repairs	Total Repairs
MR	9.8	3	0.3	0.6	0.8	5.0	5.9
LR1	9.4	3	0.2	0.4	0.6	3.0	3.5
LR2	8.6	3	0.1	0.3	0.4	2.1	2.5
LR3	8.4	3	0.1	0.2	0.4	1.5	1.8

Total cost analysis for Yeosu – Rotterdam pair in US$ per tonne during 2020.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	RFR	Repairs	RFR incl. repairs
				SCR				
MR	10.5	43	4.3	5.1	8.9	18.4		
LR1	10.0	45	2.9	4.0	6.1	13.0		
LR2	9.5	48	2.0	4.3	4.1	10.4		
LR3	9.2	49	1.8	3.4	3.6	8.8		
				NSR				
MR	10.6	29	3.0	6.0	8.0	17.0	5.7	22.7
LR1	10.2	30	2.1	4.4	5.2	11.7	3.5	15.1
LR2	9.7	31	1.5	4.6	3.6	9.6	2.4	12.1
LR3	9.5	32	1.4	4.5	3.0	8.9	1.8	10.7

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Rotterdam to a repair yard at Odense, Denmark, in US$ per tonne during 2020.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	RFR	Repairs	Total Repairs
MR	11.4	2	0.2	0.5	0.7	5.0	5.7
LR1	10.9	2	0.2	0.3	0.5	3.0	3.5
LR2	9.9	3	0.1	0.2	0.4	2.1	2.4
LR3	9.8	3	0.1	0.2	0.3	1.5	1.8

Total cost analysis for Vitino – Daesan pair in US$ per tonne, including recurring capital costs during 2018.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	STS Transfer Cost	RFR	Repairs	RFR incl. repairs
					SCR					
MR	13	42	9.4	5.1	8.7	10.4		33.7		
LR1	12.5	43	6.6	4.0	5.8	7.7		24.1		
LR2	12.8	42	5.2	4.2	3.7	6.8		19.9		
LR3	12.4	43	4.6	3.4	3.2	6.1	1.6	18.9		
					NSR					
MR	12.4	22	4.5	6.8	6.6	7.1		25.0	4.4	29.5
LR1	12.2	22	3.2	5.0	4.2	5.2		17.5	2.7	20.3
LR2	12.2	22	2.6	5.2	2.8	4.6		15.2	2.0	17.2
LR3	12.0	22	2.3	5.1	2.3	4.1	1.6	15.4	1.5	17.0

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Daesan to a repair yard at Qushan, China, in US$ per tonne, including recurring capital costs during 2018.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
MR	15.0	1	0.4	0.3	0.4	1.1	3.3	4.4
LR1	14.7	1	0.2	0.2	0.3	0.7	2.0	2.7
LR2	14.5	1	0.2	0.1	0.3	0.6	1.4	2.0
LR3	14.1	1	0.2	0.1	0.3	0.5	1.0	1.5

Total cost analysis for Vitino – Daesan pair in US$ per tonne, including recurring capital costs during 2019.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	STS Transfer Cost	RFR	Repairs	RFR incl. repairs
						SCR				
MR	13.2	41	9.2	5.0	8.4	10.3		32.9		
LR1	12.7	42	6.5	3.9	5.6	7.6		23.6		
LR2	12.9	42	5.1	4.2	3.5	6.7		19.5		
LR3	12.6	43	4.5	3.3	3.1	6.0	1.6	18.5		
						NSR				
MR	12.6	21	4.4	6.9	6.4	7.0		24.8	4.4	29.2
LR1	12.4	22	3.2	5.1	4.1	5.1		17.4	2.7	20.1
LR2	12.4	22	2.5	5.3	2.7	4.6		15.1	2.0	17.1
LR3	12.2	22	2.3	5.2	2.2	4.0	1.6	15.4	1.5	16.9

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Daesan to a repair yard at Qushan, China, in US$ per tonne, including recurring capital costs during 2019.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
MR	15.2	1	0.4	0.3	0.4	1.1	3.3	4.4
LR1	15.0	1	0.3	0.2	0.3	0.8	2.0	2.7
LR2	14.7	1	0.2	0.1	0.3	0.6	1.4	2.0
LR3	14.3	1	0.2	0.1	0.3	0.5	1.0	1.5

Total cost analysis for Vitino – Daesan pair in US$ per tonne, including recurring capital costs during 2020.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	STS Transfer Cost	RFR	Repairs	RFR incl. repairs
					SCR					
MR	13.8	39	8.8	5.1	8.1	9.8		31.9		
LR1	13.3	40	6.3	4.0	5.4	7.2		22.9		
LR2	13.6	40	4.9	4.3	3.5	6.4		19.0		
LR3	13.2	41	4.3	3.4	3.0	5.7	1.6	18.0		
					NSR					
MR	12.9	21	4.2	6.0	6.4	6.9		23.5	4.4	27.8
LR1	12.7	21	3.0	4.4	4.1	5.0		16.5	2.7	19.1
LR2	12.7	21	2.4	4.6	2.7	4.5		14.1	2.0	16.1
LR3	12.5	22	2.2	4.5	2.2	4.0	1.6	14.4	1.5	16.0

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Daesan to a repair yard at Qushan, China, in US$ per tonne, including recurring capital costs during 2020.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
MR	15.8	1	0.3	0.3	0.4	1.0	3.3	4.4
LR1	15.5	1	0.2	0.2	0.3	0.7	2.0	2.7
LR2	15.3	1	0.2	0.1	0.3	0.6	1.4	2.0
LR3	14.9	1	0.2	0.1	0.2	0.5	1.0	1.5

Total cost analysis for Mongstad – Mizushima pair in US$ per tonne, including recurring capital costs during 2018.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	RFR	Repairs	RFR incl. repairs
					SCR				
MR	13.0	37	8.5	5.1	7.8	9.4	30.8		
LR1	12.5	39	6.0	4.0	5.2	6.9	22.0		
LR2	12.8	38	4.7	4.2	3.3	6.1	18.3		
LR3	12.4	39	4.1	3.4	2.9	5.4	15.9		
					NSR				
MR	12.5	22	4.7	6.8	6.7	7.3	25.5	4.9	30.4
LR1	12.2	23	3.3	5.0	4.3	5.3	17.9	3.1	20.9
LR2	12.2	23	2.7	5.2	2.8	4.8	15.5	2.3	17.7
LR3	12.0	23	2.4	5.1	2.4	4.2	14.1	1.7	15.9

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Mizushima to a repair yard at Qushan, China (MR, LR1, LR2 tankers), and Ulsan, South Korea (LR3 tankers), in US$ per tonne, including recurring capital costs during 2018.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
MR	15.0	2	0.5	0.4	0.6	1.6	3.3	4.9
LR1	14.7	2	0.4	0.3	0.5	1.1	2.0	3.1
LR2	14.5	2	0.3	0.2	0.4	0.9	1.4	2.3
LR3	14.1	1	0.1	0.1	0.2	0.3	1.4	1.7

Total cost analysis for Mongstad – Mizushima pair in US$ per tonne, including recurring capital costs during 2019.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	RFR	Repairs	RFR incl. repairs
	SCR								
MR	13.2	37	8.2	5.0	7.5	9.2	30.0		
LR1	12.7	37	5.8	3.9	5.0	6.8	21.5		
LR2	12.9	37	4.5	4.2	3.2	6.0	17.9		
LR3	12.6	38	4.0	3.3	2.8	5.4	15.5		
	NSR								
MR	12.6	22	4.6	6.9	6.5	7.2	25.2	4.9	30.1
LR1	12.4	22	3.3	5.1	4.2	5.2	17.7	3.1	20.8
LR2	12.4	22	2.6	5.3	2.7	4.7	15.4	2.3	17.6
LR3	12.2	23	2.4	5.2	2.3	4.2	14.0	1.7	15.8

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Mizushima to a repair yard at Qushan, China (MR, LR1, LR2 tankers), and Ulsan, South Korea (LR3 tankers), in US$ per tonne, including recurring capital costs during 2019.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
MR	15.2	2	0.5	0.4	0.6	1.6	3.3	4.9
LR1	15.0	2	0.4	0.3	0.5	1.1	2.0	3.1
LR2	14.7	2	0.3	0.2	0.4	0.9	1.4	2.3
LR3	14.3	1	0.1	0.1	0.2	0.3	1.4	1.7

Total cost analysis for Mongstad – Mizushima pair in US$ per tonne, including recurring capital costs during 2020.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	RFR	Repairs	RFR incl. repairs
					SCR				
MR	13.8	35	7.9	5.1	7.3	8.8	29.2		
LR1	13.3	36	5.6	4.0	4.9	6.5	21.0		
LR2	13.6	36	4.4	4.3	3.1	5.7	17.5		
LR3	13.2	37	3.9	3.4	2.7	5.1	15.1		
					NSR				
MR	12.9	21	4.4	6.0	6.5	7.1	23.9	4.8	28.7
LR1	12.7	22	3.1	4.4	4.2	5.1	16.8	3.0	19.8
LR2	12.7	22	2.5	4.6	2.7	4.6	14.4	2.2	16.6
LR3	12.5	22	2.2	4.5	2.3	4.1	13.1	1.7	14.8

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Mizushima to a repair yard at Qushan, China (MR, LR1, LR2 tankers), and Ulsan, South Korea (LR3 tankers), in US$ per tonne, including recurring capital costs during 2020.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
MR	15.8	2	0.5	0.4	0.6	1.5	3.3	4.8
LR1	15.5	2	0.3	0.3	0.4	1.0	2.0	3.0
LR2	15.3	2	0.3	0.2	0.4	0.9	1.4	2.2
LR3	14.9	1	0.1	0.1	0.2	0.3	1.4	1.7

Total cost analysis for Yeosu – Rotterdam pair in US$ per tonne, including recurring capital costs during 2018.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	RFR	Repairs	RFR incl. repairs
					SCR				
MR	13.1	35	7.9	5.1	7.3	8.7	29.0		
LR1	12.6	36	5.6	4.0	4.8	6.4	20.8		
LR2	12.8	35	4.3	4.2	3.1	5.7	17.4		
LR3	12.5	36	3.9	3.4	2.7	5.1	15.0		
					NSR				
MR	12.4	24	5.2	6.8	7.2	8.0	27.2	6.6	33.8
LR1	12.2	25	3.7	5.0	4.6	5.8	19.1	4.1	23.2
LR2	12.2	25	3.0	5.2	3.0	5.2	16.4	3.0	19.4
LR3	12.0	25	2.7	5.1	2.5	4.6	15.0	2.3	17.3

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Rotterdam to a repair yard at Odense, Denmark, in US$ per tonne, including recurring capital costs during 2018.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
MR	13.1	2	0.5	0.4	0.7	1.6	5.0	6.6
LR1	12.8	2	0.4	0.3	0.5	1.2	3.0	4.1
LR2	12.6	2	0.3	0.2	0.4	0.9	2.1	3.0
LR3	12.4	2	0.3	0.2	0.4	0.8	1.5	2.3

Total cost analysis for Yeosu – Rotterdam pair in US$ per tonne, including recurring capital costs during 2019.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	RFR	Repairs	RFR incl. repairs
					SCR				
MR	13.2	34	7.7	5.0	7.0	8.6	28.4		
LR1	12.8	35	5.4	3.9	4.7	6.3	20.4		
LR2	13.0	35	4.2	4.2	3.0	5.6	17.0		
LR3	12.7	33	3.8	3.3	2.6	5.0	14.7		
					NSR				
MR	12.6	24	5.1	6.9	7.0	7.9	26.9	6.6	33.4
LR1	12.4	25	3.6	5.1	4.4	5.7	18.9	4.1	23.0
LR2	12.4	25	2.9	5.3	2.9	5.1	16.3	3.0	19.3
LR3	12.2	24	2.6	5.2	2.4	4.5	14.9	2.3	17.1

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Rotterdam to a repair yard at Odense, Denmark, in US$ per tonne, including recurring capital costs during 2019.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
MR	13.5	2	0.5	0.4	0.6	1.6	5.0	6.6
LR1	13.1	2	0.4	0.3	0.5	1.1	3.0	4.1
LR2	12.9	2	0.3	0.2	0.4	0.9	2.1	3.0
LR3	12.7	2	0.3	0.2	0.4	0.8	1.5	2.3

Total cost analysis for Yeosu – Rotterdam pair in US$ per tonne, including recurring capital costs during 2020.

Tanker Size	Speed (knots)	Time (days)	Fuel Cost	Transit Fees*	Operating cost	Capital cost	RFR	Repairs	RFR incl. repairs
					SCR				
MR	13.8	33	7.4	5.1	6.9	8.3	27.7		
LR1	13.3	34	5.2	4.0	4.6	6.1	19.9		
LR2	13.6	33	4.1	4.3	2.9	5.4	16.7		
LR3	13.2	34	3.6	3.4	2.6	4.8	14.4		
					NSR				
MR	13.0	23	4.8	6.0	6.9	7.6	25.3	6.4	31.7
LR1	12.8	24	3.4	4.4	4.4	5.5	17.8	3.9	21.7
LR2	12.8	24	2.8	4.6	2.9	5.0	15.2	2.9	18.1
LR3	12.6	24	2.5	4.5	2.4	4.4	13.8	2.2	16.0

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Rotterdam to a repair yard at Odense, Denmark, in US$ per tonne, including recurring capital costs during 2020.

Tanker size	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
MR	15.5	2	0.5	0.4	0.6	1.4	5.0	6.4
LR1	15.1	2	0.3	0.2	0.4	1.0	3.0	3.9
LR2	14.9	2	0.3	0.2	0.4	0.8	2.1	2.9
LR3	14.7	2	0.2	0.1	0.3	0.7	1.5	2.2

Appendix R. Calculations of optimal speeds – Chapters 5 and 6

When a tanker operates on dual-fuel Oil/LNG mode and uses LNG as a fuel (Equation (7), and assuming fuel consumption functions as presented in Equations (2), (3), (4), Section '5.3.2 Cost assessment and optimal speeds', Chapter 5):

$$RFR = \frac{1}{W} \cdot \left[\left(\frac{D_{SCR,NSR,Cape}}{(S^*_{DF\ LNG\ L,B} + S^*_{DF\ FO\ L,B}) \cdot 24}\right) \cdot \left(b \cdot \left(F_{DF\ LNG}\left(S^*_{DF\ LNG\ L,B}\right) \cdot P_{LNG} + F_{DF\ Pilot}\left(S^*_{DF\ LNG\ L,B}\right) \cdot P_{FO}\right) + c \cdot \left(F_{DF\ FO}\left(S^*_{DF\ FO\ L,B}\right) \cdot P_{FO}\right) + (C_o + C_c) + q \cdot (W \cdot P_C \cdot \frac{r}{365})\right) + C_{TI}\right]$$

The term $c \cdot \left(F_{DF\ FO}\left(S^*_{DF\ FO\ L,B}\right) \cdot P_{FO}\right)$ is set equal to zero through the binary variable, c, whilst the term: $b \cdot F_{DF\ LNG}\left(S^*_{DF\ LNG\ L,B}\right) \cdot P_{LNG}$ is retained, since $b = 1$, when assuming the use of LNG as a fuel. The only decision variable is the speed, $s^*_{DF\ LNG\ L,B}$, with the rest being data inputs to the problem. The pilot fuel oil consumption follows the same exponential relationship between speed and fuel consumption as in the other fuels. This can be explained by the fact that pilot fuel oil consumption is proportional to the engine speed, which in turn is nearly proportional to the ship speed (MAN Energy Solutions 2020). This means that the pilot fuel oil consumption varies nearly linearly with ship speed (MAN Energy Solutions 2020).

$$RFR = \frac{1}{W} \cdot \left[\left(\frac{D_{SCR,NSR,Cape}}{\left(S^*_{DF\ LNG\ L,B}\right) \cdot 24}\right) \cdot \left(b \cdot \left(F_{DF\ LNG}\left(S^*_{DF\ LNG\ L,B}\right) \cdot P_{LNG} + F_{DF\ Pilot}\left(S^*_{DF\ LNG\ L,B}\right) \cdot P_{FO}\right) + (C_o + C_c) + q \cdot (W \cdot P_C \cdot \frac{r}{365})\right) + C_{TI}\right]$$

(b equals 1 to consider LNG as a fuel)

$$= \frac{1}{W} \cdot \left[\left(\frac{D_{SCR,NSR,Cape}}{\left(S^*_{DF\ LNG\ L,B}\right) \cdot 24}\right) \cdot \left(\left(F_{DF\ LNG\ d} \cdot \left(\frac{S^*_{DF\ LNG\ L,B}}{S_d}\right)^a \cdot \left(\frac{P+L}{\nabla}\right)^{2/3} \cdot P_{LNG} + F_{DF\ Pilot\ d} \cdot \left(\frac{S^*_{DF\ LNG\ L,B}}{S_d}\right)^a \cdot \left(\frac{P+L}{\nabla}\right)^{\frac{2}{3}} \cdot P_{FO}\right) + (C_o + C_c) + q \cdot (W \cdot P_C \cdot \frac{r}{365})\right) + C_{TI}\right]$$

$$= \frac{D_{SCR,NSR,Cape}}{W \cdot S^{*}_{DF\ LNG\ L,B} \cdot 24} \cdot \frac{F_{DF\ LNG\ d} \cdot S^{*}_{DF\ LNG\ L,B}{}^{a}}{S_{d}{}^{a}} \cdot \left(\frac{P+L}{\nabla}\right)^{\frac{2}{3}} \cdot P_{LNG} + \frac{D_{SCR,NSR,Cape}}{W \cdot S^{*}_{DF\ LNG\ L,B} \cdot 24} \cdot \frac{F_{DF\ Pilot\ d} \cdot S^{*}_{DF\ LNG\ L,B}{}^{a}}{S_{d}{}^{a}} \cdot \left(\frac{P+L}{\nabla}\right)^{\frac{2}{3}} \cdot P_{FO} + (C_o + C_c) \cdot \frac{D_{SCR,NSR,Cape}}{W \cdot S^{*}_{DF\ LNG\ L,B} \cdot 24} + q \cdot \left(W \cdot P_C \cdot \frac{r}{365}\right) \cdot \frac{D_{SCR,NSR,Cape}}{W \cdot S^{*}_{DF\ LNG\ L,B} \cdot 24} + \frac{C_{TI}}{W}$$

$$= \frac{D_{SCR,NSR,Cape} \cdot F_{DF\ LNG\ d} \cdot S^{*}_{DF\ LNG\ L,B}{}^{a} \cdot \left(\frac{P+L}{\nabla}\right)^{\frac{2}{3}} \cdot P_{LNG} + D_{SCR,NSR,Cape} \cdot F_{DF\ Pilot\ d} \cdot S^{*}_{DF\ LNG\ L,B}{}^{a} \cdot \left(\frac{P+L}{\nabla}\right)^{\frac{2}{3}} \cdot P_{FO}}{W \cdot S^{*}_{DF\ LNG\ L,B} \cdot 24 \cdot S_{d}{}^{a}} + \frac{(C_o + C_c) \cdot D_{SCR,NSR,Cape}}{W \cdot S^{*}_{DF\ LNG\ L,B} \cdot 24} + \frac{q \cdot \left(W \cdot P_C \cdot \frac{r}{365}\right) \cdot D_{SCR,NSR,Cape}}{W \cdot S^{*}_{DF\ LNG\ L,B} \cdot 24} + \frac{C_{TI}}{W}$$

$$= \frac{D_{SCR,NSR,Cape} \cdot (F_{DF\ LNG\ d} \cdot P_{LNG} + F_{DF\ Pilot\ d} \cdot P_{FO}) \cdot S^{*}_{DF\ LNG\ L,B}{}^{a} \cdot \left(\frac{P+L}{\nabla}\right)^{\frac{2}{3}}}{W \cdot S^{*}_{DF\ LNG\ L,B} \cdot 24 \cdot S_{d}{}^{a}} + \frac{(C_o + C_c) \cdot D_{SCR,NSR,Cape}}{W \cdot S^{*}_{DF\ LNG\ L,B} \cdot 24} + \frac{q \cdot \left(W \cdot P_C \cdot \frac{r}{365}\right) \cdot D_{SCR,NSR,Cape}}{W \cdot S^{*}_{DF\ LNG\ L,B} \cdot 24} + \frac{C_{TI}}{W}$$

$$= \frac{D_{SCR,NSR,Cape} \cdot (F_{DF\ LNG\ d} \cdot P_{LNG} + F_{DF\ Pilot\ d} \cdot P_{FO}) \cdot S^{*}_{DF\ LNG\ L,B}{}^{(a-1)} \cdot (P+L)^{\frac{2}{3}}}{W \cdot 24 \cdot S_{d}{}^{a} \cdot \nabla^{\frac{2}{3}}} + \frac{(C_o + C_c) \cdot D_{SCR,NSR,Cape} + q \cdot \left(W \cdot P_C \cdot \frac{r}{365}\right) \cdot D_{SCR,NSR,Cape}}{W \cdot S^{*}_{DF\ LNG\ L,B} \cdot 24} + \frac{C_{TI}}{W}$$

$$= \frac{D_{SCR,NSR,Cape} \cdot (F_{DF\ LNG\ d} \cdot P_{LNG} + F_{DF\ Pilot\ d} \cdot P_{FO}) \cdot S^{*}_{DF\ LNG\ L,B}{}^{(a-1)} \cdot (P+L)^{\frac{2}{3}}}{W \cdot 24 \cdot S_{d}{}^{a} \cdot \nabla^{\frac{2}{3}}} + \frac{\left((C_o + C_c) + q \cdot \left(W \cdot P_C \cdot \frac{r}{365}\right)\right) \cdot D_{SCR,NSR,Cape}}{W \cdot 24} \cdot \frac{1}{S^{*}_{DF\ LNG\ L,B}} + \frac{C_{TI}}{W}$$

1st order derivative to obtain the optimal speed, $S^*_{DF\ LNG\ L,B}$, which minimises the RFR:

$$\frac{\partial RFR}{\partial S^*_{DF\ LNG\ L,B}} = \frac{(a-1)\cdot D_{SCR,NSR,Cape}\cdot(F_{DF\ LNG\ d}\cdot P_{LNG}+F_{DF\ Pilot\ d}\cdot P_{FO})\cdot(P+L)^{\frac{2}{3}}}{W\cdot 24\cdot {S_d}^{a}\cdot \nabla^{\frac{2}{3}}}\cdot {S^*_{DF\ LNG\ L,B}}^{(a-2)} - \frac{\left((C_o+C_c)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right)\cdot D_{SCR,NSR,Cape}}{W\cdot 24}\cdot\frac{1}{{S^*_{DF\ LNG\ L,B}}^{2}} = 0$$

$$\frac{(a-1)\cdot D_{SCR,NSR,Cape}\cdot(F_{DF\ LNG\ d}\cdot P_{LNG}+F_{DF\ Pilot\ d}\cdot P_{FO})\cdot(P+L)^{\frac{2}{3}}}{W\cdot 24\cdot {S_d}^{a}\cdot \nabla^{\frac{2}{3}}}\cdot {S^*_{DF\ LNG\ L,B}}^{(a-2)} = \frac{\left((C_o+C_c)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right)\cdot D_{SCR,NSR,Cape}}{W\cdot 24\cdot {S^*_{DF\ LNG\ L,B}}^{2}}$$

$$\frac{(a-1)\cdot(F_{DF\ LNG\ d}\cdot P_{LNG}+F_{DF\ Pilot\ d}\cdot P_{FO})\cdot(P+L)^{\frac{2}{3}}}{{S_d}^{a}\cdot \nabla^{\frac{2}{3}}}\cdot {S^*_{DF\ LNG\ L,B}}^{(a-2)} = \frac{\left((C_o+C_c)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right)}{{S^*_{DF\ LNG\ L,B}}^{2}}$$

$$(a-1)\cdot(F_{DF\ LNG\ d}\cdot P_{LNG}+F_{DF\ Pilot\ d}\cdot P_{FO})\cdot(P+L)^{\frac{2}{3}}\cdot {S^*_{DF\ LNG\ L,B}}^{(a-2)}\cdot {S^*_{DF\ LNG\ L,B}}^{2} = \left((C_o+C_c)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right)\cdot {S_d}^{a}\cdot \nabla^{\frac{2}{3}}$$

$$(a-1)\cdot(F_{DF\ LNG\ d}\cdot P_{LNG}+F_{DF\ Pilot\ d}\cdot P_{FO})\cdot(P+L)^{\frac{2}{3}}\cdot {S^*_{DF\ LNG\ L,B}}^{(a-2+2)} = \left((C_o+C_c)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right)\cdot {S_d}^{a}\cdot \nabla^{\frac{2}{3}}$$

$$(a-1)\cdot(F_{DF\ LNG\ d}\cdot P_{LNG}+F_{DF\ Pilot\ d}\cdot P_{FO})\cdot(P+L)^{\frac{2}{3}}\cdot {S^*_{DF\ LNG\ L,B}}^{a} = \left((C_o+C_c)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right)\cdot {S_d}^{a}\cdot \nabla^{\frac{2}{3}}$$

And:

$$S_{DF\ LNG\ L,B}^{*}\ {}^{a} = \frac{\left((C_o+C_c)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right)\cdot S_d{}^{a}\cdot \nabla^{\frac{2}{3}}}{(a-1)\cdot(F_{DF\ LNG\ d}\cdot P_{LNG}+F_{DF\ Pilot\ d}\cdot P_{FO})\cdot(P+L)^{\frac{2}{3}}} \quad \text{or} \quad S_{DF\ LNG\ L,B}^{*} = \sqrt[a]{\frac{\left((C_o+C_c)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right)\cdot S_d{}^{a}\cdot \nabla^{\frac{2}{3}}}{(a-1)\cdot(F_{DF\ LNG\ d}\cdot P_{LNG}+F_{DF\ Pilot\ d}\cdot P_{FO})\cdot(P+L)^{\frac{2}{3}}}}$$

The process of calculating the optimal speed when a tanker operates on dual-fuel Oil/LNG mode and uses LNG as a fuel in the analysis in Chapter 6 (Equation (13), Section '6.2.1 Modelling approach') is the same. The only difference is that the binary variable, q, does not exist in the RFR equation (Equation (7), Section '6.2.1 Modelling approach') since the in-transit inventory costs are included in the analysis in Chapter 6 by default.

Moreover, the optimal speed when a tanker conducts ballast voyages (Equation (16), Section '5.3.2 Cost assessment and optimal speeds', and Equation (16), Section '6.2.1 Modelling approach') is the same as above with the term, $q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)$, set equal to zero through the binary variable, q. The only difference is the notation of speed and fuel consumption in both Chapters 5 and 6. The 2nd order derivative results in a positive value in all cases, which ensures that the solution is a minimum. Moreover, the solution is unique and is a global minimum in the range of 0-16 i.e. between the lowest and highest speed values. The only exception is in cases where the speed is constrained, such as on ice legs within NSR or when assuming real, fixed, speeds.

When a tanker operates on HSFO-Scrubber mode (Equation (6), and assuming a fuel consumption function as presented in Equation (1), Section '5.3.2 Cost assessment and optimal speeds', Chapter 5):

The only decision variable is the speed, $s_{FO\ L,B}^{*}$, with the rest being data inputs to the problem.

$$RFR = \frac{1}{W}\cdot\left[\left(\frac{D_{SCR,NSR,Cape}}{S_{FO\ L,B}^{*}\cdot 24}\right)\cdot\left(\left(F_{FO}\left(S_{FO\ L,B}^{*}\right)\cdot P_{FO}\right)+(C_o+C_c+g\cdot C_s)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right)+C_{TI}\right]$$

$$= \frac{1}{W} \cdot \left[\left(\frac{D_{SCR,NSR,Cape}}{S^*_{FO\ L,B} \cdot 24} \right) \cdot \left(\left(F_{FO\ d} \cdot \left(\frac{S^*_{FO\ L,B}}{S_d} \right)^a \cdot \left(\frac{P+L}{\nabla} \right)^{2/3} \cdot P_{FO} \right) + (C_o + C_c + g \cdot C_s) + q \cdot (W \cdot P_C \cdot \frac{r}{365}) \right) + C_{TI} \right]$$

$$= \frac{D_{SCR,NSR,Cape}}{W \cdot S^*_{FO\ L,B} \cdot 24} \cdot \frac{F_{FO\ d} \cdot {S^*_{FO\ L,B}}^a}{{S_d}^a} \cdot \left(\frac{P+L}{\nabla} \right)^{\frac{2}{3}} \cdot P_{FO} + (C_o + C_c + g \cdot C_s) \cdot \frac{D_{SCR,NSR,Cape}}{W \cdot S^*_{FO\ L,B} \cdot 24} + q \cdot \left(W \cdot P_C \cdot \frac{r}{365} \right) \cdot \frac{D_{SCR,NSR,Cape}}{W \cdot S^*_{FO\ L,B} \cdot 24} + \frac{C_{TI}}{W}$$

$$= \frac{D_{SCR,NSR,Cape} \cdot F_{FO\ d} \cdot {S^*_{FO\ L,B}}^a \cdot \left(\frac{P+L}{\nabla} \right)^{\frac{2}{3}} \cdot P_{FO}}{W \cdot S^*_{FO\ L,B} \cdot 24 \cdot {S_d}^a} + \frac{(C_o + C_c + g \cdot C_s) \cdot D_{SCR,NSR,Cape}}{W \cdot S^*_{FO\ L,B} \cdot 24} + \frac{q \cdot \left(W \cdot P_C \cdot \frac{r}{365} \right) \cdot D_{SCR,NSR,Cape}}{W \cdot S^*_{FO\ L,B} \cdot 24} + \frac{C_{TI}}{W}$$

$$= \frac{D_{SCR,NSR,Cape} \cdot F_{FO\ d} \cdot {S^*_{FO\ L,B}}^{(a-1)} \cdot P_{FO} \cdot (P+L)^{\frac{2}{3}}}{W \cdot 24 \cdot {S_d}^a \cdot \nabla^{\frac{2}{3}}} + \frac{(C_o + C_c + g \cdot C_s) \cdot D_{SCR,NSR,Cape} + q \cdot \left(W \cdot P_C \cdot \frac{r}{365} \right) \cdot D_{SCR,NSR,Cape}}{W \cdot 24} \cdot \frac{1}{S^*_{FO\ L,B}} + \frac{C_{TI}}{W}$$

$$= \frac{D_{SCR,NSR,Cape} \cdot F_{FO\ d} \cdot {S^*_{FO\ L,B}}^{(a-1)} \cdot P_{FO} \cdot (P+L)^{\frac{2}{3}}}{W \cdot 24 \cdot {S_d}^a \cdot \nabla^{\frac{2}{3}}} + \frac{\left((C_o + C_c + g \cdot C_s) + q \cdot \left(W \cdot P_C \cdot \frac{r}{365} \right) \right) \cdot D_{SCR,NSR,Cape}}{24 \cdot W} \cdot \frac{1}{S^*_{FO\ L,B}} + \frac{C_{TI}}{W}$$

1st order derivative to obtain the optimal speed, $S^*_{FO\ L,B}$, which minimises the RFR:

$$\frac{\partial RFR}{\partial_{S^*_{FO\ L,B}}} = \frac{(a-1)\cdot D_{SCR,NSR,Cape}\cdot F_{FO\ d}\cdot P_{FO}\cdot (P+L)^{\frac{2}{3}}}{W\cdot 24\cdot {S_d}^{a}\cdot \nabla^{\frac{2}{3}}}\cdot {S^*_{FO\ L,B}}^{(a-2)} - \frac{\left((C_o+C_c+g\cdot C_s)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right)\cdot D_{SCR,NSR,Cape}}{W\cdot 24}\cdot\frac{1}{{S^*_{FO\ L,B}}^{2}} = 0$$

$$\frac{(a-1)\cdot D_{SCR,NSR,Cape}\cdot F_{FO\ d}\cdot P_{FO}\cdot (P+L)^{\frac{2}{3}}}{W\cdot 24\cdot {S_d}^{a}\cdot \nabla^{\frac{2}{3}}}\cdot {S^*_{FO\ L,B}}^{(a-2)} = \frac{\left((C_o+C_c+g\cdot C_s)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right)\cdot D_{SCR,NSR,Cape}}{W\cdot 24\cdot {S^*_{FO\ L,B}}^{2}}$$

$$\frac{(a-1)\cdot F_{FO\ d}\cdot P_{FO}\cdot (P+L)^{\frac{2}{3}}}{{S_d}^{a}\cdot \nabla^{\frac{2}{3}}}\cdot {S^*_{FO\ L,B}}^{(a-2)} = \frac{\left((C_o+C_c+g\cdot C_s)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right)}{{S^*_{FO\ L,B}}^{2}}$$

$$(a-1)\cdot F_{FO\ d}\cdot P_{FO}\cdot (P+L)^{\frac{2}{3}}\cdot {S^*_{FO\ L,B}}^{(a-2)}\cdot {S^*_{FO\ L,B}}^{2} = \left((C_o+C_c+g\cdot C_s)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right){S_d}^{a}\cdot \nabla^{\frac{2}{3}}$$

$$(a-1)\cdot F_{FO\ d}\cdot P_{FO}\cdot (P+L)^{\frac{2}{3}}\cdot {S^*_{FO\ L,B}}^{(a-2+2)} = \left((C_o+C_c+g\cdot C_s)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right){S_d}^{a}\cdot \nabla^{\frac{2}{3}}$$

$$(a-1)\cdot F_{FO\ d}\cdot P_{FO}\cdot (P+L)^{\frac{2}{3}}\cdot {S^*_{FO\ L,B}}^{a} = \left((C_o+C_c+g\cdot C_s)+q\cdot\left(W\cdot P_C\cdot\frac{r}{365}\right)\right){S_d}^{a}\cdot \nabla^{\frac{2}{3}}$$

And:

$$S_{FO\ L,B}^{*}{}^{a} = \frac{\left((C_O + C_C + g \cdot C_S) + q \cdot \left(W \cdot P_C \cdot \frac{r}{365}\right)\right) \cdot S_d{}^{a} \cdot \nabla^{\frac{2}{3}}}{(a-1) \cdot F_{FO\ d} \cdot P_{FO} \cdot (P+L)^{\frac{2}{3}}} \quad \text{or} \quad S_{FO\ L,B}^{*} = \sqrt[a]{\frac{\left((C_O + C_C + g \cdot C_S) + q \cdot \left(W \cdot P_C \cdot \frac{r}{365}\right)\right) \cdot S_d{}^{a} \cdot \nabla^{\frac{2}{3}}}{(a-1) \cdot F_{FO\ d} \cdot P_{FO} \cdot (P+L)^{\frac{2}{3}}}}$$

The process of calculating the optimal speed when a tanker operates on HSFO-Scrubber mode in the analysis in Chapter 6 (Equation (12), Section '6.2.1 Modelling approach') is the same. The only difference is that the binary variable, q, does not exist in the RFR equation (Equation (6), Section '6.2.1 Modelling approach') since the in-transit inventory costs are included in the analysis in Chapter 6 by default.

The process of calculating the optimal speed when a tanker operates on VLSFO mode is the same since the RFR equation above also refers to VLSFO mode (Equation (12), Section '5.3.2 Cost assessment and optimal speeds'). The only difference is that that the term, $g \cdot C_s$, does not exist in the RFR equation since the binary variable, g, is set equal to zero, given that under the VLSFO mode, a scrubber is not installed in the ship. The same also applies to Chapter 6 with respect to VLSFO mode (Equation (12), Section '6.2.1 Modelling approach').

Similarly, the process of calculating the optimal speed when a tanker operates on dual-fuel Oil/LNG mode under VLSFO (Equation (14), Section '5.3.2 Cost assessment and optimal speeds', and Equation (14), Section '6.2.1 Modelling approach') is the same, where the binary variable, b, is set equal to zero, and the binary variable, c, is set equal to 1 in both cases. Moreover, optimal speeds when a tanker conducts ballast voyages (Equation (15), '5.3.2 Cost assessment and optimal speeds', and Equation (15), Section '6.2.1 Modelling approach') is the same as above with the term $q \cdot \left(W \cdot P_C \cdot \frac{r}{365}\right)$, set equal to zero through the binary variable, q, and the binary variable, g, equals 1 under HSFO-Scrubber mode or zero under VLSFO mode. The only difference is the notation of speed and fuel consumption in both Chapters 5 and 6. The 2nd order derivative results in a positive value in all cases, which ensures that the solution is a minimum. Moreover, the solution is unique and is a global minimum in the range of 0-16 i.e. between the lowest and highest speed values. The only exception is in cases where the speed is constrained, such as on ice legs within NSR or when assuming real, fixed, speeds.

Appendix S1. Port characteristics – Chapter 5

Port characteristics for LR2 tankers of 115,000 dwt, LOA: 250 metres and loaded draught of 12 metres.

Port	Tanker Terminals	Berths/Jetties	DWT	LOA (metres)	Draught (metres)
Ulsan	S-Oil 2-1/Sk Corp Sk8	2	120,000/150,000	250/280	13.50/16.50
Rotterdam	11 terminals/berths for clean oil products	11	120,000 – 355,000	270 – 375	12.65 – 20.70
Bilbao	Petronor/Punta Lucero No 1, No 2	2	150,000 – 500,000	325 – 400	18.50 – 30.00
Chiba	Fuji Oil Pier	1	120,000	285	14.54
Coryton	Shellhaven Terminal (Stanford-le-Hope) South Jetty	1		275	15.00

Source: IHS Maritime (2015).

Appendix S2. LNG bunkering infrastructure/ships – Chapter 5

Port	LNG infrastructure	LNG Tank Capacity (m^3)	Country	Operations
Ulsan	LNG Bunker Ship SM Jeju LNG2	7,654	South Korea	Coastal in South Korea
Rotterdam	LNG Bunker Ship Coral Fraseri (Ice Class II)	10,000	The Netherlands	North Sea, Baltic Sea, West Mediterranean
	LNG Bunker Ship Coral Methane (Ice Class IB)	7,551	The Netherlands	North Sea, Baltic Sea, West Mediterranean
	LNG Bunker Ship Coralius (Ice Class IA)	5,600	Norway	North Sea, Baltic Sea
	LNG Bunker Ship Cardissa	6,500	The Netherlands	North Sea, Baltic Sea
Rotterdam	GATE Terminal Rotterdam	720,000	The Netherlands	Rotterdam
	LNG Bunker Barge Flexfueler 001	1,480	The Netherlands	ARA region*
	LNG Bunker Barge LNG London	2,998	The Netherlands	Rotterdam
Bilbao	Bilbao LNG Terminal	600-270,000	Spain	Spain
	LNG bunker station Bilbao	1,000	Spain	Spain
Chiba	Yokohama LNG bunkering	1,180,000	Japan	Tokyo Bay (Japan)
	LNG Bunker Ship Ecobunker Tokyo Bay	2,500	Japan	Tokyo Bay (Japan)
Coryton	Isle of Grain LNG Terminal	2,000-1,200,000	Isle of Grain	UK

Sources: DNV (2021b), Clarksons (2021). This list is indicative and non-exhaustive. A large number of LNG bunker ships and LNG bunker port terminals exist in the countries and regions mentioned in this table. *ARA region: Amsterdam-Rotterdam-Antwerp region.

Appendix T. Calculations for fuel consumption at design speed, and calculations of TPC – Chapter 5

Assumptions for the fuel consumption at the design speed for ordinary (non-ice class) and ice class tankers.

The tables and data in this Appendix refer to LR2 tankers of 115,000 dwt with the technical characteristics presented below:

Length between perpendiculars (LPP)	Beam (metres)	Scantling Draught (metres)	Design Draught (metres)	Tonnes per Centimetre Immersion (TPC)	Ballast Capacity (Tonnes)
239	44	15.0	13.5	97.23	41,400

Source: MAN Diesel and Turbo (2013c).

A design speed of 15 knots and corresponding fuel consumption at 90% of Specified Maximum Continuous Rating (SMCR), including 15% sea margin is assumed, based on a standard design and size for LR2 tankers (MAN Diesel and Turbo 2013c). The fuel consumption in tonnes per day at the design speed for each engine set-up is calculated based on the Computerised Engine Application System (CEAS) provided by MAN Energy Solutions (MAN Energy Solutions 2019a; MAN Energy Solutions 2019b). This methodological choice enables the estimation of other variables, such as the Tonnes per Centimetre Immersion (TPC), in order to estimate the actual draught depending on payload.

The calculation of actual draught (draught when loaded) based on payload allows for the consideration of other factors, including port and LNG bunkering infrastructure factors, such as the maximum depth allowed for ship accommodation. Moreover, the CEAS Engine Calculations enables the correct calculation for fuel consumption at the design speed of an ice class tanker. More specifically, Solakivi et al. (2018) refer to increased fuel consumption of ice class tankers based on the installed power and not simply on increased fuel consumption in tonnes per day.

A two-stroke engine (7G60ME - C10.5) of 13,000 kilowatts (kW) (or 17,004 kW for an ice class tanker, premium of 30.8% – Solakivi et al. 2018) is chosen to calculate fuel consumption at the design speed for oil-powered tankers, whilst a dual fuel Oil/LNG two stroke engine (7G60ME - C10.5-GI HL) is chosen to calculate fuel consumption at the design speed for dual fuel Oil/LNG-powered tankers (MAN Energy Solutions 2019b). The output of the CEAS report gives the Engine Load as a percentage (%) of the SMCR, the Engine Power in kW, and the

Specific Fuel Oil Consumption (SFOC) or Specific Gas Consumption (SGC) along with the Specific Pilot Oil Consumption (SPOC) for oil-powered and Oil/LNG-powered engine set-ups, respectively.

The function below is used to convert the fuel consumption in tonnes per day at the design speed of 15 knots for oil-powered diesel engines:

$$Fuel\ Consumption\ in\ tonnes\ per\ day$$
$$= 0.90\ Load\ SMCR \cdot Engine\ Power \cdot SFOC \cdot 10^{-6} \cdot 24$$

The function below is used to convert the fuel consumption in tonnes per day at the design speed of 15 knots for Oil/LNG-powered engines (LNG Mode):

$$Fuel\ Consumption\ in\ tonnes\ per\ day$$
$$= 0.90\ Load\ SMCR \cdot Engine\ Power \cdot SGC \cdot 10^{-6} \cdot 24$$

And for the pilot fuel oil consumption:

$$Fuel\ Consumption\ in\ tonnes\ per\ day$$
$$= 0.90\ Load\ SMCR \cdot Engine\ Power \cdot SPOC \cdot 10^{-6} \cdot 24$$

The function below is used to convert the fuel consumption in tonnes per day at the design speed of 15 knots for Oil/LNG-powered engines (Oil Mode):

$$Fuel\ Consumption\ in\ tonnes\ per\ day$$
$$= 0.90\ Load\ SMCR \cdot Engine\ Power \cdot SFOC \cdot 10^{-6} \cdot 24$$

The tables below show results of fuel consumption at the design speed of 15 knots for all tankers assumed in Chapters 5 and 6. The output of CEAS for fuel oil-related results is fuel consumption in MGO, and therefore, the values for HSFO and VLSFO are found by using relevant conversion factors.

Fuel consumption in tonnes per day at the design speed of 15 knots for oil-powered tankers.

Ordinary Tanker		
MGO	HSFO	VLSFO
43.95 (44.00)	46.68 (46.74)	45.55
Ice Class Tanker		
MGO	HSFO	VLSFO
59.43 (59.54)	63.13 (63.24)	61.59

The values in parentheses refer to fuel consumption when a scrubber is used along with the respective fuel oil. The fuel type conversions are based on calorific values (heating values) based on IMO (2016b): From MGO to HSFO: HSFO = MGO · (42,700/40,200), from MGO to VLSFO: VLSFO = MGO · (42,700/41,200).

Fuel consumption in tonnes per day at the design speed of 15 knots for dual fuel Oil/LNG-powered tankers

Ordinary Tanker		
LNG	MGO Pilot	VLSFO Mode
36.5	0.91	46.7 (45.1)
Ice Class Tanker		
LNG	MGO Pilot	VLSFO Mode
49.6	0.98	63.1 (60.9)

The values in parentheses refer to MGO consumption, based on which the VLSFO values are calculated. The fuel type conversions are based on calorific values (heating values) based on IMO (2016b): From MGO to VLSFO: VLSFO = MGO · (42,700/41,200).

The table below presents data and assumptions for the tank capacity of oil-powered and dual-fuel Oil/LNG-powered tankers.

Tanker Size (dwt)	HSFO (tonnes)	VLSFO (tonnes)*	LNG 1,700 m^3	LNG 3,600 m^3
LR2	2,415	2,415	773 tonnes of LNG – 1,700 tonnes of MGO or 1,994 tonnes of VLSFO	1,636 tonnes of LNG – 1,700 tonnes of MGO or 1,994 tonnes of VLSFO

Sources: Platts (2017a), Riviera (2018), The Motorship (2020b), Clarksons (2021). *It is assumed to be the same as HSFO.

Conversion of LNG tank capacity from cubic metres (m^3) to tonnes:

LNG 1,700 m^3		LNG 3,600 m^3	
1 tonne of LNG	2.2 m^3 of LNG	1 tonne of LNG	2.2 m^3 of LNG
773 tonnes of LNG	1,700 m^3 LNG	1,636 tonnes of LNG	3,600 m^3 LNG

Source: Platts (2017b).

The process of calculating the Tonnes per Centimetre Immersion (TPC) is presented below.

Notation	Description
C_B	It is the block coefficient and is defined as the ratio between the displacement volume, ∇, and the volume of a box with dimensions $L \cdot B \cdot D_S$ (Barrass 2005; MAN Diesel and Turbo 2013a).
D_S	It is the draught which refers to the maximum possible deadweight (dwt) tonnage and corresponds to the fully loaded dwt at full summer saltwater draught (MAN Diesel and Turbo 2013c).
C_W	It is the water plane area coefficient and is defined as the ratio between the ship's waterline area and the product of the length of waterline and the beam of the ship on the waterline (MAN Diesel and Turbo 2013a). Here, it is estimated by using a formula from Barrass (2005).
D_D	It is the design draught and equals the average loaded ship in service. This draught is less than the scantling draught and it is used for the design of the propulsion system. The dwt tonnage sometimes refers to this draught (MAN Diesel and Turbo 2013c).
∇	It is the total weight of lightship and deadweight i.e. the total weight of water displaced by the ship at a certain draught (summer, winter, or other) (ICS 2014). Displacement equals deadweight plus lightweight. According to MAN Diesel and Turbo (2013a): $\nabla = 1.17 \cdot DWT$
P	It is the weight of cargo, fresh water, fuel, lubricating oil, stores, water ballast, crew and effects, and baggage and passengers, and is measured in metric tonnes (Barrass 2005; Stopford 2009). When the ship operates in ballast, the payload includes all these elements except for cargo. According to Stopford (2009), the weight of fresh water, fuel, lubricating oil, stores, crew and effects, and baggage and passengers is approximated by using the function: $P = 0.05 \cdot DWT$.
L_{PP}	It is the length between perpendiculars. This is the length between the foremost perpendicular and the aftmost perpendicular (MAN Diesel and Turbo 2013a). The foremost perpendicular is a vertical line through the stem's intersection with the waterline, whilst the aftmost perpendicular normally coincides with the rudder axis (MAN Diesel and Turbo 2013a). According to MAN Diesel and Turbo (2013a): $L_{PP} = DWT/6$
B	It is the beam, and is the extreme width of ship, also called breadth (ICS 2014; Wärtsilä 2021).
WPA	It is the waterplane area, that is, the area of a ship's hull at a particular horizontal plane (Wärtsilä 2021).
ρ	It is the water density, measured in tonnes per cubic metre (t/m^3). The summer saltwater has a mass density of 1.025 t/m^3 (Barrass 2005).
TPC	The change in draught by one centimetre, resulting from the addition or removal of a particular mass (Wärtsilä 2021).

For tankers, it can be stated that at the Summer Loaded Waterline (SLWL)[45], the block coefficient approximately equals the deadweight coefficient, and is calculated by using the equation (Barrass 2005; MAN Diesel and Turbo 2013a):

$$C_B = \frac{\nabla}{L_{PP} \cdot B \cdot D_S}$$

For tankers, it can be stated that at the Summer Loaded Waterline (SLWL), the water plane area coefficient is calculated by using the equation (Barrass 2005):

$$C_W = C_B + K$$

Where the K value depends on ship type based on the C_B value (Barrass 2005):

$$K = \frac{1 - C_B}{3}$$

The Waterplane Area at each waterline is calculated by using the equation (Barrass 2005):

$$WPA = L_{PP} \cdot B \cdot C_W$$

The TPC is calculated by using the equation (Barrass 2005):

$$TPC = \frac{WPA}{100} \cdot \rho$$

Where, ρ, is the water density equal to 1.025 t/m^3 (Barrass 2005).

Alternatively, the TPC is calculated by using the equation (Barrass 2005):

$$TPC = \frac{WPA}{97.56}$$

The difference between the maximum dwt tonnage and payload determines the actual draught (draught when loaded), depending on the cargo weight. The actual draught is determined by the following equation:

$$Draught = D_D - \Big(\big((DWT - P)/TPC\big)/100\Big)$$

[45] SLWL is the load line of a ship when operating during summer and indicates the depth at which it may be safely loaded (MAN Diesel and Turbo 2013a). The summer freeboard draught for seawater is equal to the scantling draught (MAN Diesel and Turbo 2013a).

Appendix U1. Distance breakdown per operational mode and route – Chapter 5 (Author's calculations)

Distance breakdown for Chiba – Coryton pair on SCR at optimal speed (11,264 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Chiba – Coryton	11,264
VLSFO	VLSFO	Chiba – North Sea ECAs	10,914
	MGO	North Sea ECAs – Coryton	350
LNG-VLSFO 1,700 m^3	VLSFO	Chiba – Indian Ocean	3,464
	LNG	Indian Ocean – Coryton	7,800
LNG-VLSFO 3,600 m^3	LNG	Chiba – Coryton	11,264

Source: Dataloy (2021).

Distance breakdown for Chiba – Coryton pair on Cape of Good Hope route at optimal speed (14,696 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Chiba – Coryton	14,696
VLSFO	VLSFO	Chiba – North Sea ECAs	14,346
	MGO	North Sea ECAs – Coryton	350
LNG-VLSFO 1,700 m^3	VLSFO	Chiba – Indian Ocean	6,896
	LNG	Indian Ocean – Coryton	7,800
LNG-VLSFO 3,600 m^3	VLSFO	Chiba – Western Pacific Ocean	468
	LNG	Western Pacific Ocean – Coryton	14,228

Source: Dataloy (2021).

Distance breakdown for Chiba – Coryton pair on NSR at optimal speed (6,914 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Chiba – Cape Dezhnev	2,687
	HSFO*	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	HSFO	Cape Zhelanya – Coryton	2,168
VLSFO	VLSFO	Chiba – Cape Dezhnev	2,687
	VLSFO*	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	VLSFO	Cape Zhelanya – North Sea ECAs	1,500
	MGO	North Sea ECAs – Coryton	668
LNG-VLSFO 1,700 m^3	VLSFO	Chiba – North Pacific Ocean	762
	LNG	North Pacific Ocean – Cape Dezhnev	1,925
	LNG	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	LNG	Cape Zhelanya – Coryton	2,168
LNG-VLSFO 3,600 m^3	LNG	Chiba – Cape Dezhnev	2,687
	LNG	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	LNG	Cape Zhelanya – Coryton	2,168

Source: Dataloy (2021). *The use of MGO through ice on NSR is assumed when considering a prohibition on the use of heavy fuel oils in the Arctic.

Distance breakdown for Chiba – Coryton pair on SCR at speed = 12 knots (11,264 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Chiba – Coryton	11,264
VLSFO	VLSFO	Chiba – North Sea ECAs	10,914
	MGO	North Sea ECAs – Coryton	350
LNG-VLSFO 1,700 m^3	LNG	Chiba – Coryton	11,264
LNG-VLSFO 3,600 m^3	LNG	Chiba – Coryton	11,264

Source: Dataloy (2021).

Distance breakdown for Chiba – Coryton pair on Cape of Good Hope route at speed = 12 knots (14,696 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Chiba – Coryton	14,696
VLSFO	VLSFO	Chiba – North Sea ECAs	14,346
	MGO	North Sea ECAs – Coryton	350
LNG-VLSFO 1,700 m^3	VLSFO	Chiba – Western Pacific Ocean	2,745
	LNG	Western Pacific Ocean – Coryton	11,951
LNG-VLSFO 3,600 m^3	LNG	Chiba – Coryton	14,696

Source: Dataloy (2021).

Distance breakdown for Chiba – Coryton pair on NSR at speed = 12 knots (6,914 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Chiba – Cape Dezhnev	2,687
	HSFO*	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	HSFO	Cape Zhelanya – Coryton	2,168
VLSFO	VLSFO	Chiba – Cape Dezhnev	2,687
	VLSFO*	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	VLSFO	Cape Zhelanya – North Sea ECAs	1,500
	MGO	North Sea ECAs – Coryton	668
LNG-VLSFO 1,700 m^3	LNG	Chiba – Cape Dezhnev	2,687
	LNG	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	LNG	Cape Zhelanya – Coryton	2,168
LNG-VLSFO 3,600 m^3	LNG	Chiba – Cape Dezhnev	2,687
	LNG	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	LNG	Cape Zhelanya – Coryton	2,168

Source: Dataloy (2021). *The use of MGO through ice on NSR is assumed when considering a prohibition on the use of heavy fuel oils in the Arctic.

Distance breakdown for Ulsan – Rotterdam pair on SCR at optimal speed (10,944 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Ulsan – Rotterdam	10,944
VLSFO	VLSFO	Ulsan – North Sea ECAs	10,531
	MGO	North Sea ECAs – Rotterdam	413
LNG-VLSFO 1,700 m^3	VLSFO	Ulsan – Indian Ocean	3,144
	LNG	Indian Ocean – Rotterdam	7,800
LNG-VLSFO 3,600 m^3	LNG	Ulsan – Rotterdam	10,944

Source: Dataloy (2021).

Distance breakdown for Ulsan – Rotterdam pair on Cape of Good Hope route at optimal speed (14,371 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Ulsan – Rotterdam	14,371
VLSFO	VLSFO	Ulsan – North Sea ECAs	13,958
	MGO	North Sea ECAs – Rotterdam	413
LNG-VLSFO 1,700 m^3	VLSFO	Ulsan – Indian Ocean	6,571
	LNG	Indian Ocean – Rotterdam	7,800
LNG-VLSFO 3,600 m^3	VLSFO	Ulsan – Western Pacific Ocean	143
	LNG	Western Pacific Ocean – Rotterdam	14,228

Source: Dataloy (2021).

Distance breakdown for Ulsan – Rotterdam pair on NSR at optimal speed (7,127 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Ulsan – Cape Dezhnev	2,939
	HSFO*	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	HSFO	Cape Zhelanya – Rotterdam	2,129
VLSFO	VLSFO	Ulsan – Cape Dezhnev	2,939
	VLSFO*	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	VLSFO	Cape Zhelanya – North Sea ECAs	1,500
	MGO	North Sea ECAs – Rotterdam	629
LNG-VLSFO 1,700 m^3	VLSFO	Ulsan – North Pacific Ocean	188
	LNG	North Pacific Ocean – Cape Dezhnev	2,751
	LNG	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	LNG	Cape Zhelanya – Rotterdam	2,129
LNG-VLSFO 3,600 m^3	LNG	Ulsan – Cape Dezhnev	2,939
	LNG	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	LNG	Cape Zhelanya – Rotterdam	2,129

Source: Dataloy (2021). *The use of MGO through ice on NSR is assumed when considering a prohibition on the use of heavy fuel oils in the Arctic.

Distance breakdown for Ulsan – Rotterdam pair on SCR at speed = 12 knots (10,944 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Ulsan – Rotterdam	10,944
VLSFO	VLSFO	Ulsan – North Sea ECAs	10,531
	MGO	North Sea ECAs – Rotterdam	413
LNG-VLSFO 1,700 m^3	LNG	Ulsan – Rotterdam	10,944
LNG-VLSFO 3,600 m^3	LNG	Ulsan – Rotterdam	10,944

Source: Dataloy (2021).

Distance breakdown for Ulsan – Rotterdam pair on Cape of Good Hope route at speed = 12 knots (14,371 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Ulsan – Rotterdam	14,371
VLSFO	VLSFO	Ulsan – North Sea ECAs	13,958
	MGO	North Sea ECAs – Rotterdam	413
LNG-VLSFO 1,700 m^3	VLSFO	Ulsan – Western Pacific Ocean	2,420
	LNG	Western Pacific Ocean – Rotterdam	11,951
LNG-VLSFO 3,600 m^3	LNG	Ulsan – Rotterdam	14,371

Source: Dataloy (2021).

Distance breakdown for Ulsan – Rotterdam pair on NSR at speed = 12 knots (7,127 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Ulsan – Cape Dezhnev	2,939
	HSFO*	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	HSFO	Cape Zhelanya – Rotterdam	2,129
VLSFO	VLSFO	Ulsan – Cape Dezhnev	2,939
	VLSFO*	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	VLSFO	Cape Zhelanya – North Sea ECAs	1,500
	MGO	North Sea ECAs – Rotterdam	629
LNG-VLSFO 1,700 m^3	LNG	Ulsan – Cape Dezhnev	2,939
	LNG	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	LNG	Cape Zhelanya – Rotterdam	2,129
LNG-VLSFO 3,600 m^3	LNG	Ulsan – Cape Dezhnev	2,939
	LNG	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	LNG	Cape Zhelanya – Rotterdam	2,129

Source: Dataloy (2021). *The use of MGO through ice on NSR is assumed when considering a prohibition on the use of heavy fuel oils in the Arctic.

Distance breakdown for Ulsan – Bilbao pair on SCR at optimal speed (10,436 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Ulsan – Bilbao	10,436
VLSFO	VLSFO	Ulsan – Bilbao	10,436
LNG-VLSFO 1,700 m^3	VLSFO	Ulsan – Indian Ocean	2,636
	LNG	Indian Ocean – Bilbao	7,800
LNG-VLSFO 3,600 m^3	LNG	Ulsan – Bilbao	10,436

Source: Dataloy (2021).

Distance breakdown for Ulsan – Bilbao pair on Cape of Good Hope route at optimal speed (13,853 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Ulsan – Bilbao	13,853
VLSFO	VLSFO	Ulsan – Bilbao	13,853
LNG-VLSFO 1,700 m^3	VLSFO	Ulsan – Indian Ocean	6,503
	LNG	Indian Ocean – Bilbao	7,800
LNG-VLSFO 3,600 m^3	LNG	Ulsan – Bilbao	13,853

Source: Dataloy (2021).

Distance breakdown for Ulsan – Bilbao pair on NSR at optimal speed (7,834 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Ulsan – Cape Dezhnev	2,939
	HSFO*	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	HSFO	Cape Zhelanya – Bilbao	2,836
VLSFO	VLSFO	Ulsan – Cape Dezhnev	2,939
	VLSFO*	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	VLSFO	Cape Zhelanya – North Sea ECAs	1,854
	MGO**	North Sea ECAs – Bilbao	982
LNG-VLSFO 1,700 m^3	VLSFO	Ulsan – North Pacific Ocean	895
	LNG	North Pacific Ocean – Cape Dezhnev	2,044
	LNG	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	LNG	Cape Zhelanya – Bilbao	2,836
LNG-VLSFO 3,600 m^3	LNG	Ulsan – Cape Dezhnev	2,939
	LNG	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	LNG	Cape Zhelanya – Bilbao	2,836

Source: Dataloy (2021). *The use of MGO through ice on NSR is assumed when considering a prohibition on the use of heavy fuel oils in the Arctic. **The North Sea ECAs can be avoided by navigating from Cape Zhelanya to Bilbao via the Irish Sea than through the North Sea and Dover Strait. This increases the competitiveness of the NSR voyage, given that the distance is slightly shorter and the lower-priced VLSFO is used instead of MGO. Here, it is assumed that the tanker arrives at Bilbao via the North Sea.

Distance breakdown for Ulsan – Bilbao pair on SCR at speed = 12 knots (10,436 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Ulsan – Bilbao	10,436
VLSFO	VLSFO	Ulsan – Bilbao	10,436
LNG-VLSFO 1,700 m^3	LNG	Ulsan – Bilbao	10,436
LNG-VLSFO 3,600 m^3	LNG	Ulsan – Bilbao	10,436

Source: Dataloy (2021).

Distance breakdown for Ulsan – Bilbao pair on Cape of Good Hope route at speed = 12 knots (13,853 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Ulsan – Bilbao	13,853
VLSFO	VLSFO	Ulsan – Bilbao	13,853
LNG-VLSFO 1,700 m^3	VLSFO	Ulsan – Western Pacific Ocean	1,902
	LNG	Western Pacific Ocean – Bilbao	11,951
LNG-VLSFO 3,600 m^3	LNG	Ulsan – Bilbao	13,853

Source: Dataloy (2021).

Distance breakdown for Ulsan – Bilbao pair on NSR at speed = 12 knots (7,834 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Ulsan – Cape Dezhnev	2,939
	HSFO*	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	HSFO	Cape Zhelanya – Bilbao	2,836
VLSFO	VLSFO	Ulsan – Cape Dezhnev	2,939
	VLSFO*	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	VLSFO	Cape Zhelanya – North Sea ECAs	1,854
	MGO**	North Sea ECAs – Bilbao	982
LNG-VLSFO 1,700 m^3	LNG	Ulsan – Cape Dezhnev	2,939
	LNG	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	LNG	Cape Zhelanya – Bilbao	2,836
LNG-VLSFO 3,600 m^3	LNG	Ulsan – Cape Dezhnev	2,939
	LNG	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	LNG	Cape Zhelanya – Bilbao	2,836

Source: Dataloy (2021). *The use of MGO through ice on NSR is assumed when considering a prohibition on the use of heavy fuel oils in the Arctic. **The North Sea ECAs can be avoided by navigating from Cape Zhelanya to Bilbao via the Irish Sea than through the North Sea and Dover Strait. This increases the competitiveness of the NSR voyage, given that the distance is slightly shorter and the lower-priced VLSFO is used instead of MGO. Here, it is assumed that the tanker arrives at Bilbao via the North Sea.

Distance for ballast voyage to a repair yard on either route for Chiba – Coryton pair (711 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Coryton – Lindo Havn	711
VLSFO	MGO	Coryton – Lindo Havn	630
LNG-VLSFO 1,700 m^3	LNG	Coryton – Lindo Havn	630
LNG-VLSFO 3,600 m^3	LNG	Coryton – Lindo Havn	630

Source: Dataloy (2021).

Distance for ballast voyage to a repair yard on either route for Ulsan – Rotterdam pair (630 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Rotterdam – Lindo Havn	630
VLSFO	MGO	Rotterdam – Lindo Havn	630
LNG-VLSFO 1,700 m^3	LNG	Rotterdam – Lindo Havn	630
LNG-VLSFO 3,600 m^3	LNG	Rotterdam – Lindo Havn	630

Source: Dataloy (2021).

Distance for ballast voyage to a repair yard on either route for Ulsan – Bilbao pair (1,353 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Bilbao – Lindo Havn	1,353
VLSFO	MGO	Bilbao – Lindo Havn	1,353
LNG-VLSFO 1,700 m^3	LNG	Bilbao – Lindo Havn	1,353
LNG-VLSFO 3,600 m^3	LNG	Bilbao – Lindo Havn	1,353

Source: Dataloy (2021).

Notes:

The total LNG voyage fuel consumption depends on distance, speed, and LNG tank capacity. These three factors determine LNG fuel consumption per distance leg, and result in different LNG/VLSFO distance ratios per OD pair.

For OD pairs via SCR or Cape, it is assumed that VLSFO is used in the first distance leg(s). Then, the engine switches to LNG on the remaining legs, as well as within ECAs. If the total LNG fuel quantity is sufficient for the whole voyage, then only the use of LNG is assumed for all distance legs.

For the Ulsan-Rotterdam pair via NSR, it is assumed that VLSFO is used in the first distance leg(s). Then, the engine switches to LNG on the next distance leg(s), through ice on NSR, and on the remaining distance leg(s), as well as within ECAs. If the total LNG fuel quantity is sufficient for the whole voyage, then only the use of LNG is assumed for all distance legs.

The total LNG fuel consumption and LNG/VLSFO distance ratio depend on the speed realised on open water when using LNG as a fuel, as well as the speed realised through ice on NSR when using LNG as a fuel. The optimal speed on open water when using LNG as a fuel is 16 knots across all fuel price scenarios. This is due to the relatively low LNG price assumed across all price scenarios, and the effect of in-transit inventory costs, all of which lead to increased optimal speeds. The speed on ice varies depending on local sea ice conditions, navigation zone and month (Appendices Y3, Y4). As a result, the only determining factor for the LNG/VLSFO distance ratio is the varying speed through ice on NSR. The use of HSFO and VLSFO is assumed in the respective operational modes for all distance legs and OD pairs, regardless of speeds, since the tank capacity of either fuel is sufficient for these fuels to be used for a whole voyage on either route.

Appendix U2. LNG/VLSFO distance ratios – Chapter 5 (Author's calculations)

LNG/VLSFO distance ratio per route alternative and OD pair for the 1,700 m^3 mode.

Route	Chiba – Coryton	Ulsan – Rotterdam	Ulsan – Bilbao
		Ratio	
		Optimal Speed	
Cape	53/47	54/46	56/44
SCR	69/31	71/29	75/25
NSR	89/11	97/3	89/11
		Speed = 12 knots	
Cape	81/19	83/17	86/14
SCR	100/0	100/0	100/0
NSR	100/0	100/0	100/0

LNG/VLSFO distance ratio per route alternative and OD pair for the 3,600 m^3 mode.

Route	Chiba – Coryton	Ulsan – Rotterdam	Ulsan – Bilbao
		Ratio	
		Optimal Speed	
Cape	97/3	99/1	100/0
SCR	100/0	100/0	100/0
NSR	100/0	100/0	100/0
		Speed = 12 knots	
Cape	100/0	100/0	100/0
SCR	100/0	100/0	100/0
NSR	100/0	100/0	100/0

Notes:

These LNG/VLSFO distance ratios are calculated based on distances from Appendix U1. The total LNG voyage fuel consumption depends on distance, speed, and LNG tank capacity. A fuel consumption margin of 15% is assumed when the LNG fuel quantity is sufficient to cover all distance legs of an OD pair. This implies that the maximum LNG fuel quantity which can be consumed is 85% of that loaded in the tank (SEA LNG 2020). On the other hand, almost all LNG fuel quantity is assumed to be used before switching to VLSFO, when VLSFO is also required on a number of distance legs for an OD pair. However, in practice a certain LNG fuel quantity needs to be retained in the tank as in the first case. Some of the reasons include potential issues with the strength of the LNG fuel tank when it undergoes through a cold-warm-cold cycle i.e. filled with LNG – getting empty – filled with LNG. Thus, a certain margin would also be appropriate in this case (MAN Energy Solutions 2021). Moreover, higher margins need to be assumed when considering other energy requirements e.g. fuel consumption for boilers, auxiliary engines.

The LNG/VLSFO ratios presented above are valid for all price scenarios under optimal speeds, since these are found 16 knots across all fuel price levels. This is due to the relatively low LNG price assumed across all price scenarios, and the effect of in-transit inventory costs, all of which lead to increased optimal speeds.

Appendix V. Cost analysis – Chapter 5

Total cost analysis in US$ per tonne for Chiba – Coryton pair on HSFO-Scrubber mode.

Optimal Speed																	
Scenario	Route	Speed	Time (days)	Fuel Cost*	Transit Fees**	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR*	Repairs	RFR incl. Repairs*	Discounted Fees	RFR incl. Discounted Fees*	RFR incl. Discounted Fees and Repairs*	No Fees	RFR incl. No Fees*	RFR incl. Repairs and No Fees*
Low	Cape	16.0	38	3.4		3.8	6.2	2.6	16.1								
Base		16.0	38	6.9		3.8	6.2	5.2	22.1								
High		15.2	40	9.4		4.0	6.6	8.2	28.1								
Low	SCR	16.0	29	2.6	4.0	3.1	4.8	2.0	16.5								
Base		16.0	29	5.3	4.0	3.1	4.8	4.0	21.1								
High		15.2	31	7.2	4.0	3.2	5.0	6.3	25.7								
Low	NSR	13.7	21	1.8/2.0	4.9	3.1	4.4	1.4	15.7/15.8	3.0	18.7/18.8	5.1	15.9/16.0	18.9/19.0	0.1	10.9/11.0	13.9/14.0
Base		13.5	21	3.5/3.8	5.6	3.1	4.5	2.9	19.6/19.9	3.2	22.8/23.1	5.1	19.1/19.4	22.3/22.6	0.1	14.1/14.4	17.3/17.6
High		12.8	23	4.5/5.0	10.8	3.2	4.7	4.6	27.8/28.3	3.3	31.1/31.6	5.1	22.2/22.7	25.5/26.0	0.1	17.2/17.7	20.5/21.0

*Differentials when MGO is not used/used through ice on NSR. **Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Speed = 12 knots																	
Scenario	Route	Speed	Time (days)	Fuel Cost*	Transit Fees**	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR*	Repairs	RFR incl. Repairs*	Discounted Fees	RFR incl. Discounted Fees*	RFR incl. Discounted Fees and Repairs*	No Fees	RFR incl. No Fees*	RFR incl. Repairs and No Fees*
Low	Cape	12.0	51	1.9		5.1	8.3	3.4	18.8								
Base		12.0	51	3.9		5.1	8.3	6.9	24.2								
High		12.0	51	5.8		5.1	8.3	10.4	29.6								
Low	SCR	12.0	39	1.5	4.0	4.0	6.4	2.6	18.5								
Base		12.0	39	3.0	4.0	4.0	6.4	5.3	22.7								
High		12.0	39	4.5	4.0	4.0	6.4	8.0	26.9								
Low	NSR	11.4	25	1.1/1.3	4.9	3.5	5.3	1.7	16.6/16.8	3.1	19.7/19.9	5.1	16.8/17.0	19.9/20.1	0.1	11.8/12.0	14.9/15.1
Base		11.4	25	2.3/2.6	5.6	3.5	5.3	3.4	20.1/20.5	3.2	23.4/23.7	5.1	19.7/20.0	22.9/23.2	0.1	14.7/15.0	17.9/18.2
High		11.4	25	3.4/3.9	10.8	3.5	5.3	5.1	28.1/28.6	3.3	31.4/31.9	5.1	22.5/23.0	25.8/26.3	0.1	17.5/18.0	20.8/21.3

*Differentials when MGO is not used/used through ice on NSR. **Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Total cost analysis in US$ per tonne for Ulsan – Rotterdam pair on HSFO-Scrubber mode.

Optimal Speed																	
Scenario	Route	Speed	Time (days)	Fuel Cost*	Transit Fees**	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR*	Repairs	RFR incl. Repairs*	Discounted Fees	RFR incl. Discounted Fees*	RFR incl. Discounted Fees and Repairs*	No Fees	RFR incl. No Fees*	RFR incl. Repairs and No Fees*
Low	Cape	16.0	37	3.4		3.7	6.1	2.5	15.7								
Base		16.0	37	6.7		3.7	6.1	5.1	21.6								
High		15.2	39	9.2		3.9	6.4	8.0	27.5								
Low	SCR	16.0	29	2.6	4.0	3.0	4.7	1.9	16.1								
Base		16.0	29	5.1	4.0	3.0	4.7	3.9	20.6								
High		15.2	30	7.0	4.0	3.1	4.9	6.1	25.1								
Low	NSR	13.8	22	1.9/2.0	4.9	3.1	4.5	1.4	15.9/16.1	2.9	18.9/19.0	5.1	16.1/16.3	19.1/19.2	0.1	11.1/11.3	14.1/14.2
Base		13.6	22	3.6/3.9	5.6	3.2	4.6	3.0	20.0/20.3	3.1	23.0/23.3	5.1	19.5/19.8	22.6/22.9	0.1	14.5/14.8	17.6/17.9
High		12.8	23	4.7/5.1	10.8	3.3	4.9	4.7	28.3/28.8	3.2	31.5/31.9	5.1	22.7/23.1	25.9/26.3	0.1	17.7/18.1	20.9/21.3

*Differentials when MGO is not used/used through ice on NSR. **Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Speed = 12 knots																	
Scenario	Route	Speed	Time (days)	Fuel Cost*	Transit Fees**	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR*	Repairs	RFR incl. Repairs*	Discounted Fees	RFR incl. Discounted Fees*	RFR incl. Discounted Fees and Repairs*	No Fees	RFR incl. No Fees*	RFR incl. Repairs and No Fees*
Low	Cape	12.0	50	1.9		5.0	8.1	3.3	18.4								
Base		12.0	50	3.8		5.0	8.1	6.7	23.7								
High		12.0	50	5.7		5.0	8.1	10.2	29.0								
Low	SCR	12.0	38	1.4	4.0	3.9	6.2	2.5	18.1								
Base		12.0	38	2.9	4.0	3.9	6.2	5.1	22.2								
High		12.0	38	4.3	4.0	3.9	6.2	7.7	26.2								
Low	NSR	11.5	26	1.2/1.3	4.9	3.6	5.5	1.7	16.9/17.1	3.0	19.9/20.1	5.1	17.1/17.3	20.2/20.3	0.1	12.1/12.3	15.2/15.3
Base		11.5	26	2.4/2.7	5.6	3.6	5.5	3.5	20.6/20.9	3.1	23.7/24.0	5.1	20.1/20.4	23.2/23.5	0.1	15.1/15.4	18.2/18.5
High		11.5	26	3.5/4.0	10.8	3.6	5.5	5.3	28.6/29.1	3.2	31.8/32.3	5.1	23.0/23.5	26.2/26.7	0.1	18.0/18.5	21.2/21.7

*Differentials when MGO is not used/used through ice on NSR. **Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Total cost analysis in US$ per tonne for Ulsan – Bilbao pair on HSFO-Scrubber mode.

Optimal Speed																	
Scenario	Route	Speed	Time (days)	Fuel Cost*	Transit Fees**	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR*	Repairs	RFR incl. Repairs*	Discounted Fees	RFR incl. Discounted Fees*	RFR incl. Discounted Fees and Repairs*	No Fees	RFR incl. No Fees*	RFR incl. Repairs and No Fees*
Low	Cape	16.0	36	3.3		3.6	5.9	2.4	15.2								
Base		16.0	36	6.5		3.6	5.9	4.9	20.9								
High		15.2	38	8.8		3.8	6.2	7.7	26.5								
Low	SCR	16.0	27	2.4	4.0	2.8	4.4	1.8	15.6								
Base		16.0	27	4.9	4.0	2.8	4.4	3.7	19.9								
High		15.2	29	6.7	4.0	3.0	4.7	5.8	24.1								
Low	NSR	14.0	23	2.1/2.3	4.9	3.3	4.9	1.6	16.9/17.0	3.7	20.5/20.7	5.1	17.1/17.2	20.8/20.9	0.1	12.1/12.2	15.8/15.9
Base		13.7	24	4.0/4.3	5.6	3.4	5.0	3.2	21.3/21.6	4.0	25.2/25.6	5.1	20.8/21.1	24.8/25.1	0.1	15.8/16.1	19.8/20.1
High		13	25	5.2/5.7	10.8	3.5	5.3	5.1	29.9/30.4	4.2	34.2/34.6	5.1	24.3/24.8	28.5/29.0	0.1	19.3/19.8	23.5/24.0

*Differentials when MGO is not used/used through ice on NSR. **Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Speed = 12 knots																	
Scenario	Route	Speed	Time (days)	Fuel Cost*	Transit Fees**	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR*	Repairs	RFR incl. Repairs*	Discounted Fees	RFR incl. Discounted Fees*	RFR incl. Discounted Fees and Repairs*	No Fees	RFR incl. No Fees*	RFR incl. Repairs and No Fees*
Low	Cape	12.0	48	1.8		4.8	7.8	3.2	17.7								
Base		12.0	48	3.7		4.8	7.8	6.5	22.8								
High		12.0	48	5.5		4.8	7.8	9.8	27.9								
Low	SCR	12.0	36	1.4	4.0	3.7	5.9	2.4	17.5								
Base		12.0	36	2.8	4.0	3.7	5.9	4.9	21.3								
High		12.0	36	4.1	4.0	3.7	5.9	7.4	25.2								
Low	NSR	11.5	28	1.3/1.5	4.9	3.9	6.0	1.9	18.0/18.1	3.9	21.9/22.1	5.1	18.2/18.3	22.1/22.3	0.1	13.2/13.3	17.1/17.3
Base		11.5	28	2.6/2.9	5.6	3.9	6.0	3.8	21.9/22.2	4.1	26.0/26.3	5.1	21.4/21.7	25.5/25.8	0.1	16.4/16.7	20.5/20.8
High		11.5	28	3.9/4.4	10.8	3.9	6.0	5.8	30.3/30.7	4.3	34.6/35.0	5.1	24.7/25.1	28.9/29.4	0.1	19.7/20.1	23.9/24.4

*Differentials when MGO is not used/used through ice on NSR. **Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Total cost analysis in US$ per tonne for Chiba – Coryton pair on VLSFO mode.

Optimal Speed																	
Scenario	Route	Speed	Time (days)	Fuel Cost*	Transit Fees**	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR*	Repairs	RFR incl. Repairs*	Discounted Fees	RFR incl. Discounted Fees*	RFR incl. Discounted Fees and Repairs*	No Fees	RFR incl. No Fees*	RFR incl. Repairs and No Fees*
Low	Cape	16.0	38	5.4		3.8	5.9	2.6	17.6								
Base		14.1	43	8.4		4.3	6.7	5.9	25.2								
High		13.0	47	10.7		4.7	7.2	9.6	32.2								
Low	SCR	16.0	29	4.1	4.0	3.1	4.5	2.0	17.7								
Base		14.1	33	6.4	4.0	3.4	5.1	4.5	23.5								
High		13.0	36	8.2	4.0	3.7	5.5	7.3	28.8								
Low	NSR	13.7	21	2.793/ 2.795	4.9	3.1	4.2	1.4	16.457/ 16.459	3.1	19.532/ 19.534	5.1	16.663/ 16.665	19.738/ 19.740	0.1	11.663/ 11.665	14.738/ 14.740
Base		12.3	23	4.186/ 4.190	5.6	3.3	4.7	3.2	21.050/ 21.055	3.3	24.340/ 24.345	5.1	20.565/ 20.570	23.855/ 23.860	0.1	15.565/ 15.570	18.855/ 18.860
High		11.6	25	5.477/ 5.483	10.8	3.5	5.0	5.1	29.778/ 29.784	3.4	33.218/ 33.225	5.1	24.162/ 24.169	27.603/ 27.609	0.1	19.162/ 19.169	22.603/ 22.609

*Differentials when MGO is not used/used through ice on NSR. **Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Speed = 12 knots																	
Scenario	Route	Speed	Time (days)	Fuel Cost*	Transit Fees**	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR*	Repairs	RFR incl. Repairs*	Discounted Fees	RFR incl. Discounted Fees*	RFR incl. Discounted Fees and Repairs*	No Fees	RFR incl. No Fees*	RFR incl. Repairs and No Fees*
Low	Cape	12.0	51	3.0		5.1	7.8	3.4	19.4								
Base		12.0	51	6.0		5.1	7.8	6.9	25.9								
High		12.0	51	9.1		5.1	7.8	10.4	32.4								
Low	SCR	12.0	39	2.3	4.0	4.0	6.0	2.6	19.0								
Base		12.0	39	4.6	4.0	4.0	6.0	5.3	24.0								
High		12.0	39	7.0	4.0	4.0	6.0	8.0	29.0								
Low	NSR	11.4	25	1.774/ 1776	4.9	3.5	5.0	1.7	16.975/ 16.977	3.2	20.126/ 20.128	5.1	17.181/ 17.184	20.332/ 20.334	0.1	12.181/ 12.184	15.332/ 15.334
Base		11.4	25	3.548/ 3553	5.6	3.5	5.0	3.4	21.159/ 21.163	3.3	24.456/ 24.460	5.1	20.674/ 20.678	23.971/ 23.976	0.1	15.674/ 15.678	18.971/ 18.976
High		11.4	25	5.322/ 5.329	10.8	3.5	5.0	5.1	29.782/ 29.789	3.4	33.226/ 33.232	5.1	24.167/ 24.173	27.610/ 27.617	0.1	19.167/ 19.173	22.610/ 22.617

*Differentials when MGO is not used/used through ice on NSR. **Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Total cost analysis in US$ per tonne for Ulsan – Rotterdam pair on VLSFO mode.

Optimal Speed																	
Scenario	Route	Speed	Time (days)	Fuel Cost*	Transit Fees**	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR*	Repairs	RFR incl. Repairs*	Discounted Fees	RFR incl. Discounted Fees*	RFR incl. Discounted Fees and Repairs*	No Fees	RFR incl. No Fees*	RFR incl. Repairs and No Fees*
Low	Cape	16.0	37	5.3		3.7	5.8	2.5	17.2								
Base		14.1	42	8.2		4.2	6.5	5.7	24.7								
High		13.0	46	10.5		4.6	7.1	9.3	31.5								
Low	SCR	16.0	29	4.0	4.0	3.0	4.4	1.9	17.3								
Base		14.1	32	6.3	4.0	3.3	5.0	4.4	22.9								
High		13.0	35	8.0	4.0	3.6	5.4	7.1	28.1								
Low	NSR	13.7	22	2.897/ 2899	4.9	3.1	4.3	1.4	16.768/ 16.771	3.0	19.750/ 19.752	5.1	16.975/ 16.977	19.956/ 19.958	0.1	11.975/ 11.977	14.956/ 14.958
Base		12.3	24	4.333/ 4.337	5.6	3.4	4.8	3.3	21.490/ 21.494	3.2	24.661/ 24.666	5.1	21.005/ 21.009	24.176/ 24.181	0.1	16.005/ 16.009	19.176/ 19.181
High		11.6	26	5.662/ 5.668	10.8	3.6	5.1	5.2	30.332/ 30.338	3.3	33.637/ 33.643	5.1	24.716/ 24.723	28.021/ 28.028	0.1	19.716/ 19.723	23.021/ 23.028

*Differentials when MGO is not used/used through ice on NSR. **Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Speed = 12 knots																	
Scenario	Route	Speed	Time (days)	Fuel Cost*	Transit Fees**	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR*	Repairs	RFR incl. Repairs*	Discounted Fees	RFR incl. Discounted Fees*	RFR incl. Discounted Fees and Repairs*	No Fees	RFR incl. No Fees*	RFR incl. Repairs and No Fees*
Low	Cape	12.0	50	3.0		5.0	7.7	3.3	18.9								
Base		12.0	50	5.9		5.0	7.7	6.7	25.3								
High		12.0	50	8.9		5.0	7.7	10.2	31.7								
Low	SCR	12.0	38	2.3	4.0	3.9	5.8	2.5	18.6								
Base		12.0	38	4.5	4.0	3.9	5.8	5.1	23.4								
High		12.0	38	6.8	4.0	3.9	5.8	7.7	28.3								
Low	NSR	11.5	26	1.833/ 1.836	4.9	3.6	5.2	1.7	17.310/ 17.312	3.0	20.358/ 20.360	5.1	17.516/ 17.518	20.564/ 20.566	0.1	12.516/ 12.518	15.564/ 15.566
Base		11.5	26	3.667/ 3.671	5.6	3.6	5.2	3.5	21.603/ 21.608	3.2	24.781/ 24.786	5.1	21.119/ 21.123	24.296/ 24.301	0.1	16.119/ 16.123	19.296/ 19.301
High		11.5	26	5.500/ 5.507	10.8	3.6	5.2	5.3	30.336/ 30.343	3.3	33.644/ 33.650	5.1	24.721/ 24.727	28.029/ 28.035	0.1	19.721/ 19.727	23.029/ 23.035

*Differentials when MGO is not used/used through ice on NSR. **Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Total cost analysis in US$ per tonne for Ulsan – Bilbao pair on VLSFO mode.

Optimal Speed																	
Scenario	Route	Speed	Time (days)	Fuel Cost*	Transit Fees**	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR*	Repairs	RFR incl. Repairs*	Discounted Fees	RFR incl. Discounted Fees*	RFR incl. Discounted Fees and Repairs*	No Fees	RFR incl. No Fees*	RFR incl. Repairs and No Fees*
Low	Cape	16.0	36	5.1		3.6	5.5	2.4	16.6								
Base		14.1	41	7.9		4.1	6.3	5.5	23.8								
High		13.0	44	10.1		4.4	6.8	9.0	30.3								
Low	SCR	16.0	27	3.8	4.0	2.8	4.2	1.8	16.7								
Base		14.1	31	6.0	4.0	3.2	4.7	4.2	22.1								
High		13.0	33	7.6	4.0	3.5	5.1	6.8	27.0								
Low	NSR	13.9	23	3.243/ 3.245	4.9	3.3	4.7	1.6	17.805/ 17.807	3.8	21.626/ 21.628	5.1	18.011/ 18.013	21.832/ 21.834	0.1	13.011/ 13.013	16.832/ 16.834
Base		12.4	26	4.819/ 4.824	5.6	3.6	5.3	3.6	22.951/ 22.955	4.2	27.179/ 27.183	5.1	22.466/ 22.470	26.694/ 26.698	0.1	17.466/ 17.040	21.694/ 21.698
High		11.7	28	6.275/ 6.282	10.8	3.8	5.6	5.7	32.172/ 32.179	4.5	36.687/ 36.693	5.1	26.557/ 26.563	31.071/ 31.078	0.1	21.557/ 21.563	26.071/ 26.078

*Differentials when MGO is not used/used through ice on NSR. **Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Speed = 12 knots																	
Scenario	Route	Speed	Time (days)	Fuel Cost*	Transit Fees**	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR*	Repairs	RFR incl. Repairs*	Discounted Fees	RFR incl. Discounted Fees*	RFR incl. Discounted Fees and Repairs*	No Fees	RFR incl. No Fees*	RFR incl. Repairs and No Fees*
Low	Cape	12.0	48	2.9		4.8	7.4	3.2	18.3								
Base		12.0	48	5.7		4.8	7.4	6.5	24.4								
High		12.0	48	8.6		4.8	7.4	9.8	30.5								
Low	SCR	12.0	36	2.1	4.0	3.7	5.6	2.4	17.9								
Base		12.0	36	4.3	4.0	3.7	5.6	4.9	22.5								
High		12.0	36	6.4	4.0	3.7	5.6	7.4	27.1								
Low	NSR	11.5	28	2.031/ 2033	4.9	3.9	5.7	1.9	18.422/ 18.424	4.0	22.385/ 22.387	5.1	18.628/ 18.630	22.591/ 22.594	0.1	13.628/ 13.630	17.591/ 17.594
Base		11.5	28	4.061/ 4.066	5.6	3.9	5.7	3.8	23.080/ 23.084	4.2	27.322/ 27.326	5.1	22.595/ 22.599	26.837/ 26.841	0.1	17.595/ 17.599	21.837/ 21.841
High		11.5	28	6.092/ 6.098	10.8	3.9	5.7	5.8	32.178/ 32.184	4.5	36.698/ 36.704	5.1	26.562/ 26.569	31.082/ 31.089	0.1	21.562/ 21.569	26.082/ 26.089

*Differentials when MGO is not used/used through ice on NSR. **Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Total cost analysis in US$ per tonne for Chiba – Coryton pair on LNG-VLSFO 1,600 m^3 mode.

Optimal Speed																	
Scenario	Route	Speed	Time (days)	Fuel Cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Repairs	RFR incl. Repairs	Discounted Fees	RFR incl. Discounted Fees	RFR incl. Discounted Fees and Repairs	No Fees	RFR incl. No Fees	RFR incl. Repairs and No Fees
Low	Cape	16.0	38	4.1		3.8	6.1	2.6	16.6								
Base		15.1	41	6.5		4.1	6.5	5.5	22.6								
High		14.4	42	8.6		4.2	6.8	8.6	28.3								
Low	SCR	16.0	29	2.8	4.0	3.1	4.7	2.0	16.5								
Base		15.4	31	4.5	4.0	3.2	4.9	4.1	20.7								
High		14.9	31	6.1	4.0	3.3	5.0	6.4	24.8								
Low	NSR	13.7	21	1.7	4.9	3.1	4.3	1.4	15.4	3.0	18.4	5.2	15.6	18.6	0.2	10.6	13.6
Base		13.5	21	2.7	5.6	3.1	4.4	2.9	18.7	3.1	21.8	5.2	18.3	21.3	0.2	13.3	16.3
High		13.3	22	3.7	10.8	3.1	4.5	4.4	26.4	3.1	29.6	5.2	20.8	24.0	0.2	15.8	19.0

*Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Speed = 12 knots																	
Scenario	Route	Speed	Time (days)	Fuel Cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Repairs	RFR incl. Repairs	Discounted Fees	RFR incl. Discounted Fees	RFR incl. Discounted Fees and Repairs	No Fees	RFR incl. No Fees	RFR incl. Repairs and No Fees
Low	Cape	12.0	51	1.9		5.1	8.2	3.4	18.6								
Base		12.0	51	3.3		5.1	8.2	6.9	23.5								
High		12.0	51	4.8		5.1	8.2	10.4	28.4								
Low	SCR	12.0	39	1.2	4.0	4.0	6.3	2.6	18.2								
Base		12.0	39	2.0	4.0	4.0	6.3	5.3	21.6								
High		12.0	39	2.9	4.0	4.0	6.3	8.0	25.1								
Low	NSR	11.4	25	0.9	4.9	3.5	5.2	1.7	16.3	3.1	19.4	5.2	16.5	19.6	0.2	11.5	14.6
Base		11.4	25	1.5	5.6	3.5	5.2	3.4	19.3	3.1	22.5	5.2	18.8	22.0	0.2	13.8	17.0
High		11.4	25	2.2	10.8	3.5	5.2	5.1	26.8	3.2	30.0	5.2	21.2	24.4	0.2	16.2	19.4

*Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Total cost analysis in US$ per tonne for Ulsan – Rotterdam pair on LNG-VLSFO 1,600 m^3 mode.

Optimal Speed																	
Scenario	Route	Speed	Time (days)	Fuel Cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Repairs	RFR incl. Repairs	Discounted Fees	RFR incl. Discounted Fees	RFR incl. Discounted Fees and Repairs	No Fees	RFR incl. No Fees	RFR incl. Repairs and No Fees
Low	Cape	16.0	37	4.0		3.7	6.0	2.5	16.2								
Base		15.1	40	6.3		4.0	6.4	5.4	22.0								
High		14.5	41	8.4		4.1	6.6	8.4	27.6								
Low	SCR	16.0	29	2.7	4.0	3.0	4.6	1.9	16.1								
Base		15.4	30	4.3	4.0	3.1	4.7	4.0	20.2								
High		15.0	30	5.8	4.0	3.2	4.9	6.2	24.1								
Low	NSR	13.8	22	1.6	4.9	3.1	4.5	1.4	15.6	2.9	18.4	5.2	15.8	18.6	0.2	10.8	13.6
Base		13.7	22	2.6	5.6	3.1	4.5	2.9	18.8	3.0	21.8	5.2	18.3	21.3	0.2	13.3	16.3
High		13.7	22	3.6	10.8	3.2	4.5	4.4	26.5	3.0	29.5	5.2	20.8	23.9	0.2	15.8	18.9

*Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Speed = 12 knots																	
Scenario	Route	Speed	Time (days)	Fuel Cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Repairs	RFR incl. Repairs	Discounted Fees	RFR incl. Discounted Fees	RFR incl. Discounted Fees and Repairs	No Fees	RFR incl. No Fees	RFR incl. Repairs and No Fees
Low	Cape	12.0	50	1.8		5.0	8.0	3.3	18.1								
Base		12.0	50	3.2		5.0	8.0	6.7	22.9								
High		12.0	50	4.6		5.0	8.0	10.2	27.7								
Low	SCR	12.0	38	1.2	4.0	3.9	6.1	2.5	17.8								
Base		12.0	38	2.0	4.0	3.9	6.1	5.1	21.1								
High		12.0	38	2.8	4.0	3.9	6.1	7.7	24.5								
Low	NSR	11.5	26	1.0	4.9	3.6	5.4	1.7	16.6	3.0	19.6	5.2	16.8	19.8	0.2	11.8	14.8
Base		11.5	26	1.6	5.6	3.6	5.4	3.5	19.7	3.0	22.8	5.2	19.2	22.3	0.2	14.2	17.3
High		11.5	26	2.2	10.8	3.6	5.4	5.3	27.3	3.1	30.3	5.2	21.6	24.7	0.2	16.6	19.7

*Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Total cost analysis in US$ per tonne for Ulsan – Bilbao pair on LNG-VLSFO 1,600 m^3 mode.

Optimal Speed																	
Scenario	Route	Speed	Time (days)	Fuel Cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Repairs	RFR incl. Repairs	Discounted Fees	RFR incl. Discounted Fees	RFR incl. Discounted Fees and Repairs	No Fees	RFR incl. No Fees	RFR incl. Repairs and No Fees
Low	Cape	16.0	36	3.8		3.6	5.8	2.4	15.6								
Base		15.1	38	6.0		3.8	6.1	5.2	21.1								
High		14.5	40	8.0		4.0	6.4	8.1	26.4								
Low	SCR	16.0	27	2.5	4.0	2.8	4.4	1.8	15.5								
Base		15.5	28	4.0	4.0	2.9	4.5	3.8	19.3								
High		15.1	29	5.5	4.0	3.0	4.6	5.9	23.0								
Low	NSR	14.0	23	1.9	4.9	3.3	4.8	1.6	16.6	3.6	20.2	5.2	16.8	20.4	0.2	11.8	15.4
Base		13.7	24	3.1	5.6	3.4	4.9	3.2	20.3	3.8	24.1	5.2	19.8	23.6	0.2	14.8	18.6
High		13.5	24	4.3	10.8	3.4	5.0	4.9	28.3	4.0	32.3	5.2	22.7	26.7	0.2	17.7	21.7

*Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Speed = 12 knots																	
Scenario	Route	Speed	Time (days)	Fuel Cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Repairs	RFR incl. Repairs	Discounted Fees	RFR incl. Discounted Fees	RFR incl. Discounted Fees and Repairs	No Fees	RFR incl. No Fees	RFR incl. Repairs and No Fees
Low	Cape	12.0	48	1.7		4.8	7.7	3.2	17.4								
Base		12.0	48	3.0		4.8	7.7	6.5	22.0								
High		12.0	48	4.2		4.8	7.7	9.8	26.5								
Low	SCR	12.0	36	1.1	4.0	3.7	5.8	2.4	17.1								
Base		12.0	36	1.9	4.0	3.7	5.8	4.9	20.4								
High		12.0	36	2.6	4.0	3.7	5.8	7.4	23.6								
Low	NSR	11.5	28	1.1	4.9	3.9	5.9	1.9	17.6	3.9	21.5	5.2	17.8	21.7	0.2	12.8	16.7
Base		11.5	28	1.8	5.6	3.9	5.9	3.8	21.0	4.0	24.9	5.2	20.5	24.5	0.2	15.5	19.5
High		11.5	28	2.5	10.8	3.9	5.9	5.8	28.8	4.1	32.8	5.2	23.1	27.2	0.2	18.1	22.2

*Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Total cost analysis in US$ per tonne for Chiba – Coryton pair on LNG-VLSFO 3,700 m^3 mode.

Optimal Speed																	
Scenario	Route	Speed	Time (days)	Fuel Cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Repairs	RFR incl. Repairs	Discounted Fees	RFR incl. Discounted Fees	RFR incl. Discounted Fees and Repairs	No Fees	RFR incl. No Fees	RFR incl. Repairs and No Fees
Low	Cape	16.0	38	2.9		3.8	6.6	2.6	15.8								
Base		15.9	38	4.8		3.8	6.6	5.2	20.5								
High		15.9	39	6.8		3.8	6.6	7.8	25.1								
Low	SCR	16.0	29	2.2	4.0	3.1	5.0	2.0	16.2								
Base		16.0	29	3.6	4.0	3.1	5.0	4.0	19.7								
High		16.0	29	5.1	4.0	3.1	5.0	6.0	23.2								
Low	NSR	13.7	21	1.5	4.9	3.1	4.7	1.4	15.6	3.0	18.6	5.2	15.8	18.8	0.2	10.8	13.8
Base		13.7	21	2.5	5.6	3.1	4.7	2.8	18.7	3.1	21.8	5.2	18.2	21.3	0.2	13.2	16.3
High		13.7	21	3.5	10.8	3.1	4.7	4.3	26.3	3.1	29.4	5.2	20.7	23.8	0.2	15.7	18.8

*Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Speed = 12 knots																	
Scenario	Route	Speed	Time (days)	Fuel Cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Repairs	RFR incl. Repairs	Discounted Fees	RFR incl. Discounted Fees	RFR incl. Discounted Fees and Repairs	No Fees	RFR incl. No Fees	RFR incl. Repairs and No Fees
Low	Cape	12.0	51	1.6		5.1	8.8	3.4	18.8								
Base		12.0	51	2.7		5.1	8.8	6.9	23.4								
High		12.0	51	3.7		5.1	8.8	10.4	28.0								
Low	SCR	12.0	39	1.2	4.0	4.0	6.7	2.6	18.6								
Base		12.0	39	2.0	4.0	4.0	6.7	5.3	22.1								
High		12.0	39	2.9	4.0	4.0	6.7	8.0	25.6								
Low	NSR	11.4	25	0.9	4.9	3.5	5.6	1.7	16.7	3.1	19.8	5.2	16.9	20.0	0.2	11.9	15.0
Base		11.4	25	1.5	5.6	3.5	5.6	3.4	19.8	3.1	22.9	5.2	19.3	22.4	0.2	14.3	17.4
High		11.4	25	2.2	10.8	3.5	5.6	5.1	27.2	3.2	30.4	5.2	21.6	24.8	0.2	16.6	19.8

*Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Total cost analysis in US$ per tonne for Ulsan – Rotterdam pair on LNG-VLSFO 3,700 m^3 mode.

Optimal Speed																	
Scenario	Route	Speed	Time (days)	Fuel Cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Repairs	RFR incl. Repairs	Discounted Fees	RFR incl. Discounted Fees	RFR incl. Discounted Fees and Repairs	No Fees	RFR incl. No Fees	RFR incl. Repairs and No Fees
Low	Cape	16.0	37	2.8		3.7	6.4	2.5	15.4								
Base		16.0	37	4.6		3.7	6.4	5.1	19.9								
High		16.0	38	6.5		3.7	6.4	7.6	24.3								
Low	SCR	16.0	29	2.1	4.0	3.0	4.9	1.9	15.9								
Base		16.0	29	3.5	4.0	3.0	4.9	3.9	19.2								
High		16.0	29	4.9	4.0	3.0	4.9	5.8	22.6								
Low	NSR	13.8	22	1.5	4.9	3.1	4.8	1.4	15.9	2.9	18.8	5.2	16.1	19.0	0.2	11.1	14.0
Base		13.8	22	2.6	5.6	3.1	4.8	2.9	19.1	3.0	22.0	5.2	18.6	21.5	0.2	13.6	16.5
High		13.8	22	3.6	10.8	3.1	4.8	4.4	26.7	3.0	29.7	5.2	21.1	24.1	0.2	16.1	19.1

*Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Speed = 12 knots																	
Scenario	Route	Speed	Time (days)	Fuel Cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Repairs	RFR incl. Repairs	Discounted Fees	RFR incl. Discounted Fees	RFR incl. Discounted Fees and Repairs	No Fees	RFR incl. No Fees	RFR incl. Repairs and No Fees
Low	Cape	12.0	50	1.5		5.0	8.6	3.3	18.4								
Base		12.0	50	2.6		5.0	8.6	6.7	22.9								
High		12.0	50	3.6		5.0	8.6	10.2	27.3								
Low	SCR	12.0	38	1.2	4.0	3.9	6.5	2.5	18.2								
Base		12.0	38	2.0	4.0	3.9	6.5	5.1	21.6								
High		12.0	38	2.8	4.0	3.9	6.5	7.7	25.0								
Low	NSR	11.5	26	1.0	4.9	3.6	5.8	1.7	17.0	3.0	20.0	5.2	17.2	20.2	0.2	12.2	15.2
Base		11.5	26	1.6	5.6	3.6	5.8	3.5	20.1	3.0	23.2	5.2	19.7	22.7	0.2	14.7	17.7
High		11.5	26	2.2	10.8	3.6	5.8	5.3	27.7	3.1	30.8	5.2	22.1	25.2	0.2	17.1	20.2

*Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Total cost analysis in US$ per tonne for Ulsan – Bilbao pair on LNG-VLSFO 3,700 m^3 mode.

Optimal Speed																	
Scenario	Route	Speed	Time (days)	Fuel Cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Repairs	RFR incl. Repairs	Discounted Fees	RFR incl. Discounted Fees	RFR incl. Discounted Fees and Repairs	No Fees	RFR incl. No Fees	RFR incl. Repairs and No Fees
Low	Cape	16.0	36	2.6		3.6	6.2	2.4	14.9								
Base		16.0	36	4.4		3.6	6.2	4.9	19.1								
High		16.0	36	6.2		3.6	6.2	7.3	23.4								
Low	SCR	16.0	27	2.0	4.0	2.8	4.7	1.8	15.3								
Base		16.0	27	3.3	4.0	2.8	4.7	3.7	18.5								
High		16.0	27	4.7	4.0	2.8	4.7	5.5	21.8								
Low	NSR	14.0	23	1.7	4.9	3.3	5.2	1.6	16.8	3.6	20.4	5.2	17.0	20.6	0.2	12.0	15.6
Base		14.0	23	2.9	5.6	3.3	5.2	3.2	20.2	3.8	24.0	5.2	19.7	23.5	0.2	14.7	18.5
High		14.0	23	4.0	10.8	3.3	5.2	4.8	28.1	4.0	32.1	5.2	22.5	26.4	0.2	17.5	21.4

*Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Speed = 12 knots																	
Scenario	Route	Speed	Time (days)	Fuel Cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Repairs	RFR incl. Repairs	Discounted Fees	RFR incl. Discounted Fees	RFR incl. Discounted Fees and Repairs	No Fees	RFR incl. No Fees	RFR incl. Repairs and No Fees
Low	Cape	12.0	48	1.5		4.8	8.3	3.2	17.8								
Base		12.0	48	2.5		4.8	8.3	6.5	22.1								
High		12.0	48	3.5		4.8	8.3	9.8	26.4								
Low	SCR	12.0	36	1.1	4.0	3.7	6.2	2.4	17.5								
Base		12.0	36	1.9	4.0	3.7	6.2	4.9	20.8								
High		12.0	36	2.6	4.0	3.7	6.2	7.4	24.0								
Low	NSR	11.5	28	1.1	4.9	3.9	6.4	1.9	18.1	3.9	22.0	5.2	18.3	22.2	0.2	13.3	17.2
Base		11.5	28	1.8	5.6	3.9	6.4	3.8	21.5	4.0	25.4	5.2	21.0	24.9	0.2	16.0	19.9
High		11.5	28	2.5	10.8	3.9	6.4	5.8	29.2	4.1	33.3	5.2	23.6	27.7	0.2	18.6	22.7

*Transit fees refer to Suez Canal Tolls or Official Icebreaking fees and relevant costs.

Total cost analysis for a ballast voyage from the port of Coryton to a repair yard at Odense, Denmark, in US$ per tonne.

Optimal Speed								
Scenario	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
HSFO-Scrubber								
Low	16.0	2	0.2	0.2	0.4	0.8	2.3	3.0
Base	15.3	2	0.3	0.2	0.4	0.9	2.3	3.2
High	13.4	2	0.3	0.2	0.5	1.0	2.3	3.3
VLSFO								
Low	16.0	2	0.3	0.2	0.4	0.8	2.3	3.1
Base	13.1	2	0.3	0.2	0.5	1.0	2.3	3.3
High	11.4	3	0.4	0.3	0.5	1.2	2.3	3.4
LNG-VLSFO 1,600 m^3 and LNG-VLSFO 3,700 m^3								
Low	16.0	2	0.1	0.2	0.4	0.7	2.3	3.0
Base	16.0	2	0.2	0.2	0.4	0.8	2.3	3.1
High	15.5	2	0.3	0.2	0.4	0.9	2.3	3.1

Speed = 12 knots								
Scenario	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
HSFO-Scrubber								
Low	12.0	2	0.1	0.3	0.5	0.9	2.3	3.1
Base	12.0	2	0.2	0.3	0.5	1.0	2.3	3.2
High	12.0	2	0.3	0.3	0.5	1.1	2.3	3.3
VLSFO								
Low	12.0	2	0.1	0.3	0.5	0.9	2.3	3.2
Base	12.0	2	0.3	0.3	0.5	1.0	2.3	3.3
High	12.0	2	0.4	0.3	0.5	1.2	2.3	3.4
LNG-VLSFO 1,600 m^3 and LNG-VLSFO 3,700 m^3								
Low	12.0	2	0.1	0.3	0.5	0.8	2.3	3.1
Base	12.0	2	0.1	0.3	0.5	0.9	2.3	3.1
High	12.0	2	0.2	0.3	0.5	0.9	2.3	3.2

Total cost analysis for a ballast voyage from the port of Rotterdam to a repair yard at Odense, Denmark, in US$ per tonne.

Optimal Speed								
Scenario	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
HSFO-Scrubber								
Low	16.0	2	0.1	0.2	0.3	0.7	2.3	2.9
Base	15.3	2	0.3	0.2	0.4	0.8	2.3	3.1
High	13.4	2	0.3	0.2	0.4	0.9	2.3	3.2
VLSFO								
Low	16.0	2	0.2	0.2	0.3	0.7	2.3	3.0
Base	13.1	2	0.3	0.2	0.4	0.9	2.3	3.2
High	11.4	2	0.4	0.2	0.5	1.1	2.3	3.3
LNG-VLSFO 1,600 m^3 and LNG-VLSFO 3,700 m^3								
Low	16.0	2	0.1	0.2	0.3	0.6	2.3	2.9
Base	16.0	2	0.2	0.2	0.3	0.7	2.3	3.0
High	15.5	2	0.3	0.2	0.4	0.8	2.3	3.0

Speed = 12 knots								
Scenario	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
HSFO-Scrubber								
Low	12.0	2	0.1	0.2	0.5	0.8	2.3	3.0
Base	12.0	2	0.2	0.2	0.5	0.9	2.3	3.1
High	12.0	2	0.2	0.2	0.5	0.9	2.3	3.2
VLSFO								
Low	12.0	2	0.1	0.2	0.4	0.8	2.3	3.0
Base	12.0	2	0.3	0.2	0.4	0.9	2.3	3.2
High	12.0	2	0.4	0.2	0.4	1.1	2.3	3.3
LNG-VLSFO 1,600 m^3 and LNG-VLSFO 3,700 m^3								
Low	12.0	2	0.1	0.2	0.5	0.7	2.3	3.0
Base	12.0	2	0.1	0.2	0.5	0.8	2.3	3.0
High	12.0	2	0.2	0.2	0.5	0.8	2.3	3.1

Total cost analysis for a ballast voyage from the port of Bilbao to a repair yard at Odense, Denmark, in US$ per tonne.

Optimal Speed								
Scenario	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
HSFO-Scrubber								
Low	16.0	4	0.3	0.4	0.7	1.4	2.3	3.7
Base	15.3	4	0.6	0.4	0.8	1.7	2.3	4.0
High	13.4	4	0.7	0.4	0.9	2.0	2.3	4.2
VLSFO								
Low	16.0	1	0.5	0.4	0.7	1.6	2.3	3.8
Base	13.1	1	0.7	0.5	0.9	2.0	2.3	4.2
High	11.4	1	0.8	0.5	1.0	2.3	2.3	4.5
LNG-VLSFO 1,600 m^3 and LNG-VLSFO 3,700 m^3								
Low	16.0	4	0.3	0.4	0.7	1.4	2.3	3.6
Base	16.0	4	0.4	0.4	0.7	1.5	2.3	3.8
High	15.5	4	0.6	0.4	0.8	1.7	2.3	4.0

Speed = 12 knots								
Scenario	Speed (knots)	Time (days)	Fuel Cost	Operating cost	Capital cost	RFR	Repairs	Total Repairs
HSFO-Scrubber								
Low	12.0	5	0.2	0.5	1.0	1.7	2.3	3.9
Base	12.0	5	0.4	0.5	1.0	1.8	2.3	4.1
High	12.0	5	0.5	0.5	1.0	2.0	2.3	4.3
VLSFO								
Low	12.0	1	0.3	0.5	0.9	1.7	2.3	4.0
Base	12.0	1	0.6	0.5	0.9	2.0	2.3	4.2
High	12.0	1	0.8	0.5	0.9	2.3	2.3	4.5
LNG-VLSFO 1,600 m^3 and LNG-VLSFO 3,700 m^3								
Low	12.0	5	0.1	0.5	1.0	1.6	2.3	3.9
Base	12.0	5	0.2	0.5	1.0	1.7	2.3	4.0
High	12.0	5	0.3	0.5	1.0	1.8	2.3	4.1

Sensitivity analysis results for HSFO-Scrubber mode.*

ΔRFR	HSFO-Scrubber		MGO on NSR		HSFO-Scrubber			MGO on NSR			HSFO-Scrubber			MGO on NSR		
	Low Fuel - Jet/Gasoil Prices – High USD/RUB rate				Base Case						High Fuel - Jet/Gasoil Prices – Low USD/RUB rate					
	Official Fees	Independent Navigation	Official Fees	Independent Navigation	Official Fees	Discounted Fees	Independent Navigation	Official Fees	Discounted Fees	Independent Navigation	Official Fees	Discounted Fees	Independent Navigation	Official Fees	Discounted Fees	Independent Navigation
Chiba – Coryton																
Optimal Speed																
SCR-NSR	0.8	5.6	0.7	5.5	1.5	2.0	7.0	1.2	1.7	6.7	-2.1	3.5	8.5	-2.6	3.0	8.0
	(-2.2)	(2.6)	(-2.3)	(2.4)	(-1.6)	(-1.2)	(3.8)	(-1.9)	(-1.5)	(3.5)	(-5.4)	(0.2)	(5.2)	(-5.9)	(-0.3)	(4.7)
Cape-NSR	0.4	5.2	0.3	5.1	2.5	3.0	8.0	2.2	2.7	7.7	0.3	5.9	10.9	-0.2	5.5	10.5
	(-2.6)	(2.2)	(-2.7)	(2.1)	(-0.6)	(-0.1)	(4.9)	(-0.9)	(-0.4)	(4.6)	(-3.0)	(2.6)	(7.6)	(-3.5)	(2.2)	(7.2)
SCR-Cape	0.4		0.4		-1.0			-1.0			-2.4			-2.4		
12 knots																
SCR-NSR	1.9	6.7	1.8	6.6	2.5	3.0	8.0	2.2	2.7	7.7	-1.3	4.3	9.3	-1.7	3.9	8.9
	(-1.2)	(3.6)	(-1.3)	(3.5)	(-0.7)	(-0.2)	(4.8)	(-1.0)	(-0.5)	(4.5)	(-4.6)	(1.0)	(6.0)	(-5.1)	(0.6)	(5.6)
Cape-NSR	2.2	7.0	2.0	6.8	4.0	4.5	9.5	3.7	4.2	9.2	1.5	7.1	12.1	1.0	6.6	11.6
	(-0.9)	(3.8)	(-1.1)	(3.7)	(0.8)	(1.3)	(6.3)	(0.5)	(1.0)	(6.0)	(-1.8)	(3.8)	(8.8)	(-2.3)	(3.3)	(8.3)
SCR-Cape	-0.2		-0.2		-1.5			-1.5			-2.8			-2.8		
Ulsan – Rotterdam																
Optimal Speed																
SCR-NSR	0.2	5.0	0.0	4.8	0.7	1.1	6.1	0.4	0.8	5.8	-3.2	2.4	7.4	-3.7	1.9	6.9
	(-2.7)	(2.1)	(-2.9)	(1.9)	(-2.4)	(-1.9)	(3.1)	(-2.7)	(-2.2)	(2.8)	(-6.4)	(-0.8)	(4.2)	(-6.8)	(-1.2)	(3.8)
Cape-NSR	-0.2	4.6	-0.4	4.4	1.7	2.2	7.2	1.4	1.8	6.8	-0.8	4.8	9.8	-1.3	4.4	9.4
	(-3.1)	(1.7)	(-3.3)	(1.5)	(-1.4)	(-0.9)	(4.1)	(-1.7)	(-1.2)	(3.8)	(-4.0)	(1.6)	(6.6)	(-4.4)	(1.2)	(6.2)
SCR-Cape	0.4		0.4		-1.0			-1.0			-2.4			-2.4		
12 knots																
SCR-NSR	1.2	6.0	1.1	5.9	1.6	2.1	7.1	1.3	1.8	6.8	-2.4	3.2	8.2	-2.9	2.7	7.7
	(-1.8)	(3.0)	(-2.0)	(2.8)	(-1.5)	(-1.0)	(4.0)	(-1.8)	(-1.3)	(3.7)	(-5.6)	(0.0)	(5.0)	(-6.1)	(-0.5)	(4.5)
Cape-NSR	1.4	6.2	1.3	6.1	3.1	3.6	8.6	2.8	3.3	8.3	0.3	5.9	10.9	-0.1	5.5	10.5
	(-1.6)	(3.2)	(-1.7)	(3.1)	(0.0)	(0.5)	(5.5)	(-0.3)	(0.2)	(5.2)	(-2.9)	(2.8)	(7.8)	(-3.3)	(2.3)	(7.3)
SCR-Cape	-0.2		-0.2		-1.5			-1.5			-2.8			-2.8		
Ulsan – Bilbao																
Optimal Speed																
SCR-NSR	-1.3	3.5	-1.5	3.3	-1.4	-0.9	4.1	-1.7	-1.2	3.8	-5.8	-0.2	4.8	-6.2	-0.6	4.4
	(-5.0)	(-0.2)	(-5.1)	(-0.3)	(-5.4)	(-4.9)	(0.1)	(-5.7)	(-5.2)	(-0.2)	(-10.0)	(-4.4)	(0.6)	(-10.5)	(-4.9)	(0.1)
Cape-NSR	-1.7	3.1	-1.9	2.9	-0.4	0.1	5.1	-0.7	-0.2	4.8	-3.4	2.2	7.2	-3.9	1.8	6.8
	(-5.4)	(-0.6)	(-5.6)	(-0.8)	(-4.4)	(-3.9)	(1.1)	(-4.7)	(-4.2)	(0.8)	(-7.6)	(-2.0)	(3.0)	(-8.1)	(-2.5)	(2.5)
SCR-Cape	0.4		0.4		-1.0			-1.0			-2.4			-2.4		
12 knots																
SCR-NSR	-0.5	4.3	-0.7	4.1	-0.6	-0.1	4.9	-0.9	-0.4	4.6	-5.1	0.5	5.5	-5.6	0.1	5.1
	(-4.4)	(0.4)	(-4.6)	(0.2)	(-4.7)	(-4.2)	(0.8)	(-5.0)	(-4.5)	(0.5)	(-9.4)	(-3.8)	(1.2)	(-9.8)	(-4.2)	(0.8)
Cape-NSR	-0.3	4.5	-0.4	4.4	0.9	1.4	6.4	0.6	1.1	6.1	-2.4	3.2	8.2	-2.8	2.8	7.8
	(-4.2)	(0.6)	(-4.4)	(0.4)	(-3.2)	(-2.7)	(2.3)	(-3.5)	(-3.0)	(2.0)	(-6.6)	(-1.0)	(4.0)	(-7.1)	(-1.5)	(3.5)
SCR-Cape	-0.2		-0.2		-1.5			-1.5			-2.7			-2.7		

*RFR Differentials in parentheses refer to results when ice damage repairs are factored in the analysis. MGO on NSR refer to the use of MGO through ice on NSR.

Sensitivity analysis results for VLSFO mode.*

ΔRFR	VLSFO		MGO on NSR		VLSFO			MGO on NSR			VLSFO			MGO on NSR		
	Low Fuel - Jet/Gasoil Prices – High USD/RUB rate				Base Case						High Fuel - Jet/Gasoil Prices – Low USD/RUB rate					
	Official Fees	Independent Navigation	Official Fees	Independent Navigation	Official Fees	Discounted Fees	Independent Navigation	Official Fees	Discounted Fees	Independent Navigation	Official Fees	Discounted Fees	Independent Navigation	Official Fees	Discounted Fees	Independent Navigation
Chiba – Coryton																
Optimal Speed																
SCR-NSR	1.2	6.0	1.2	6.0	2.4	2.9	7.9	2.4	2.9	7.9	-1.0	4.6	9.6	-1.0	4.6	9.6
	(-1.9)	(2.9)	(-1.9)	(2.9)	(-0.9)	(-0.4)	(4.6)	(-0.9)	(-0.4)	(4.6)	(-4.4)	(1.2)	(6.2)	(-4.4)	(1.2)	(6.2)
Cape-NSR	1.2	6.0	1.2	6.0	4.2	4.7	9.7	4.2	4.7	9.7	2.4	8.0	13.0	2.4	8.0	13.0
	(-1.9)	(2.9)	(-1.9)	(2.9)	(0.9)	(1.4)	(6.4)	(0.9)	(1.4)	(6.4)	(-1.0)	(4.6)	(9.6)	(-1.1)	(4.6)	(9.6)
SCR-Cape	0.0		0.0		-1.7			-1.7			-3.4			-3.4		
12 knots																
SCR-NSR	2.0	6.8	2.0	6.8	2.8	3.3	8.3	2.8	3.3	8.3	-0.8	4.8	9.8	-0.8	4.8	9.8
	(-1.1)	(3.7)	(-1.1)	(3.7)	(-0.5)	(0.0)	(5.0)	(-0.5)	(0.0)	(5.0)	(-4.3)	(1.4)	(6.4)	(-4.3)	(1.4)	(6.4)
Cape-NSR	2.4	7.2	2.4	7.2	4.7	5.2	10.2	4.7	5.2	10.2	2.6	8.2	13.2	2.6	8.2	13.2
	(-0.8)	(4.0)	(-0.8)	(4.0)	(1.4)	(1.9)	(6.9)	(1.4)	(1.9)	(6.9)	(-0.8)	(4.8)	(9.8)	(-0.8)	(4.8)	(9.8)
SCR-Cape	-0.4		-0.4		-1.9			-1.9			-3.4			-3.4		
Ulsan – Rotterdam																
Optimal Speed																
SCR-NSR	0.5	5.3	0.5	5.3	1.4	1.9	6.9	1.4	1.9	6.9	-2.2	3.4	8.4	-2.2	3.4	8.4
	(-2.5)	(2.3)	(-2.5)	(2.3)	(-1.7)	(-1.2)	(3.8)	(-1.7)	(-1.2)	(3.8)	(-5.5)	(0.1)	(5.1)	(-5.5)	(0.1)	(5.1)
Cape-NSR	0.5	5.3	0.5	5.3	3.2	3.7	8.7	3.2	3.7	8.7	1.1	6.7	11.7	1.1	6.7	11.7
	(-2.5)	(2.3)	(-2.5)	(2.3)	(0.0)	(0.5)	(5.5)	(0.0)	(0.5)	(5.5)	(-2.2)	(3.4)	(8.4)	(-2.2)	(3.4)	(8.4)
SCR-Cape	0.0		0.0		-1.7			-1.7			-3.4			-3.4		
12 knots																
SCR-NSR	1.3	6.1	1.3	6.1	1.8	2.3	7.3	1.8	2.3	7.3	-2.1	3.5	8.5	-2.1	3.5	8.5
	(-1.8)	(3.0)	(-1.8)	(3.0)	(-1.4)	(-0.9)	(4.1)	(-1.4)	(-0.9)	(4.1)	(-5.4)	(0.2)	(5.2)	(-5.4)	(0.2)	(5.2)
Cape-NSR	1.6	6.4	1.6	6.4	3.7	4.2	9.2	3.7	4.2	9.2	1.3	7.0	12.0	1.3	6.9	11.9
	(-1.4)	(3.4)	(-1.4)	(3.4)	(0.5)	(1.0)	(6.0)	(0.5)	(1.0)	(6.0)	(-2.0)	(3.6)	(8.6)	(-2.0)	(3.6)	(8.6)
SCR-Cape	-0.4		-0.4		-1.9			-1.9			-3.4			-3.4		
Ulsan – Bilbao																
Optimal Speed																
SCR-NSR	-1.1	3.7	-1.1	3.7	-0.9	-0.4	4.6	-0.9	-0.4	4.6	-5.2	0.4	5.4	-5.2	0.4	5.4
	(-5.0)	(-0.2)	(-5.0)	(-0.2)	(-5.1)	(-4.6)	(0.4)	(-5.1)	(-4.6)	(0.4)	(-9.7)	(-4.1)	(0.9)	(-9.7)	(-4.1)	(0.9)
Cape-NSR	-1.2	3.6	-1.2	3.6	0.8	1.3	6.3	0.8	1.3	6.3	-1.9	3.8	8.8	-1.9	3.8	8.8
	(-5.0)	(-0.2)	(-5.0)	(-0.2)	(-3.4)	(-2.9)	(2.1)	(-3.4)	(-2.9)	(2.1)	(-6.4)	(-0.7)	(4.3)	(-6.4)	(-0.8)	(4.2)
SCR-Cape	0.0		0.0		-1.7			-1.7			-3.3			-3.3		
12 knots																
SCR-NSR	-0.5	4.3	-0.5	4.3	-0.6	-0.1	4.9	-0.6	-0.1	4.9	-5.0	0.6	5.6	-5.0	0.6	5.6
	(-4.5)	(0.3)	(-4.5)	(0.3)	(-4.8)	(-4.3)	(0.7)	(-4.8)	(-4.3)	(0.7)	(-9.5)	(-3.9)	(1.1)	(-9.6)	(-3.9)	(1.1)
Cape-NSR	-0.2	4.6	-0.2	4.6	1.3	1.8	6.8	1.3	1.8	6.8	-1.6	4.0	9.0	-1.7	4.0	9.0
	(-4.1)	(0.7)	(-4.1)	(0.7)	(-2.9)	(-2.4)	(2.6)	(-2.9)	(-2.4)	(2.6)	(-6.2)	(-0.6)	(4.4)	(-6.2)	(-0.6)	(4.4)
SCR-Cape	-0.4		-0.4		-1.9			-1.9			-3.4			-3.4		

*RFR Differentials in parentheses refer to results when ice damage repairs are factored in the analysis. MGO on NSR refer to the use of MGO through ice on NSR.

Sensitivity analysis results for LNG-VLSFO mode with tank capacities of 1,700 m^3 and 3,600 m^3.*

ΔRFR	LNG-VLSFO at 1,700 m^3		LNG-VLSFO at 3,600 m^3		LNG-VLSFO at 1,700 m^3			LNG-VLSFO at 3,600 m^3			LNG-VLSFO at 1,700 m^3			LNG-VLSFO at 3,600 m^3		
	Low Fuel - Jet/Gasoil Prices – High USD/RUB rate				Base Case						High Fuel - Jet/Gasoil Prices – Low USD/RUB rate					
	Official Fees	Independent Navigation	Official Fees	Independent Navigation	Official Fees	Discounted Fees	Independent Navigation	Official Fees	Discounted Fees	Independent Navigation	Official Fees	Discounted Fees	Independent Navigation	Official Fees	Discounted Fees	Independent Navigation
								Chiba – Coryton								
								Optimal Speed								
SCR-NSR	1.1	5.9	0.6	5.4	2.0	2.5	7.5	1.0	1.5	6.5	-1.6	4.0	9.0	-3.1	2.5	7.5
	(-1.9)	(2.9)	(-2.3)	(2.5)	(-1.1)	(-0.6)	(4.4)	(-2.1)	(-1.6)	(3.4)	(-4.8)	(0.8)	(5.8)	(-6.3)	(-0.6)	(4.4)
Cape-NSR	1.2	6.0	0.2	5.0	3.9	4.3	9.3	1.8	2.2	7.2	1.9	7.5	12.5	-1.2	4.4	9.4
	(-1.8)	(3.0)	(-2.7)	(2.1)	(0.8)	(1.3)	(6.3)	(-1.3)	(-0.8)	(4.2)	(-1.3)	(4.3)	(9.3)	(-4.4)	(1.3)	(6.3)
SCR-Cape	-0.1		0.4		-1.9			-0.8			-3.5			-1.9		
								12 knots								
SCR-NSR	1.9	6.7	1.9	6.7	2.3	2.8	7.8	2.3	2.8	7.8	-1.7	3.9	8.9	-1.7	4.0	9.0
	(-1.2)	(3.6)	(-1.2)	(3.6)	(-0.8)	(-0.3)	(4.7)	(-0.8)	(-0.3)	(4.7)	(-4.9)	(0.7)	(5.7)	(-4.8)	(0.8)	(5.8)
Cape-NSR	2.3	7.0	2.1	6.9	4.2	4.6	9.6	3.6	4.1	9.1	1.6	7.2	12.2	0.7	6.3	11.3
	(-0.8)	(4.0)	(-1.0)	(3.8)	(1.0)	(1.5)	(6.5)	(0.5)	(1.0)	(6.0)	(-1.6)	(4.0)	(9.0)	(-2.5)	(3.1)	(8.1)
SCR-Cape	-0.4		- 0.3		-1.8			-1.3			-3.3			-2.4		
								Ulsan – Rotterdam								
								Optimal Speed								
SCR-NSR	0.6	5.4	0.0	4.8	1.4	1.9	6.9	0.2	0.7	5.7	-2.4	3.2	8.2	-4.1	1.5	6.5
	(-2.3)	(2.5)	(-2.9)	(1.9)	(-1.6)	(-1.1)	(3.9)	(-2.8)	(-2.3)	(2.7)	(-5.4)	(0.2)	(5.2)	(-7.1)	(-1.5)	(3.5)
Cape-NSR	0.6	5.4	-0.4	4.4	3.2	3.7	8.7	0.8	1.3	6.3	1.1	6.7	11.7	-2.4	3.2	8.2
	(-2.2)	(2.6)	(-3.3)	(1.5)	(0.3)	(0.8)	(5.8)	(-2.1)	(-1.7)	(3.3)	(-1.9)	(3.7)	(8.7)	(-5.4)	(0.2)	(5.2)
SCR-Cape	-0.1		0.4		-1.8			-0.6			-3.5			-1.7		
								12 knots								
SCR-NSR	1.1	5.9	1.1	5.9	1.4	1.9	6.9	1.4	1.9	6.9	-2.7	2.9	7.9	-2.7	2.9	7.9
	(-1.9)	(2.9)	(-1.9)	(2.9)	(-1.6)	(-1.1)	(3.9)	(-1.6)	(-1.1)	(3.9)	(-5.8)	(-0.2)	(4.8)	(-5.8)	(-0.2)	(4.8)
Cape-NSR	1.5	6.3	1.4	6.2	3.2	3.7	8.7	2.7	3.2	8.2	0.4	6.0	11.0	-0.4	5.3	10.3
	(-1.5)	(3.3)	(-1.6)	(3.2)	(0.1)	(0.6)	(5.6)	(-0.3)	(0.2)	(5.2)	(-2.7)	(3.0)	(8.0)	(-3.4)	(2.2)	(7.2)
SCR-Cape	-0.4		-0.2		-1.8			-1.3			-3.2			-2.4		
								Ulsan – Bilbao								
								Optimal Speed								
SCR-NSR	-1.1	3.7	-1.4	3.4	-1.0	-0.5	4.5	-1.7	-1.2	3.8	-5.4	0.2	5.2	-6.3	-0.7	4.3
	(-4.7)	(0.1)	(-5.0)	(-0.3)	(-4.8)	(-4.3)	(0.7)	(-5.5)	(-5.0)	(0.0)	(-9.3)	(-3.7)	(1.3)	(-10.3)	(-4.7)	(0.3)
Cape-NSR	-1.1	3.7	-1.9	2.9	0.8	1.3	6.3	-1.1	-0.6	4.4	-1.9	3.7	8.7	-4.7	0.9	5.9
	(-4.7)	(0.1)	(-5.5)	(-0.7)	(-2.9)	(-2.4)	(2.6)	(-4.9)	(-4.4)	(0.6)	(-5.9)	(-0.3)	(4.7)	(-8.7)	(-3.1)	(1.9)
SCR-Cape	0.0		0.5		-1.8			-0.6			-3.5			-1.6		
								12 knots								
SCR-NSR	-0.5	4.3	-0.6	4.2	-0.6	-0.1	4.9	-0.7	-0.2	4.8	-5.2	0.4	5.4	-5.2	0.4	5.4
	(-4.4)	(0.4)	(-4.4)	(0.3)	(-4.6)	(-4.1)	(0.9)	(-4.7)	(-4.2)	(0.8)	(-9.2)	(-3.6)	(1.4)	(-9.3)	(-3.7)	(1.3)
Cape-NSR	-0.2	4.6	-0.4	4.4	1.0	1.5	6.5	0.6	1.1	6.1	-2.2	3.4	8.4	-2.9	2.7	7.7
	(-4.1)	(0.7)	(-4.2)	(0.6)	(-3.0)	(-2.5)	(2.5)	(-3.4)	(-2.9)	(2.1)	(-6.3)	(-0.7)	(4.3)	(-6.9)	(-1.3)	(3.7)
SCR-Cape	-0.3		-0.2		-1.6			-1.3			-2.9			-2.3		

*RFR Differentials in parentheses refer to results when ice damage repairs are factored in the analysis.

Appendix W1. Distance breakdown per operational mode and route – Chapter 6 (Author's calculations)

Distance breakdown for Ust-Luga – Ulsan pair on SCR (12,298 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Ust-Luga – Ulsan	12,298
VLSFO	MGO	Ust-Luga – North Sea ECAs	1,768
	VLSFO	North Sea ECAs – Ulsan	10,530
LNG-VLSFO 1,700 m^3	LNG	Ust-Luga – Indian Ocean	7,800
	VLSFO	Indian Ocean – Ulsan	4,498

Source: Dataloy (2021).

Distance breakdown for Ust-Luga – Ulsan pair on NSR (7,846 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Ust-Luga – Cape Zhelanya	2,848
	HSFO*	Cape Zhelanya – Cape Dezhnev (NSR)	2,059
	HSFO	Cape Dezhnev – Ulsan	2,939
VLSFO	MGO	Ust-Luga – North Sea ECAs	1,371
	VLSFO	North Sea ECAs – Cape Zhelanya	1,477
	VLSFO*	Cape Zhelanya – Cape Dezhnev (NSR)	2,059
	VLSFO	Cape Dezhnev – Ulsan	2,939
LNG-VLSFO 1,700 m^3 1st voyage			
Average Speed on NSR (July): 8.9 knots	LNG	Ust-Luga – Cape Zhelanya	2,848
	LNG	Cape Zhelanya – Cape Dezhnev (NSR)	2,059
	LNG	Cape Dezhnev – North Pacific Ocean	2,252
	VLSFO	North Pacific Ocean – Ulsan	687
4th voyage			
Average Speed on NSR (September): 11.9 knots	LNG	Ust-Luga – Cape Zhelanya	2,848
	LNG	Cape Zhelanya – Cape Dezhnev (NSR)	2,059
	LNG	Cape Dezhnev – North Pacific Ocean	1,752
	VLSFO	North Pacific Ocean – Ulsan	1,187
7th voyage			
Average Speed on NSR (November): 11 knots	LNG	Ust-Luga – Cape Zhelanya	2,848
	LNG	Cape Zhelanya – Cape Dezhnev (NSR)	2,059
	LNG	Cape Dezhnev – North Pacific Ocean	1,917
	VLSFO	North Pacific Ocean – Ulsan	1,022

Source: Dataloy (2021). *The use of MGO through ice on the NSR is assumed when considering a prohibition on the use of heavy fuel oils in the Arctic.

Distance breakdown for Ulsan – Rotterdam pair on SCR (10,944 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Ulsan – Rotterdam	10,944
VLSFO	VLSFO	Ulsan – North Sea ECAs	10,531
	MGO	North Sea ECAs – Rotterdam	413
LNG-VLSFO 1,700 m^3	VLSFO	Ulsan – Indian Ocean	3,144
	LNG	Indian Ocean – Rotterdam	7,800

Source: Dataloy (2021).

Distance breakdown for Ulsan – Rotterdam pair on NSR (7,127 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Ulsan – Cape Dezhnev	2,939
	HSFO*	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	HSFO	Cape Zhelanya – Rotterdam	2,129
VLSFO	VLSFO	Ulsan – Cape Dezhnev	2,939
	VLSFO*	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	VLSFO	Cape Zhelanya – North Sea ECAs	1,500
	MGO	North Sea ECAs – Rotterdam	629
LNG-VLSFO 1,700 m^3			
2nd voyage			
Average Speed on NSR (August): 10.7 knots	VLSFO	Ulsan – North Pacific Ocean	250
	LNG	North Pacific Ocean – Cape Dezhnev	2,689
	LNG	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	LNG	Cape Zhelanya – Rotterdam	2,129
5th voyage			
Average Speed on NSR (October): 11 knots	VLSFO	Ulsan – North Pacific Ocean	303
	LNG	North Pacific Ocean – Cape Dezhnev	2,636
	LNG	Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	LNG	Cape Zhelanya – Rotterdam	2,129

Source: Dataloy (2021). *The use of MGO through ice on the NSR is assumed when considering a prohibition on the use of heavy fuel oils in the Arctic.

Distance breakdown for Ballast voyage (3rd and 6th voyages) either on SCR or NSR (1,414 n.m.)

Operational Mode	Fuel Type	Voyage leg per route	Distance (n.m.)
HSFO-Scrubber	HSFO	Rotterdam – Ust-Luga	1,414
VLSFO	MGO	Rotterdam – Ust-Luga	1,414
LNG-VLSFO 1,700 m^3	LNG	Rotterdam – Ust-Luga	1,414

Source: Dataloy (2021).

Notes:

The total LNG voyage fuel consumption depends on distance, speed, and LNG tank capacity. These three factors determine LNG fuel consumption per distance leg, and result in different LNG/VLSFO ratios per OD pair.

For the Ust-Luga - Ulsan pair via SCR, it is assumed that LNG is used within ECAs and the remaining distance leg(s) until the LNG tank gets empty. Then, the engine switches to VLSFO as a fuel for the remaining voyage distance.

For the Ust-Luga - Ulsan pair via NSR, it is assumed that LNG is used within ECAs, on the next distance leg(s), through ice on NSR, and on the remaining distance leg(s) until the LNG tank gets empty. Then, the engine switches to VLSFO for the remaining voyage distance.

For the Ulsan - Rotterdam pair via SCR, it is assumed that VLSFO is used in the first distance leg(s). Then, the engine switches to LNG on the remaining distance leg(s), as well as within ECAs.

For the Ulsan - Rotterdam pair via NSR, it is assumed that VLSFO is used in the first distance leg(s). Then, the engine switches to LNG on the next distance leg(s), through ice on NSR, and on the remaining distance leg(s), as well as within ECAs.

The total LNG fuel consumption and LNG/VLSFO distance ratio depend on the speed realised on open water when using LNG as a fuel, as well as the speed realised through ice on NSR when using LNG as a fuel. The optimal speed on open water when using LNG as a fuel is 16 knots across all fuel price scenarios. This is due to the relatively low LNG price assumed across all price scenarios, and the effect of in-transit inventory costs, all of which lead to increased optimal speeds. The speed on ice varies depending on local sea ice conditions, navigation zone and month (Appendices Y3, Y4). As a result, the only determining factor for the LNG/VLSFO distance ratio is the varying speed through ice on NSR. The use of HSFO and VLSFO is assumed in the respective operational modes for all distance legs and OD pairs, regardless of speeds, since the tank capacity of either fuel is sufficient for these fuels to be used for a whole voyage on either route.

Appendix W2. LNG/VLSFO distance ratios – Chapter 6 (Author's calculations)

LNG/VLSFO distance ratio per route alternative for Ust-Luga – Ulsan pair.

Route	1st voyage	4th voyage	7th voyage
SCR	63/37	63/37	63/37
NSR	91/9	85/15	87/13

LNG/VLSFO distance ratio per route alternative for Ulsan – Rotterdam pair.

Route	2nd voyage	5th voyage
SCR	71/29	71/29
NSR	96/4	96/4

Notes:

These LNG/VLSFO distance ratios are calculated based on distances from Appendix W1. The total LNG voyage fuel consumption depends on distance, speed, and LNG tank capacity. A fuel consumption margin of 15% is assumed when the LNG fuel quantity is sufficient to cover all distance legs of an OD pair. This implies that the maximum LNG fuel quantity which can be consumed is 85% of that loaded in the tank (SEA LNG 2020). On the other hand, almost all LNG fuel quantity is assumed to be used before switching to VLSFO, when VLSFO is also required on a number of distance legs for an OD pair. However, in practice a certain LNG fuel quantity needs to be retained in the tank as in the first case. Some of the reasons include potential issues with the strength of the LNG fuel tank when it undergoes through a cold-warm-cold cycle i.e. filled with LNG – getting empty – filled with LNG. Thus, a certain margin would also be appropriate in this case (MAN Energy Solutions 2021). Moreover, higher margins need to be assumed when considering other energy requirements e.g. fuel consumption for boilers, auxiliary engines.

The LNG/VLSFO ratios presented above are valid for all price scenarios under optimal speeds, since these are found 16 knots across all fuel price levels. This is due to the relatively low LNG price assumed across all price scenarios, and the effect of in-transit inventory costs, all of which lead to increased optimal speeds.

Appendix X1. Port characteristics – Chapter 6

Port characteristics for LR2 tankers of 115,000 dwt, LOA: 250 metres and loaded draught of 12 metres.

Port	Tanker Terminals	Berths/Jetties	DWT	LOA (metres)	Draught (metres)
Ust-Luga	Oil Products Terminal Nos 1-3/Nos 4-5/ SIBUR Terminal Nos 6-7	7	Up to 120,000	535 – 1,250	17.50
Rotterdam	11 terminals/berths for clean oil products		120,000 – 355,000	270 – 375	12.65 – 20.70
Ulsan	S-Oil 2-1/Sk Corp Sk8	2	120,000/150,000	250/280	13.50/16.50

Source: IHS Maritime (2015).

Appendix X2. LNG bunkering infrastructure/ships – Chapter 6

Port	LNG infrastructure	LNG Tank Capacity (m^3)	Country	Operations
Ust-Luga	LNG Bunker Ship Optimus (Ice Class IA)	6,000	Lithuania	Northeast Baltic Sea
	LNG Bunker Ship Kairos (Ice Class IA)	7,500	Lithuania	North Sea, Baltic Sea
	LNG Bunker Ship Dmitry Mendeleev (Ice Class IA)	5,800	Russia (Baltic)	Baltic Sea
Rotterdam, Ust-Luga	LNG Bunker Ship Coral Fraseri (Ice Class II)	10,000	The Netherlands	North Sea, Baltic Sea, West Mediterranean
	LNG Bunker Ship Coral Methane (Ice Class IB)	7,551	The Netherlands	North Sea, Baltic Sea, West Mediterranean
	LNG Bunker Ship Coralius (Ice Class IA)	5,600	Norway	North Sea, Baltic Sea
	LNG Bunker Ship Cardissa	6,500	The Netherlands	North Sea, Baltic Sea
Rotterdam	GATE Terminal Rotterdam	720,000	The Netherlands	Rotterdam
	LNG Bunker Barge Flexfueler 001	1,480	The Netherlands	ARA region*
	LNG Bunker Barge LNG London	2,998	The Netherlands	Rotterdam
Ulsan	LNG Bunker Ship SM Jeju LNG2	7,654	South Korea	Coastal in South Korea

Sources: DNV (2021b), Clarksons (2021). This list is indicative and non-exhaustive. A large number of LNG bunker ships and LNG bunker port terminals exist in the countries and regions mentioned in this table. *ARA region: Amsterdam-Rotterdam-Antwerp region.

Appendix Y1. Speed statistics for ice class IA tankers during the 2011-2019 summer/autumn ice seasons.

Arctic Sea	Descriptive Statistics	Month				
	Speed (knots)	July	August	September	October	November
East Kara Sea	Minimum	6.1	5.8	6.5	4.7	12.6
	Mean	10.6	10.3	11.8	9.8	12.6
	Maximum	14.9	14.1	13.9	13.9	12.6
	Standard Deviation	3.2	3.1	2.3	2.9	N.A.
West Laptev Sea	Minimum	10.1	5.5	9.6	7.1	8.8
	Mean	11.2	11.1	12.2	10.5	8.8
	Maximum	12.6	14.4	14.3	13.7	8.8
	Standard Deviation	1.0	2.6	1.6	1.7	N.A.
East Laptev Sea	Minimum	8.9	11.0	10.9	9.4	5.1
	Mean	11.6	13.4	13.2	12.8	5.1
	Maximum	14.6	16.2	15.4	16.0	5.1
	Standard Deviation	2.3	1.5	1.3	1.9	N.A.
East Siberian Sea (West)	Minimum	2.6	7.0	5.1	2.0	7.1
	Mean	8.1	10.5	10.9	10.5	8.6
	Maximum	13.0	16.0	13.3	16.9	10.2
	Standard Deviation	3.8	2.2	2.3	4.5	2.2
East Siberian Sea (East)	Minimum	3.4	3.4	8.2	8.1	8.9
	Mean	6.2	9.1	11.6	11.5	9.5
	Maximum	10.5	14.0	14.8	15.9	10.2
	Standard Deviation	2.8	3.5	1.9	2.5	0.9
Chukchi Sea	Minimum	2.6	6.0	8.5	7.4	7.7
	Mean	8.6	11.3	12.3	12.3	11.2
	Maximum	14.0	15.7	15.9	15.9	14.8
	Standard Deviation	4.9	2.7	1.9	2.7	5.0

Source: Author's calculations based on Bloomberg (2021).

Appendix Y2. Start and end points of AIS data

Location	Longitude	Latitude
Cape Zhelanya	68° 19′ 38″	77° 14′ 51″
End of East Kara Sea (Vilkitsky Strait)	103° 24′ 18″	77° 53′ 51″
End of West Laptev Sea	128° 47′ 36″	77° 19′ 43″
Dmitry Laptev Strait	141° 59′ 11″	72° 59′ 05″
Sannikov Strait	140° 20′ 55″	74° 31′ 45″
End of East Laptev Sea (North of the New Siberian Islands)	139° 45′ 43″	76° 55′ 17″
End of East Siberian Sea (West)	164° 47′ 09″	73° 55′ 35″
End of East Siberian Sea (East) (Wrangel Island)	178° 15′ 35″	70° 12′ 17″
Chukchi Sea (Cape Dezhnev)	-169° 14′ 17″	65° 55′ 07″

Source: Author’s calculations based on Bloomberg (2021).

Appendix Y3. Speed and time on the NSR (Figures 6.3 - 6.7) – Chapter 6 (Author's calculations)

July

Arctic Sea	Speed	Time
East Kara Sea	10.6	2
West Laptev Sea	11.2	1
East Laptev Sea	11.6	1
East Siberian Sea West	8.1	2
East Siberian Sea East	6.2	2
Chukchi Sea	8.6	2

August

Arctic Sea	Speed	Time
Chukchi Sea	11.3	1
East Siberian Sea East	9.1	2
East Siberian Sea West	10.5	1
East Laptev Sea	13.4	1
West Laptev Sea	11.1	1
East Kara Sea	10.3	2

September

Arctic Sea	Speed	Time
East Kara Sea	11.8	2
West Laptev Sea	12.2	1
East Laptev Sea	13.2	1
East Siberian Sea West	10.9	1
East Siberian Sea East	11.6	1
Chukchi Sea	12.3	1

October

Arctic Sea	Speed	Time
Chukchi Sea	12.3	1
East Siberian Sea East	11.5	1
East Siberian Sea West	10.5	1
East Laptev Sea	12.8	1
West Laptev Sea	10.5	1
East Kara Sea	9.8	2

November

Arctic Sea	Speed	Time
East Kara Sea	9.8	2
West Laptev Sea	10.5	1
East Laptev Sea	12.8	1
East Siberian Sea West	10.5	1
East Siberian Sea East	11.5	1
Chukchi Sea	12.3	1

Appendix Y4. Speed – time relationship within and outside NSR across all laden voyages (Figure 6.9) – Chapter 6 (Author's calculations)

HSFO-Scrubber mode

Voyage	Ust-Luga – Ulsan (1st voyage)	Ulsan – Rotterdam (2nd voyage)	Ust-Luga – Ulsan (4th voyage)	Ulsan – Rotterdam (5th voyage)	Ust-Luga – Ulsan (7th voyage)
Month	July	August	September	October	November-December
Days within NSR	10	8	7	8	8
Days outside NSR	16	14	16	14	16
Speed on NSR	8.9	10.7	11.9	11.0	11.0
Optimal Voyage Speed	12.9	13.8	14.3	13.9	14.0

VLSFO mode

Voyage	Ust-Luga – Ulsan (1st voyage)	Ulsan – Rotterdam (2nd voyage)	Ust-Luga – Ulsan (4th voyage)	Ulsan – Rotterdam (5th voyage)	Ust-Luga – Ulsan (7th voyage)
Month	July	August	September	October	November-December
Days within NSR	10	8	7	8	8
Days outside NSR	18	16	18	16	18
Speed on NSR	8.9	10.7	11.9	11.0	11.0
Optimal Voyage Speed	11.7	12.5	12.9	12.6	12.6

LNG-VLSFO 1,700 m^3 mode

Voyage	Ust-Luga – Ulsan (1st voyage)	Ulsan – Rotterdam (2nd voyage)	Ust-Luga – Ulsan (4th voyage)	Ulsan – Rotterdam (5th voyage)	Ust-Luga – Ulsan (7th voyage)
Month	July	August	September	October	November-December
Days within NSR	10	8	7	8	8
Days outside NSR	15	13	16	13	15
Speed on NSR	8.9	10.7	11.9	11.0	11.0
Optimal Voyage Speed	13.0	13.9	14.3	14.1	14.0

Appendix Y5. Seasonal operations dates – Chapter 6 (Author's calculations)

SCR HSFO-Scrubber (Low Fuel/Commodity Prices)

OD pair	Port Loading	In-Transit	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	33 days 3 July - 4 August	2 days 5-6 August
2. Ulsan - Rotterdam	2 days 7-8 August	30 days 9 August - 7 September	2 days 8-9 September
3. Rotterdam - Ust-Luga		4 days 10-13 September	
4. Ust-Luga - Ulsan	2 days 14-15 September	33 days 16 September - 18 October	2 days 19-20 October
5. Ulsan - Rotterdam	2 days 21-22 October	30 days 23 October - 21 November	2 days 22-23 November
6. Rotterdam - Ust-Luga		4 days 24-27 November	
7. Ust-Luga - Ulsan	2 days 28-29 November	33 days 30 November - 1 January	2 days 2-3 January

SCR HSFO-Scrubber (Base Case)

OD pair	Port Loading	In-Transit	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	33 days 3 July - 4 August	2 days 5-6 August
2. Ulsan - Rotterdam	2 days 7-8 August	30 days 9 August - 7 September	2 days 8-9 September
3. Rotterdam - Ust-Luga		4 days 10-13 September	
4. Ust-Luga - Ulsan	2 days 14-15 September	33 days 16 September - 18 October	2 days 19-20 October
5. Ulsan - Rotterdam	2 days 21-22 October	30 days 23 October - 21 November	2 days 22-23 November
6. Rotterdam - Ust-Luga		4 days 24-27 November	
7. Ust-Luga - Ulsan	2 days 28-29 November	33 days 30 November - 1 January	2 days 2-3 January

SCR HSFO-Scrubber (High Fuel/Commodity Prices)

OD pair	Port Loading	In-Transit	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	35 days 3 July - 6 August	2 days 7-8 August
2. Ulsan - Rotterdam	2 days 9-10 August	31 days 11 August - 10 September	2 days 11-12 September
3. Rotterdam - Ust-Luga		4 days 13-16 September	
4. Ust-Luga - Ulsan	2 days 17-18 September	35 days 19 September - 23 October	2 days 24-25 October
5. Ulsan - Rotterdam	2 days 26-27 October	31 days 28 October - 27 November	2 days 28-29 November
6. Rotterdam - Ust-Luga		4 days 30 November - 3 December	
7. Ust-Luga - Ulsan	2 days 4-5 December	35 days 6 December - 9 January	2 days 10-11 January

NSR HSFO-Scrubber (Low Fuel/Commodity Prices)

OD pair	Port Loading	In-Transit	Inside NSR	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	25 days 3-27 July	10 days 10-19 July	2 days 28-29 July
2. Ulsan - Rotterdam	2 days 30-31 August	21 days 1-21 August	8 days 9-16 August	2 days 22-23 August
3. Rotterdam - Ust-Luga		4 days 24-27 August		
4. Ust-Luga - Ulsan	2 days 28-29 August	22 days 30 August - 20 September	7 days 6-12 September	2 days 21-22 September
5. Ulsan - Rotterdam	2 days 23-24 September	21 days 25 September - 15 October	8 days 3-10 October	2 days 16-17 October
6. Rotterdam - Ust-Luga		4 days 18-21 October		
7. Ust-Luga - Ulsan	2 days 22-23 October	23 days 24 October - 15 November	8 days 31 October - 7 November	2 days 16-17 November

NSR HSFO-Scrubber (Base Case)

OD pair	Port Loading	In-Transit	Inside NSR	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	25 days 3-27 July	10 days 10-19 July	2 days 28-29 July
2. Ulsan - Rotterdam	2 days 30-31 July	22 days 1-22 August	8 days 9-16 August	2 days 23-24 August
3. Rotterdam - Ust-Luga		4 days 25-28 August		
4. Ust-Luga - Ulsan	2 days 29-30 August	23 days 31 August - 22 September	7 days 8-14 September	2 days 23-24 September
5. Ulsan - Rotterdam	2 days 25-26 September	21 days 27 September - 17 October	8 days 5-12 October	2 days 18-19 October
6. Rotterdam - Ust-Luga		4 days 20-23 October		
7. Ust-Luga - Ulsan	2 days 24-25 October	23 days 26 October - 17 November	8 days 2-9 November	2 days 18-19 November

NSR HSFO-Scrubber (High Fuel/Commodity Prices)

OD pair	Port Loading	In-Transit	Inside NSR	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	27 days 3-29 July	10 days 11-20 July	2 days 30-31 July
2. Ulsan - Rotterdam	2 days 1-2 August	23 days 3-25 August	8 days 12-19 August	2 days 26-27 August
3. Rotterdam - Ust-Luga		4 days 28-31 August		
4. Ust-Luga - Ulsan	2 days 1-2 September	24 days 3-26 September	7 days 11-17 September	2 days 27-28 September
5. Ulsan - Rotterdam	2 days 29-30 September	23 days 1-23 October	8 days 11-17 October	2 days 24-25 October
6. Rotterdam - Ust-Luga		4 days 26-29 October		
7. Ust-Luga - Ulsan	2 days 30-31 October	26 days 1-25 November	8 days 9-16 November	2 days 26-27 November

SCR VLSFO (Low Fuel/Commodity Prices)

OD pair	Port Loading	In-Transit	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	33 days 3 July - 4 August	2 days 5-6 August
2. Ulsan - Rotterdam	2 days 7-8 August	30 days 9 August - 7 September	2 days 8-9 September
3. Rotterdam - Ust-Luga		4 days 10-13 September	
4. Ust-Luga - Ulsan	2 days 14-15 September	33 days 16 September - 18 October	2 days 19-20 October
5. Ulsan - Rotterdam	2 days 21-22 October	30 days 23 October - 21 November	2 days 22-23 November
6. Rotterdam - Ust-Luga		4 days 24-27 November	
7. Ust-Luga - Ulsan	2 days 28-29 November	33 days 30 November - 1 January	2 days 2-3 January

SCR VLSFO (Base Case)

OD pair	Port Loading	In-Transit	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	38 days 3 July - 9 August	2 days 10-11 August
2. Ulsan - Rotterdam	2 days 12-13 August	33 days 14 August - 15 September	2 days 16-17 September
3. Rotterdam - Ust-Luga		4 days 18-21 September	
4. Ust-Luga - Ulsan	2 days 22-23 September	38 days 24 September - 31 October	2 days 1-2 November
5. Ulsan - Rotterdam	2 days 3-4 November	33 days 5 November - 7 December	2 days 8-9 December
6. Rotterdam - Ust-Luga		4 days 10-13 December	
7. Ust-Luga - Ulsan	2 days 14-15 December	38 days 16 December - 22 January	2 days 23-24 January

SCR VLSFO (High Fuel/Commodity Prices)

OD pair	Port Loading	In-Transit	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	41 days 3 July - 12 August	2 days 13-14 August
2. Ulsan - Rotterdam	2 days 15-16 August	36 days 17 August - 21 September	2 days 22-23 September
3. Rotterdam - Ust-Luga		5 days 24-28 September	
4. Ust-Luga - Ulsan	2 days 29-30 September	41 days 1 October - 10 November	2 days 11-12 November
5. Ulsan - Rotterdam	2 days 13-14 November	36 days 15 November - 20 December	2 days 21-22 December
6. Rotterdam - Ust-Luga		5 days 23-27 December	
7. Ust-Luga - Ulsan	2 days 28-29 December	41 days 30 December - 8 January	2 days 9-10 January

NSR VLSFO (Low Fuel/Commodity Prices)

OD pair	Port Loading	In-Transit	Inside NSR	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	25 days 3-27 July	10 days 10-19 July	2 days 28-29 July
2. Ulsan - Rotterdam	2 days 30-31 July	21 days 1-21 August	8 days 8-15 August	2 days 22-23 August
3. Rotterdam - Ust-Luga		4 days 24-27 August		
4. Ust-Luga - Ulsan	2 days 28-29 August	22 days 30 August - 20 September	7 days 6-12 September	2 days 21-22 September
5. Ulsan - Rotterdam	2 days 23-24 September	21 days 25 September - 15 October	8 days 2-9 October	2 days 16-17 October
6. Rotterdam - Ust-Luga		4 days 18-21 October		
7. Ust-Luga - Ulsan	2 days 22-23 October	23 days 24 October - 15 November	8 days 31 October - 7 November	2 days 16-17 November

NSR VLSFO (Base Case)

OD pair	Port Loading	In-Transit	Inside NSR	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	28 days 3-30 July	10 days 12-21 July	2 days 31 July – 1 August
2. Ulsan - Rotterdam	2 days 2-3 August	24 days 4-27 August	8 days 13-20 August	2 days 28-29 August
3. Rotterdam - Ust-Luga		4 days 30 August - 2 September		
4. Ust-Luga - Ulsan	2 days 3-4 September	25 days 5-29 September	7 days 14-20 September	2 days 30 September - 1 October
5. Ulsan - Rotterdam	2 days 2-3 October	24 days 4-27 October	8 days 13-20 October	2 days 28-29 October
6. Rotterdam - Ust-Luga		4 days 30 October - 2 November		
7. Ust-Luga - Ulsan	2 days 3-4 November	26 days 5-30 November	8 days 14-21 November	2 days 1-2 December

NSR VLSFO (High Fuel/Commodity Prices)

OD pair	Port Loading	In-Transit	Inside NSR	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	30 days 3 July - 1 August	10 days 13-22 July	2 days 2-3 August
2. Ulsan - Rotterdam	2 days 4-5 August	25 days 6-30 August	8 days 16-23 August	2 days 31 August – 1 September
3. Rotterdam - Ust-Luga		5 days 2-6 September		
4. Ust-Luga - Ulsan	2 days 7-8 September	27 days 9 September - 5 October	7 days 19-25 September	2 days 6-7 October
5. Ulsan - Rotterdam	2 days 8-9 October	25 days 10 October - 3 November	8 days 20-27 October	2 days 4-5 November
6. Rotterdam - Ust-Luga		5 days 6-10 November		
7. Ust-Luga - Ulsan	2 days 11-12 November	28 days 13 November - 10 December	8 days 23-30 November	2 days 11-12 December

SCR LNG-VLSFO 1,700 m^3 (Low Fuel/Commodity Prices)

OD pair	Port Loading	In-Transit	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	33 days 3 July - 4 August	2 days 5-6 August
2. Ulsan - Rotterdam	2 days 7-8 August	30 days 9 August - 7 September	2 days 8-9 September
3. Rotterdam - Ust-Luga		4 days 10-13 September	
4. Ust-Luga - Ulsan	2 days 14-15 September	33 days 16 September - 18 October	2 days 19-20 October
5. Ulsan - Rotterdam	2 days 21-22 October	30 days 23 October - 21 November	2 days 22-23 November
6. Rotterdam - Ust-Luga		4 days 24-27 November	
7. Ust-Luga - Ulsan	2 days 28-29 November	33 days 30 November - 1 January	2 days 2-3 January

SCR LNG-VLSFO 1,700 m^3 (Base Case)

OD pair	Port Loading	In-Transit	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	35 days 3 July - 6 August	2 days 7-8 August
2. Ulsan - Rotterdam	2 days 9-10 August	31 days 11 August - 10 September	2 days 11-12 September
3. Rotterdam - Ust-Luga		4 days 13-16 September	
4. Ust-Luga - Ulsan	2 days 17-18 September	35 days 19 September - 23 October	2 days 24-25 October
5. Ulsan - Rotterdam	2 days 26-27 October	31 days 28 October - 27 November	2 days 28-29 November
6. Rotterdam - Ust-Luga		4 days 30 November - 3 December	
7. Ust-Luga - Ulsan	2 days 4-5 December	35 days 6 December - 9 January	2 days 10-11 January

SCR LNG-VLSFO 1,700 m^3 (High Fuel/Commodity Prices)

OD pair	Port Loading	In-Transit	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	36 days 3 July - 7 August	2 days 8-9 August
2. Ulsan - Rotterdam	2 days 10-11 August	31 days 12 August - 11 September	2 days 12-13 September
3. Rotterdam - Ust-Luga		5 days 14-18 September	
4. Ust-Luga - Ulsan	2 days 19-20 September	36 days 21 September - 26 October	2 days 27-28 October
5. Ulsan - Rotterdam	2 days 29-30 October	31 days 31 October - 30 November	2 days 1-2 December
6. Rotterdam - Ust-Luga		5 days 3-7 December	
7. Ust-Luga - Ulsan	2 days 8-9 December	36 days 10 December - 14 January	2 days 15-16 January

NSR LNG-VLSFO 1,700 m^3 (Low Fuel/Commodity Prices)

OD pair	Port Loading	In-Transit	Inside NSR	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	25 days 3-27 July	10 days 10-19 July	2 days 28-29 July
2. Ulsan - Rotterdam	2 days 30-31 July	21 days 1-21 August	8 days 9-16 August	2 days 22-23 August
3. Rotterdam - Ust-Luga		4 days 24-27 August		
4. Ust-Luga - Ulsan	2 days 28-29 August	22 days 30 August - 20 September	7 days 6-12 September	2 days 21-22 September
5. Ulsan - Rotterdam	2 days 23-24 September	21 days 25 September - 15 October	8 days 3-10 October	2 days 16-17 October
6. Rotterdam - Ust-Luga		4 days 18-21 October		
7. Ust-Luga - Ulsan	2 days 22-23 October	23 days 24 October - 15 November	9 days 31 October - 7 November	2 days 16-17 November

NSR LNG-VLSFO 1,700 m^3 (Base Case)

OD pair	Port Loading	In-Transit	Inside NSR	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	25 days 3-27 July	10 days 10-19 July	2 days 28-29 July
2. Ulsan - Rotterdam	2 days 30-31 July	21 days 1-21 August	8 days 9-16 August	2 days 22-23 August
3. Rotterdam - Ust-Luga		4 days 24-27 August		
4. Ust-Luga - Ulsan	2 days 28-29 August	23 days 30 August - 21 September	7 days 6-12 September	2 days 22-23 September
5. Ulsan - Rotterdam	2 days 24-25 September	21 days 26 September - 16 October	8 days 4-11 October	2 days 17-18 October
6. Rotterdam - Ust-Luga		4 days 19-22 October		
7. Ust-Luga - Ulsan	2 days 23-24 October	23 days 25 October - 16 November	8 days 1-8 November	2 days 17-18 November

NSR LNG-VLSFO 1,700 m^3 (High Fuel/Commodity Prices)

OD pair	Port Loading	In-Transit	Inside NSR	Port Unloading
1. Ust-Luga - Ulsan	2 days 1-2 July	25 days 3-27 July	10 days 10-19 July	2 days 28-29 July
2. Ulsan - Rotterdam	2 days 30-31 July	21 days 1-21 August	8 days 9-16 August	2 days 22-23 August
3. Rotterdam - Ust-Luga		4 days 24-27 August		
4. Ust-Luga - Ulsan	2 days 28-29 August	23 days 30 August - 21 September	7 days 6-12 September	2 days 22-23 September
5. Ulsan - Rotterdam	2 days 24-25 September	21 days 26 September - 16 October	8 days 4-11 October	2 days 17-18 October
6. Rotterdam - Ust-Luga		4 days 19-22 October		
7. Ust-Luga - Ulsan	2 days 23-24 October	24 days 25 October - 17 November	8 days 1-8 November	2 days 18-19 November

Appendix Z. Cost analysis – Chapter 6

HSFO-Scrubber (Low Fuel and Naphtha/Jet Fuel Prices – High USD/RUB Exchange rates)

OD pair	Speed (knots)	Time (days)	Days in Port/Canal	Fuel cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Discounted Fees	RFR incl. Disc. Fees	No Fees	RFR incl. No Fees	Fuel Cost (MGO on NSR)	RFR (MGO on NSR)	RFR incl. Discounted Fees (MGO on NSR)	RFR incl. No Fees (MGO on NSR)
SCR																	
1. Ust-Luga - Ulsan	16.0	32	5	2.9	4.0	3.3	5.2	2.0	17.5								
2. Ulsan - Rotterdam	16.0	29	5	2.6	4.0	3.0	4.7	1.9	16.2								
3. Rotterdam - Ust-Luga	16.0	4		0.2		0.4	0.6		1.2								
4. Ust-Luga - Ulsan	16.0	32	5	2.9	4.0	3.3	5.2	2.0	17.5								
5. Ulsan - Rotterdam	16.0	29	5	2.6	4.0	3.0	4.7	1.9	16.2								
6. Rotterdam - Ust-Luga	16.0	4		0.2		0.4	0.6		1.2								
7. Ust-Luga - Ulsan	16.0	32	5	2.9	4.0	3.3	5.2	2.0	17.5								
NSR																	
1. Ust-Luga - Ulsan	13.2	25	4	2.0	5.7	3.5	5.2	1.5	17.9	5.2	17.5	0.2	12.5	2.2	18.1	17.6	12.6
2. Ulsan - Rotterdam	14.0	21	4	1.9	5.6	3.1	4.5	1.4	16.6	5.2	16.1	0.2	11.1	2.1	16.7	16.3	11.3
3. Rotterdam - Ust-Luga	16.0	4		0.3		0.4	0.8		1.5		1.5		1.5	0.3	1.5	1.5	1.5
4. Ust-Luga - Ulsan	14.7	22	4	2.2	5.6	3.2	4.7	1.4	17.1	5.2	16.7	0.2	11.7	2.4	17.3	16.9	11.9
5. Ulsan - Rotterdam	14.2	21	4	1.9	5.6	3.1	4.4	1.4	16.5	5.2	16.0	0.2	11.0	2.1	16.7	16.2	11.2
6. Rotterdam - Ust-Luga	16.0	4		0.3		0.4	0.8		1.5		1.5		1.5	0.3	1.5	1.5	1.5
7. Ust-Luga - Ulsan	14.3	23	4	2.1	5.6	3.3	4.8	1.4	17.3	5.2	16.8	0.2	11.8	2.3	17.5	17.0	12.0

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

HSFO-Scrubber (Base Case)

OD pair	Speed (knots)	Time (days)	Days in Port/Canal	Fuel cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Discounted Fees	RFR incl. Disc. Fees	No Fees	RFR incl. No Fees	Fuel Cost (MGO on NSR)	RFR (MGO on NSR)	RFR incl. Discounted Fees (MGO on NSR)	RFR incl. No Fees (MGO on NSR)
SCR																	
1. Ust-Luga - Ulsan	16.0	32	5	5.8	4.0	3.3	5.2	4.0	22.3								
2. Ulsan - Rotterdam	16.0	29	5	5.1	4.0	3.0	4.7	3.9	20.7								
3. Rotterdam - Ust-Luga	15.9	4		0.5		0.4	0.6		1.5								
4. Ust-Luga - Ulsan	16.0	32	5	5.8	4.0	3.3	5.2	4.0	22.3								
5. Ulsan - Rotterdam	16.0	29	5	5.1	4.0	3.0	4.7	3.9	20.7								
6. Rotterdam - Ust-Luga	15.9	4		0.5		0.4	0.6		1.5								
7. Ust-Luga - Ulsan	16.0	32	5	5.8	4.0	3.3	5.2	4.0	22.3								
NSR																	
1. Ust-Luga - Ulsan	12.9	25	4	3.8	5.7	3.5	5.3	3.2	21.5	5.2	21.0	0.2	16.0	4.1	21.7	21.3	16.3
2. Ulsan - Rotterdam	13.8	22	4	3.6	5.6	3.1	4.5	2.9	19.9	5.2	19.4	0.2	14.4	4.0	20.2	19.8	14.8
3. Rotterdam - Ust-Luga	15.3	4		0.6		0.4	0.8		1.8		1.8		1.8	0.6	1.8	1.8	1.8
4. Ust-Luga - Ulsan	14.3	23	4	4.2	5.6	3.3	4.8	2.9	20.7	5.2	20.2	0.2	15.2	4.6	21.1	20.6	15.6
5. Ulsan - Rotterdam	13.9	21	4	3.7	5.6	3.1	4.5	2.9	19.8	5.2	19.4	0.2	14.4	4.0	20.2	19.7	14.7
6. Rotterdam - Ust-Luga	15.3	4		0.6		0.4	0.8		1.8		1.8		1.8	0.6	1.8	1.8	1.8
7. Ust-Luga - Ulsan	14.0	23	4	4.1	5.6	3.3	4.9	2.9	20.9	5.2	20.4	0.2	15.4	4.4	21.2	20.7	15.7

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

HSFO-Scrubber (High Fuel and Naphtha/Jet Fuel Prices – Low USD/RUB Exchange rates)

OD pair	Speed (knots)	Time (days)	Days in Port/Canal	Fuel cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Discounted Fees	RFR incl. Disc. Fees	No Fees	RFR incl. No Fees	Fuel Cost (MGO on NSR)	RFR (MGO on NSR)	RFR incl. Discounted Fees (MGO on NSR)	RFR incl. No Fees (MGO on NSR)
SCR																	
1. Ust-Luga - Ulsan	15.1	34	5	7.7	4.0	3.5	5.6	6.4	27.1								
2. Ulsan - Rotterdam	15.2	30	5	7.0	4.0	3.1	4.9	6.1	25.1								
3. Rotterdam - Ust-Luga	13.9	4		0.6		0.4	0.7		1.668								
4. Ust-Luga - Ulsan	15.1	34	5	7.7	4.0	3.5	5.6	6.4	27.1								
5. Ulsan - Rotterdam	15.2	30	5	7.0	4.0	3.1	4.9	6.1	25.1								
6. Rotterdam - Ust-Luga	13.9	4		0.6		0.4	0.7		1.70								
7. Ust-Luga - Ulsan	15.1	34	5	7.7	4.0	3.5	5.6	6.4	27.1								
NSR																	
1. Ust-Luga - Ulsan	12.2	27	4	4.9	10.8	3.7	5.6	5.0	30.0	5.2	24.4	0.2	19.4	5.2	30.4	24.8	19.8
2. Ulsan - Rotterdam	13.0	23	4	4.7	10.8	3.3	4.8	4.7	28.2	5.2	22.6	0.2	17.6	5.2	28.7	23.1	18.1
3. Rotterdam - Ust-Luga	13.4	4		0.7		0.5	0.9		2.1		2.1		2.1	0.7	2.1	2.1	2.1
4. Ust-Luga - Ulsan	13.5	24	4	5.4	10.8	3.4	5.1	4.6	29.2	5.2	23.6	0.2	18.6	6.0	29.9	24.2	19.2
5. Ulsan - Rotterdam	13.2	23	4	4.8	10.8	3.2	4.8	4.6	28.2	5.2	22.6	0.2	17.6	5.3	28.7	23.1	18.1
6. Rotterdam - Ust-Luga	13.4	4		0.7		0.5	0.9		2.1		2.1		2.1	0.7	2.1	2.1	2.1
7. Ust-Luga - Ulsan	13.2	25	4	5.2	10.8	3.5	5.2	4.7	29.4	5.2	23.8	0.2	18.8	5.8	29.9	24.3	19.3

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

VLSFO (Low Fuel and Naphtha/Jet Fuel Prices – High USD/RUB Exchange rates)

OD pair	Speed (knots)	Time (days)	Days in Port/Canal	Fuel cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Discounted Fees	RFR incl. Disc. Fees	No Fees	RFR incl. No Fees	Fuel Cost (MGO on NSR)	RFR (MGO on NSR)	RFR incl. Discounted Fees (MGO on NSR)	RFR incl. No Fees (MGO on NSR)
SCR																	
1. Ust-Luga - Ulsan	16.0	32	5	4.5	4.0	3.3	4.9	2.0	18.8								
2. Ulsan - Rotterdam	16.0	29	5	4.0	4.0	3.0	4.4	1.9	17.3								
3. Rotterdam - Ust-Luga	16.0	4		0.4		0.4	0.6		1.3								
4. Ust-Luga - Ulsan	16.0	32	5	4.5	4.0	3.3	4.9	2.0	18.8								
5. Ulsan - Rotterdam	16.0	29	5	4.0	4.0	3.0	4.4	1.9	17.3								
6. Rotterdam - Ust-Luga	16.0	4		0.4		0.4	0.6		1.3								
7. Ust-Luga - Ulsan	16.0	32	5	4.5	4.0	3.3	4.9	2.0	18.8								
NSR																	
1. Ust-Luga - Ulsan	13.2	25	4	3.179	5.7	3.5	5.0	1.5	18.831	5.2	18.346	0.2	13.346	3.181	18.832	18.347	13.347
2. Ulsan - Rotterdam	13.9	21	4	2.935	5.6	3.1	4.3	1.5	17.419	5.2	16.934	0.2	11.934	2.937	17.421	16.936	11.936
3. Rotterdam - Ust-Luga	16.0	4		0.537		0.4	0.7		1.662		1.662		1.662	0.537	1.662	1.662	1.662
4. Ust-Luga - Ulsan	14.7	22	4	3.429	5.6	3.2	4.5	1.4	18.144	5.2	17.659	0.2	12.659	3.431	18.147	17.662	12.662
5. Ulsan - Rotterdam	14.1	21	4	2.964	5.6	3.1	4.2	1.4	17.352	5.2	16.867	0.2	11.867	2.967	17.354	16.869	11.869
6. Rotterdam - Ust-Luga	16.0	4		0.537		0.4	0.7		1.662		1.662		1.662	0.537	1.662	1.662	1.662
7. Ust-Luga - Ulsan	14.3	23	4	3.350	5.6	3.3	4.6	1.4	18.279	5.2	17.795	0.2	12.795	3.353	18.282	17.797	12.797

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

VLSFO (Base Case)

OD pair	Speed (knots)	Time (days)	Days in Port/Canal	Fuel cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Discounted Fees	RFR incl. Disc. Fees	No Fees	RFR incl. No Fees	Fuel Cost (MGO on NSR)	RFR (MGO on NSR)	RFR incl. Discounted Fees (MGO on NSR)	RFR incl. No Fees (MGO on NSR)
SCR																	
1. Ust-Luga - Ulsan	14.0	37	5	6.9	4.0	3.8	5.6	4.6	24.9								
2. Ulsan - Rotterdam	14.2	32	5	6.3	4.0	3.3	4.9	4.4	23.0								
3. Rotterdam - Ust-Luga	13.6	4		0.6		0.4	0.7		1.7								
4. Ust-Luga - Ulsan	14.0	37	5	6.9	4.0	3.8	5.6	4.6	24.9								
5. Ulsan - Rotterdam	14.2	32	5	6.3	4.0	3.3	4.9	4.4	23.0								
6. Rotterdam - Ust-Luga	13.6	4		0.6		0.4	0.7		1.7								
7. Ust-Luga - Ulsan	14.0	37	5	6.9	4.0	3.8	5.6	4.6	24.9								
NSR																	
1. Ust-Luga - Ulsan	11.7	28	4	4.548	5.7	3.8	5.6	3.5	23.103	5.2	22.618	0.2	17.618	4.551	23.106	22.621	17.621
2. Ulsan - Rotterdam	12.5	24	4	4.403	5.6	3.4	4.8	3.3	21.464	5.2	20.979	0.2	15.979	4.408	21.468	20.984	15.984
3. Rotterdam - Ust-Luga	13.1	4		0.717		0.5	0.9		2.093		2.093		2.093	0.717	2.093	2.093	2.093
4. Ust-Luga - Ulsan	12.9	25	4	5.047	5.6	3.5	5.1	3.2	22.512	5.2	22.027	0.2	17.027	5.052	22.518	22.033	17.033
5. Ulsan - Rotterdam	12.6	24	4	4.462	5.6	3.4	4.7	3.2	21.410	5.2	20.925	0.2	15.925	4.467	21.415	20.930	15.930
6. Rotterdam - Ust-Luga	13.1	4		0.717		0.5	0.9		2.093		2.093		2.093	0.717	2.093	2.093	2.093
7. Ust-Luga - Ulsan	12.6	26	4	4.890	5.6	3.6	5.2	3.3	22.604	5.2	22.119	0.2	17.119	4.895	22.609	22.124	17.124

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

VLSFO (High Fuel and Naphtha/Jet Fuel Prices – Low USD/RUB Exchange rates)

OD pair	Speed (knots)	Time (days)	Days in Port/Canal	Fuel cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Discounted Fees	RFR incl. Disc. Fees	No Fees	RFR incl. No Fees	Fuel Cost (MGO on NSR)	RFR (MGO on NSR)	RFR incl. Discounted Fees (MGO on NSR)	RFR incl. No Fees (MGO on NSR)
SCR																	
1. Ust-Luga - Ulsan	12.9	40	5	8.8	4.0	4.1	6.1	7.5	30.4								
2. Ulsan - Rotterdam	13.1	35	5	8.0	4.0	3.6	5.4	7.1	28.1								
3. Rotterdam - Ust-Luga	11.9	5		0.7		0.5	0.8		1.9								
4. Ust-Luga - Ulsan	12.9	40	5	8.8	4.0	4.1	6.1	7.5	30.4								
5. Ulsan - Rotterdam	13.1	35	5	8.0	4.0	3.6	5.4	7.1	28.1								
6. Rotterdam - Ust-Luga	11.9	5		0.7		0.5	0.8		1.9								
7. Ust-Luga - Ulsan	12.9	40	5	8.8	4.0	4.1	6.1	7.5	30.4								
NSR																	
1. Ust-Luga - Ulsan	11.0	30	4	5.853	10.8	4.0	5.9	5.6	32.129	5.2	3.928	0.2	8.928	5.858	32.134	26.519	21.519
2. Ulsan - Rotterdam	11.7	25	4	5.765	10.8	3.5	5.1	5.2	30.319	5.2	3.446	0.2	8.446	5.772	30.326	24.711	19.711
3. Rotterdam - Ust-Luga	11.4	5		0.821		0.5	1.0		2.396		-0.483		-0.483	0.821	2.396	2.396	2.396
4. Ust-Luga - Ulsan	12.0	27	4	6.601	10.8	3.7	5.4	5.1	31.634	5.2	4.424	0.2	9.424	6.610	31.642	26.027	21.027
5. Ulsan - Rotterdam	11.9	25	4	5.854	10.8	3.5	5.0	5.1	30.277	5.2	3.487	0.2	8.487	5.861	30.285	24.669	19.669
6. Rotterdam - Ust-Luga	11.4	5		0.821		0.5	1.0		2.396		-0.483		-0.483	0.821	2.396	2.396	2.396
7. Ust-Luga - Ulsan	11.8	28	4	6.367	10.8	3.8	5.6	5.2	31.683	5.2	4.374	0.2	9.374	6.374	31.690	26.075	21.075

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

LNG-VLSFO 1,700 m^3 (Low Fuel and Naphtha/Jet Fuel Prices – High USD/RUB Exchange rates)

OD pair	Speed (knots)	Time (days)	Days in Port/Canal	Fuel cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Discounted Fees	RFR incl. Disc. Fees	No Fees	RFR incl. No Fees
SCR													
1. Ust-Luga - Ulsan	16.0	32	5	3.2	4.0	3.3	5.1	2.0	17.7				
2. Ulsan - Rotterdam	16.0	29	5	2.7	4.0	3.0	4.6	1.9	16.2				
3. Rotterdam - Ust-Luga	16.0	4		0.2		0.4	0.6		1.2				
4. Ust-Luga - Ulsan	16.0	32	5	3.2	4.0	3.3	5.1	2.0	17.7				
5. Ulsan - Rotterdam	16.0	29	5	2.7	4.0	3.0	4.6	1.9	16.2				
6. Rotterdam - Ust-Luga	16.0	4		0.2		0.4	0.6		1.2				
7. Ust-Luga - Ulsan	16.0	32	5	3.2	4.0	3.3	5.1	2.0	17.7				
NSR													
1. Ust-Luga - Ulsan	13.2	25	4	1.8	5.7	3.5	5.1	1.5	17.6	5.2	17.2	0.2	12.2
2. Ulsan - Rotterdam	14.0	21	4	1.6	5.6	3.1	4.4	1.4	16.2	5.2	15.7	0.2	10.7
3. Rotterdam - Ust-Luga	16.0	4		0.3		0.4	0.8		1.4		1.4		1.4
4. Ust-Luga - Ulsan	14.6	22	4	2.1	5.6	3.2	4.6	1.4	16.9	5.2	16.5	0.2	11.5
5. Ulsan - Rotterdam	14.2	21	4	1.6	5.6	3.1	4.3	1.4	16.1	5.2	15.6	0.2	10.6
6. Rotterdam - Ust-Luga	16.0	4		0.3		0.4	0.8		1.4		1.4		1.4
7. Ust-Luga - Ulsan	14.3	23	4	2.0	5.6	3.3	4.7	1.4	17.1	5.2	16.6	0.2	11.6

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

LNG-VLSFO 1,700 m^3 (Base Case)

OD pair	Speed (knots)	Time (days)	Days in Port/Canal	Fuel cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Discounted Fees	RFR incl. Disc. Fees	No Fees	RFR incl. No Fees
SCR													
1. Ust-Luga - Ulsan	15.2	34	5	5.1	4.0	3.5	5.4	4.2	22.2				
2. Ulsan - Rotterdam	15.4	30	5	4.3	4.0	3.1	4.7	4.0	20.2				
3. Rotterdam - Ust-Luga	16.0	4		0.3		0.4	0.6		1.3				
4. Ust-Luga - Ulsan	15.2	34	5	5.1	4.0	3.5	5.4	4.2	22.2				
5. Ulsan - Rotterdam	15.4	30	5	4.3	4.0	3.1	4.7	4.0	20.2				
6. Rotterdam - Ust-Luga	16.0	4		0.3		0.4	0.6		1.3				
7. Ust-Luga - Ulsan	15.2	34	5	5.1	4.0	3.5	5.4	4.2	22.2				
NSR													
1. Ust-Luga - Ulsan	13.0	25	4	2.9	5.7	3.5	5.2	3.1	20.5	5.2	20.0	0.2	15.0
2. Ulsan - Rotterdam	13.9	21	4	2.7	5.6	3.1	4.4	2.9	18.8	5.2	18.3	0.2	13.3
3. Rotterdam - Ust-Luga	16.0	4		0.4		0.4	0.8		1.6		1.6		1.6
4. Ust-Luga - Ulsan	14.2	23	4	3.3	5.6	3.3	4.7	2.9	19.8	5.2	19.4	0.2	14.4
5. Ulsan - Rotterdam	14.0	21	4	2.7	5.6	3.1	4.4	2.9	18.7	5.2	18.2	0.2	13.2
6. Rotterdam - Ust-Luga	16.0	4		0.4		0.4	0.8		1.6		1.6		1.6
7. Ust-Luga - Ulsan	14.0	23	4	3.2	5.6	3.3	4.8	2.9	19.9	5.2	19.5	0.2	14.5

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.

LNG-VLSFO 1,700 m^3 (High Fuel and Naphtha/Jet Fuel Prices – Low USD/RUB Exchange rates)

OD pair	Speed (knots)	Time (days)	Days in Port/Canal	Fuel cost	Transit Fees*	Operating Cost	Capital Cost	In-Transit Inventory Cost	RFR	Discounted Fees	RFR incl. Disc. Fees	No Fees	RFR incl. No Fees
SCR													
1. Ust-Luga - Ulsan	14.7	35	5	6.8	4.0	3.6	5.6	6.5	26.5				
2. Ulsan - Rotterdam	15.0	30	5	5.9	4.0	3.2	4.9	6.2	24.1				
3. Rotterdam - Ust-Luga	16.0	4		0.5		0.4	0.6		1.4				
4. Ust-Luga - Ulsan	14.7	35	5	6.8	4.0	3.6	5.6	6.5	26.5				
5. Ulsan - Rotterdam	15.0	30	5	5.9	4.0	3.2	4.9	6.2	24.1				
6. Rotterdam - Ust-Luga	16.0	4		0.5		0.4	0.6		1.4				
7. Ust-Luga - Ulsan	14.7	35	5	6.8	4.0	3.6	5.6	6.5	26.5				
NSR													
1. Ust-Luga - Ulsan	12.9	25	4	4.1	10.8	3.5	5.2	4.8	28.4	5.2	22.8	0.2	17.8
2. Ulsan - Rotterdam	13.9	21	4	3.7	10.8	3.1	4.4	4.4	26.4	5.2	20.8	0.2	15.8
3. Rotterdam - Ust-Luga	15.5	4		0.6		0.4	0.8		1.8		1.8		1.8
4. Ust-Luga - Ulsan	14.0	23	4	4.5	10.8	3.3	4.8	4.4	27.8	5.2	22.2	0.2	17.2
5. Ulsan - Rotterdam	14.0	21	4	3.7	10.8	3.1	4.4	4.3	26.4	5.2	20.8	0.2	15.8
6. Rotterdam - Ust-Luga	15.5	4		0.6		0.4	0.8		1.8		1.8		1.8
7. Ust-Luga - Ulsan	13.8	24	4	4.4	10.8	3.4	4.9	4.5	27.9	5.2	22.3	0.2	17.3

*Transit fees refer to Suez Canal Tolls or Icebreaking fees and relevant costs.