Transportation Research Part A 151 (2021) 28–51

Contents lists available at ScienceDirect

Transportation Research Part A

journal homepage: www.elsevier.com/locate/tra

A techno-economic environmental cost model for Arctic shipping

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A R T I C L E I N F O

Keywords:
Arctic shipping
Zero emissions
Damage costs
Profit maximisation
Alternative fuels

A B S T R A C T

The purpose of this article is to provide a case for advancing methods in Arctic shipping towards a more complete approach. A methods assessment was used to identify core concepts in Arctic shipping and to develop a modelling approach that integrates together policy, alternative fuels, emissions and microeconomic theory - enabling the exploration of financial and implicit damage costs, opportunities and environmental risks within Arctic shipping. The integration of these paradigms can lead to more detailed insights into the economic feasibility of Arctic routes under different policy scenarios. The results indicate that by 2035 under both a business as usual and an Arctic zero emission ECA policy scenario, combined Arctic-Suez transits becomes financially viable for a Handymax wet bulker with a moderate ice class. By 2050 the transpolar route becomes accessible for 5 months for these vessels. The results also show that implicit damage costs cannot be overlooked and that it is possible to advance towards more holistic methods for assessing economic and environmental risks and opportunities in Arctic shipping. Through the incorporation of these factors, this framework can be used to assist policymakers with maximising societal welfare.

1. Introduction

Due to global warming the Arctic is ocean is melting, so new potential shipping routes have emerged attracting interest from industry. The Arctic routes are shorter than their traditional counterparts due to the Earth's curvature and this theoretically enables reduced costs and more trade. Nonetheless, there is not a clear consensus on how Arctic shipping routes will develop and what this will entail for the region and beyond.

The 3 main Arctic shipping routes which have been considered in literature are the Northern Sea Route (NSR), the Transpolar Sea Route (TSR) and the North-West Passage (NWP) (Smith and Stephenson, 2013; Stephenson et al., 2013; Theocharis et al., 2018). The NSR involves transiting through the Russian Arctic, the TSR through the North Pole and the NWP involves the Canadian Arctic - the shortest route is the TSR. In terms of accessibility, the NSR is presently considered accessible to ships with a 1B ice class equivalency and is currently being used by a handful of 1A ice class equivalent ships. There is a consensus that the accessibility of the NSR will increase due to a reduction in sea ice extent enabling ships with no ice class to transit through, however there are still large uncertainties concerning accessibility projections through the TSR (Aksenov et al., 2017; CHNL Information office, 2021; Melia, 2016; Melia et al., 2017a, 2015; Smith and Stephenson, 2013). Some studies predict that the TSR will begin opening around the mid-21st

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https://doi.org/10.1016/j.tra.2021.06.022
Received 22 May 2020; Received in revised form 11 June 2021; Accepted 20 June 2021
Available online 16 July 2021
0965-8564/

century (Melia, 2016; Smith and Stephenson, 2013; Stephenson and Smith, 2015).

1.1. Aim and scope

The core aim of this study is to build upon previous methods to construct a more inclusive modelling framework that can assess the economic feasibility of Arctic shipping under different policy scenarios and the principal focus of this article is Europe-Asia shipping dynamics. The Arctic routes considered are the NSR, the TSR and an intermediary route which bisects the NSR and TSR, as shown in Section 3.1. The NWP is excluded from consideration due to its relatively inferior accessibility (Ostreng et al., 2013). The Suez Canal Route is assumed to be the sole alternative to Trans-Arctic routes. The modelling framework is tested with a Handymax wet bulker.

The environment considered by the model can be broken down into sea ice encountered and emissions. The sea ice encountered affects ship speed and fuel consumption. The model does not include analysis of navigational risks and uncertainties related to sea ice or infrastructure. Emissions from ships are the only form of environmental pollution considered, other forms of pollution (e.g. noise/plastic) are outside the remit of this study. The proposed framework enables an assessment of present and future costs posed to the Arctic from shipping emissions, as well as fuel uptake in Arctic shipping under different policy scenarios. Through incorporating societal cost and a range of alternative fuels, energy and policy solutions can be found to mitigate the environmental risks of disappearing Arctic summer sea ice.

The paper is structured as follows, Section 2 presents a critical assessment of the methods used throughout the Arctic shipping literature and wider Arctic science, and it is structured thematically which enables the literature to be grouped under their corresponding themes. This is followed by Section 3 where based off the methods and concepts discussed in Section 2, an architecture for a techno-economic model is proposed and outlined. Section 4 demonstrates the capabilities of the model in the results section and this is followed by Sections 5 and 6 which discuss and conclude the results respectively.

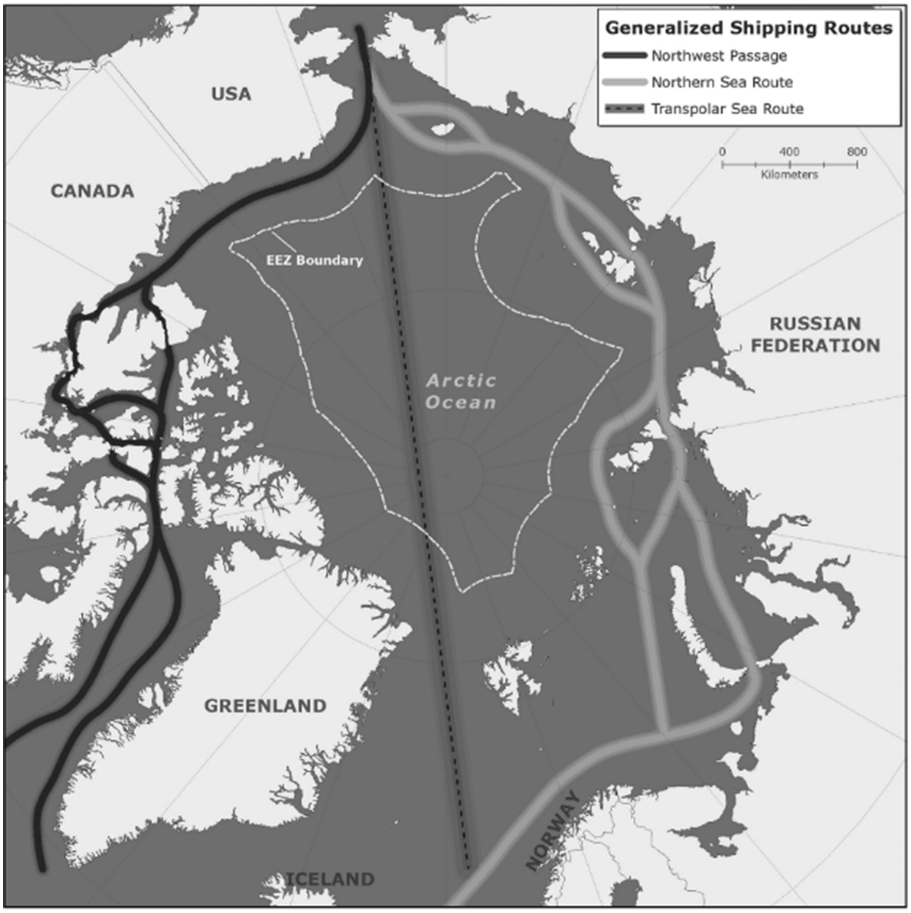

Fig. 1. A projection of the 3 main Arctic routes, the NSR, the TSR and the NWP superimposed onto the Arctic Ocean. Reprinted from Stevenson et al. (2019), copyright (2019) with permission from Elsevier.

2. Assessment of previous methods

2.1. Trade and route selection

Many articles have explored the effect that new shipping routes will have on industry and international trade dynamics. Transport cost models have been used to analyse the routes with respect to the industry and gravity models have been used to analyse the effects on trade (Bekkers et al., 2016; Bensassi et al., 2016; Buixadé Farré et al., 2014; Cariou and Faury, 2015; Ørts Hansen et al., 2016; Yangjun et al., 2018; Zhang et al., 2016a). More recently, the influence of critical parameters over the commercial feasibility of Arctic routes have been studied (Cariou et al., 2019; Cheaitou et al., 2020; Faury et al., 2020; Theocharis et al., 2019).

The literature on Arctic shipping route selection tends to involve cost-modelling a reference vessel's operations across the Arctic against competing routes (Cariou and Faury, 2015; Furuichi and Otsuka, 2015, 2013; Lasserre, 2015; Lasserre et al., 2011; Ørts Hansen et al., 2016; Theocharis et al., 2018). Some qualitative studies explore less tangible factors, such as route reliability and operational risks through surveys and interviews with operators (Beveridge et al., 2016; Lasserre et al., 2011; Solvang et al., 2018; Stott, 2014). The main assumption is that the competitive route is the cheapest route. However, there is some evidence to suggest that the commercial feasibility of the NSR depends on the strategy of the operator and economic conditions. Profit maximisation, high fuel costs and oil prices favoured the NSR, indicating that the competitiveness of Arctic routes may be more nuanced (Faury et al., 2020). There is also an emerging body of work on what the environmental effects of Arctic shipping are (Lindstad et al., 2016; Schröder et al., 2017; Stephenson et al., 2018; Winther et al., 2017; Zhu et al., 2018). The study by Zhu et al. (2018) analyses the environmental costs of air pollution and savings from transit times, the environmental costs were adapted from Korzhenevych et al. (2014) and this approach expands upon analysis of shipping costs by enabling the analysis of the damage costs of emissions. This article aims to account for the effect that Arctic shipping will have on the Arctic environment.

The effect that the melting Arctic will have on international trade is a theme which some researchers have recently delved into (Bekkers et al., 2016; Bensassi et al., 2016; Yangjun et al., 2018; Yumashev et al., 2017). International trade is a key driver for maritime activity, goods which are extracted or produced from distant regions get transported to markets where they are demanded (Smith, 2012). An article by Yumashev et al. (2017) combines the technical detail of bottom-up modelling with the behavioural realism of a top-down gravity model, enabling a multi-dimensional analysis of a complex situation. There are articles and papers which incorporate sea ice resistance and the effects of sea ice on navigational risk (Omre, 2012; Rigot-müller et al., 2019). This study aims to build on the co-dependencies between economics, sea ice and emissions by integrating further policy with alternative fuel uptake.

2.2. Fuels

Adopting zero-carbon technologies is one of the strategies through which greenhouse-gas mitigation targets can be achieved (Balcombe et al., 2019; Bouman et al., 2017; Brynolf et al., 2014; Han, 2010). It is what links shipping activity to air pollution and any consequential environmental effects, it bridges the natural and social sciences together through altering the commercial profile and emissions of a vessel. Fuel transitions are an area attracting attention from governments and industry and with an industry wide debate on how to replace residual fuel oil taking place, there is a natural overlap with Arctic shipping as fuel costs form the largest cost factor in simulations. The shipping sector looks to meet the objectives agreed in the IMO initial strategy, to at least halve GHG emissions by 2050 on 2008 levels. (Argyros et al., 2014; Department for Transport, 2019; Lasserre, 2015; Lloyd's Register; UMAS, 2017; Raucci et al., 2017b; Wan et al., 2018). Some studies have incorporated fuels and emissions into the environmental analysis of Arctic shipping and the positive contributions already made in this field can be expanded upon to incorporate this aspect in the proposed modelling approach (Corbett et al., 2010; Larsen et al., 2016; Schröder et al., 2017; Winther et al., 2017).

2.3. Emission species

The review in Theocharis et al. (2018) suggests the effects of shipping activity in the Arctic and its environmental impacts needs to be researched thoroughly. Studies by Law and Stohl. (2007) and Quinn et al. (2008) recommend that all emissions which contribute to radiative forcing in the Arctic should be targeted to slow down regional and global warming. Shipping currently contributes to a range of emissions which accelerate regional and global warming, it is therefore paramount that the type and volume of emissions can be characterised and ascertained as accurately as possible. The crux of using a more balanced analysis, is that policy inputs can be tested to see how they affect overall Arctic shipping emissions and the trade-off between economic gains and societal cost can be assessed. An evaluation enabled through a techno-economic framework.

Current greenhouse gas emissions (GHGs) determine the extent to which sea ice extent will lessen and therefore, how accessible the routes will be (Melia, 2016). Complex climate models from CMIP5 are used to capture the mechanisms behind radiative forcing in the Arctic (Bellouin et al., 2011; Hibbard et al., 2007; Khon et al., 2017; Notz and Stroeve, 2018, 2016; Sand et al., 2016; Stroeve et al., 2012). Studies by Melia, Haines and Hawkins, (2016); Aksenov et al. (2017) use data produced from complex climate models to gauge the accessibility of Arctic routes. In Khon et al. (2017) the navigable period is calculated from a range of CMIP5 projections and averaged. Integrating sea ice analysis with techno-economic shipping models can help to produce more robust results and this has been evidenced with economic/decision based analysis of Arctic shipping (Bensassi et al., 2016; Rigot-müller et al., 2019; Yumashev et al., 2017). Connecting sea ice analysis to techno - economic, fuels and emissions analysis will aid in understanding the costs for Arctic shipping from a techno - economic and emissions point of view.

2.3.1. Greenhouse gases, air pollution, and black carbon

The effects of GHGs are well documented, and the Arctic is already the fastest warming region of the planet so it is important that this trend is not accelerated through unsustainable shipping (AMAP, 2017; Khon et al., 2010). Methane and Nitrous Oxide have a 100-year global warming potential (GWP) of 34 and 298 respectively, meaning they are 34 to 298 times more potent than CO_2, in terms of their global warming impact over a 100 year horizon. Therefore both gases deserve attention despite being emitted in smaller quantities relative to carbon dioxide (IPCC, 2013a). This area has already received attention within Arctic shipping and beyond (Lindstad et al., 2016; Notz and Stroeve, 2016; Schröder et al., 2017; Stephenson et al., 2018). Nonetheless, given that emissions south of the Arctic circle also interact with the Arctic climate and accelerate warming, it is necessary and justified to include lifecycle emissions of ships in any analysis (Stroeve et al., 2012).

Emission species such as Nitrogen Oxides (NO_x) and aerosols/particulate matter (PM) have complex and diverse effects on the Arctic climate. Nitrogen Oxides lead to the production of Ozone in the lower atmosphere, it is a gas that is both toxic and a GHG. Ozone is not directly emitted from ships but is a product of species reacting in the presence of sunlight, these species are known as Ozone precursors (Sand et al., 2016). However, NO_x also has a cooling effect as it depletes methane in the atmosphere, this leads to contradicting forcing effects (Fuglestvedt et al., 2010; IPCC, 2013a). Lastly, NO_x is also responsible for harmful health effects on local populations. Shipping in the Canadian Arctic has led to an increase in NO_x and Ozone levels (Aliabadi et al., 2015; Law et al., 2017). Similarly, different subsets of PM have opposite effects with organic carbon (OC) having a cooling effect and black carbon (BC) having a strong forcing impact (IPCC, 2013b). The case of NO_x and PM demonstrate the complexity of the Arctic climate and how exhaust emissions can interact with the local atmosphere.

Black carbon is a subset of PM and they both contribute to an increase in radiative forcing through reducing the albedo of snow and ice (Bond et al., 2013). Studies on PM and BC are gaining momentum and traction and it is one of the main reasons behind the draft Heavy Fuel Oil (HFO) ban in the Arctic (Comer et al., 2017; Council, 2017a, 2017b; IMO, 2019a; U.S. Environmental Protection Agency, 2016). Increases in shipping activity and the usage of fossil fuels in Arctic regions will cause BC emissions to rise and deposit into local areas, accelerating feedback cycles and melting ice. The locality of Arctic shipping emissions is closely connected with the impact that they will have on the local environment (Lindstad et al., 2016). Emissions in the Arctic are especially important given the low threshold for passing the Arctic summer sea ice tipping point (see Fig. 2).

The graph in Fig. 2 shows that the Arctic summer sea ice tipping element is only slightly above the 2° target set by the Paris agreement. The darker colour at the tip of each bar represents the increased likelihood that the tipping point will be passed at that corresponding temperature. Therefore if the mean surface temperature rises beyond 2°, Arctic summer sea ice is one of multiple Earth systems which will suffer from irreversible changes (Schellnhuber et al., 2016). It is critical that species which contribute to forcing are

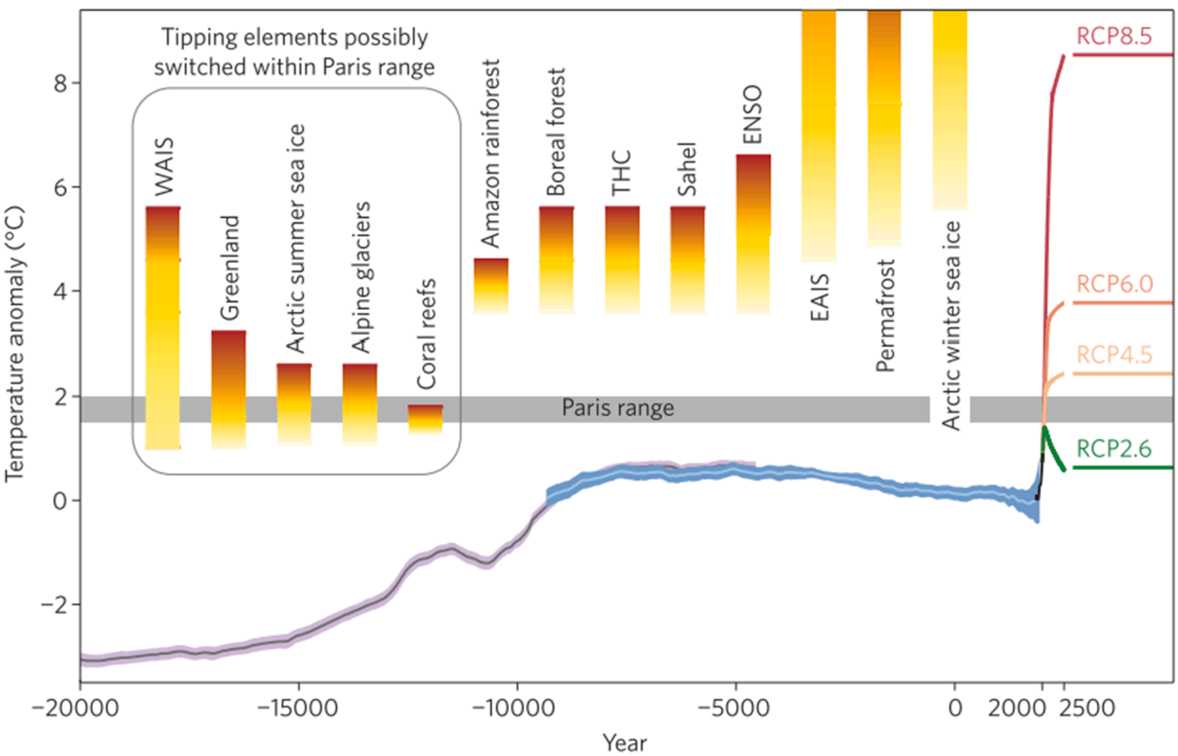

Fig. 2. The warming tipping points for each biosystem. Sourced from Schellnhuber et al. (2016).

targeted to minimise the chance of passing the tipping point, which if passed will irreversibly amplify warming and cause significant change (Lenton, 2012; Lenton et al., 2008; Schellnhuber et al., 2016). In addition to there being unique tipping points for each ecosystem, there is a risk that these tipping points may cascade –preventing stabilisation of temperature increases which culminate in a 'Hothouse Earth' scenario (Lenton et al., 2019; Steffen et al., 2018). Therefore, there is a significant need to assess the benefits and trade-offs of Arctic shipping in light of environmental concerns.

2.4. Policy

The main governing body for international shipping is the International Maritime Organisation (IMO). The introduction of the initial greenhouse gas strategy is going to have consequences for global shipping in addition to Arctic shipping (IMO, 2018). The main purpose of introducing environmental policy is to address market failure, caused by overlooking environmental costs (Hepburn, 2010). With respect to Arctic shipping, there have been concerns over whether or not the environmental costs outweigh the economic benefits (Lindstad, Bright and Strømman, 2016; Zhu et al., 2018). The effect of deploying Arctic policy instruments such as a pollution tax, an emission control area (ECA) or slow steaming needs to be studied more thoroughly and it has been suggested that the efficacy of Arctic policy measures may be sensitive to various factors like thick sea ice coverage (Cheaitou et al., 2020; UMAS, E4tech, Frontier, 2019). Whilst presently only emissions are considered, this framework can be expanded to include other costs.

Policies can take two approaches, a 'command and control' (C&C) or a 'market-based' approach with both having their pros and cons (Behrendt et al., 2010). Its geographic extent can vary from local to global depending on the authority involved. Modelling the effects of policy is important, especially in the case of the Arctic as it will assist the policymakers in maximising the welfare of all agents in the industry, whilst simultaneously preventing market failures.

The main benefit of a command and control approach is that it allows the regulatory body more control over what design standards the industry in question should adopt, but at the expense of cost efficiency (Behrendt et al., 2010). Command and control policies often involve the introduction of new technology and performance standards (Goulder and Parry, 2006; Sterner and Robinson, 2018). Examples in shipping include the NO_x tier III requirements, Sulphur Cap and Polar Code (IMO, 2016a, 2015). In this paper, only a C&C approach is considered but there is scope for adding market-based policies in a further development of the model.

3. Model architecture

A model was constructed to demonstrate proof of concept for an integrated approach, using an economic profit maximisation framework. Economic profit underpins and links the different paradigms together and is distinct from financial profit as it can include implicit costs. In this case economic profit is a function of the fuel the ship uses and it enables an investigation of which technologies can maximise profit for the agent.

Fig. 3 outlines how the themes within Arctic shipping are linked together under a closed system. The economic feasibility of Arctic routes will drive shipping activity there, which in turn influences the volume of emissions which take place in the Arctic, creating a need for environmental policy that will change ship design standards. The alterations to the ship specifications change the costs of operating through Arctic routes, ultimately affecting its economic viability.

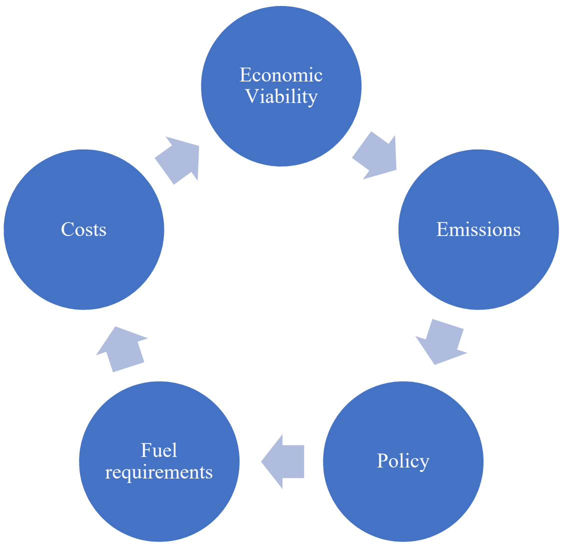

Fig. 3. The illustration shows how economic viability drives emissions, forcing policymakers to increase ship design and operating standards, consequentially increasing costs, altering the NSR's economic feasibility.

The original ship design specifications are obtained from the Whole Ship Model (WSM) which can then be modified to acquire parameters for ice strengthened variants (Calleya et al., 2017). Section 3.2. explains how this is done in detail. Given that a range of fuels are being considered, different ship designs based off design speed must also be included to account for changes to engine and fuel. Additional ship specifications for each IMO size and category were obtained from the IMO 3rd GHG study annexes (Smith et al., 2014). With respect to time, the model provides a cross-sectional analysis of the years 2020, 2035 and 2050 so that the timescale aligns with the IMO initial GHG strategy's guidelines. Furthermore, the timeline does not extend too far into the future where modelling projections become uncertain (Melia et al. 2017).

3.1. Sea ice

The CMIP5 model HadGEM-2-ES was selected, because its co-ordinate system is compatible with the method in which the Arctic routes have been defined (longitude and latitude) (Bellouin et al., 2011). The NSR route was defined using the website S&P Global Platts (2019) and the second route is seen as the intermediary route which follows the same trajectory as the NSR, but the latitude is exactly halfway between the North Pole and the NSR. However, it is still assumed that it would pass through the Russian EEZ. The third and final route is assumed to be the TSR, with the start and end points being the same as the other 2 routes. The starting and destination port is assumed to be Mongstad and Mizushima respectively, as in Zhang et al. (2016a).

The ice thickness from a representative concentration pathway (RCP) 4.5 scenario experiment was selected as it is assumed to be the intermediate case. The routes are illustrated in Fig. 4 and to obtain the distance, it was broken down into its constituent waypoints. The distance between each waypoint can be calculated using the great circle equation and then the distances are summed together to obtain the total route distance (Chen et al., 2004; Kifana and Abdurohman, 2012).

The illustrations in Fig. 4 don't represent the whole route, only the Arctic component as the starting and end points for each route are the same. The routes only diverge upon entering the geographic Arctic and converge again upon exiting the Arctic. The equivalent sea ice thickness concept is used as it provides greater fidelity in terms of representing the ice conditions local to the ship, compared to exclusively using the thickness data extracted from the HadGEM model. For this model, it is defined as the product of sea ice thickness and sea ice area fraction (Bergström et al., 2017).

$$H_{eq} = H_{thick} \times H_{af} \tag{1}$$

where H_{eq} is the equivalent sea ice thickness, H_{thick} is the sea ice thickness and H_{af} is the sea ice area fraction. The data for the thickness and area fraction was obtained from the HadGEM-2-ES model, the equivalent sea ice thickness was the primary variable used to construct the navigable period. The variable can then be cross referenced with POLARIS risk index values, to construct navigable periods based off the reference vessel's ice class (Aksenov et al., 2017; IMO, 2016b; Melia et al., 2017a; Stephenson et al., 2013).

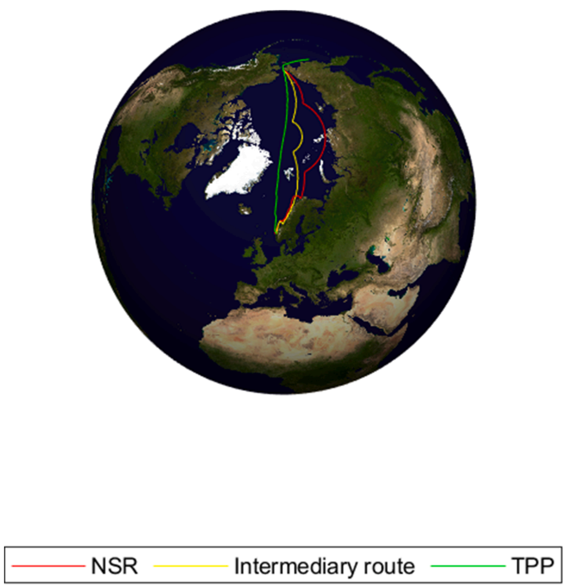

Fig. 4. An illustration of the Arctic routes considered by this model. Created using the climate data toolbox, source: (Greene et al., 2019).

3.2. Ice class modifications

A convincing study on the operating and commercial performance of ice strengthened ships relative to their open water counterparts is presented by Solakivi, Kiiski and Ojala (2019), and Solakivi, Kiiski and Ojala (2018). For this study, a Handymax wet bulker was chosen to test the proposed framework with. Given the significant differences and the introduction of the Polar Code (IMO, 2015) any rigorous analysis of Arctic shipping must incorporate operational and commercial changes to the vessel which come as a result of ice strengthening (IMO, 2015).

It was found in Solakivi, Kiiski and Ojala (2018) that no significant difference existed between the Polar Class (PC) and Finnish-Swedish-Ice-Class-Rules (FSICR) regimes. Of the ships which transited through the NSR between 2012 and 2018, 63% of ships had an ice class of Arc 4 which is roughly equivalent to a FSICR of 1A (CHNL Information office, 2021; Clarksons, 2020; Finnish Transport Safety Agency, 2017; Solakivi et al., 2018; Zhang et al., 2016b).

It was assumed that an Arctic bound ship will be built to an Arc4/1A specification as this is the modal ice class for ships bound for the NSR, meaning it cannot break through more than 0.8 m first-year ice independently (Kujala et al., 2018).

The IMO stipulates at what ice thicknesses necessitate an icebreaker escort and at which speed (3kts) the vessel should follow when being escorted by an icebreaker (IMO, 2016b) Through keeping power fixed and making speed a function of ice thickness, operating profiles and navigable windows can be constructed for each annual cross-section. Ice resistance was calculated using Lindqvist's equations as this takes hull geometry into account (Lindqvist, 1989).

$$IB = \begin{cases} v < 3kn, IB = 1 \\ v > 3kn, IB = 0 \end{cases} \tag{2}$$

Eq. (2) shows that if the speed (v) is below 3 knots then an icebreaker escort (IB) is required. For a certain scenario the route was avoided entirely if the thickness was greater than 0.8 m since this is the maximum allowable thickness at 1A level. The ice data has a monthly temporal resolution and so the navigable period can only be defined in multiples of 30 days.

Log linear regression models were created to predict the installed power of ice class vessels, installed power from the Clarksons World Fleet Register (WFR) is the dependent variable (Clarksons, 2020). The data for all variables was acquired from the Clarksons (WFR) where databases with open water vessels and ice class 1A ships could be extracted (Clarksons, 2020).

$$ln(P_{ice}) = 2.6851 + 0.5958 \times ln(dwt_{ice}) + 0.2307 \times Cat_{ice} \tag{3}$$

where P_{ice} is the installed power of the ice strengthened wet bulker, dwt_{ice} refers to the deadweight tonnage of the ice strengthened reference vessel, Cat_{ice} is a categorical variable which takes a binary value of 1 or 0 depending on whether or not the vessel has an ice class. This model uses data from WSM for deadweight and installed power specifications, the ice class design specifications were calculated by the proposed model as WSM exclusively produced values for open water (OW) vessels (Calleya et al., 2017). Using the ship specifications calculated using Eq. (3) and from WSM the energy demand of a ship can be calculated along with the fuel consumed.

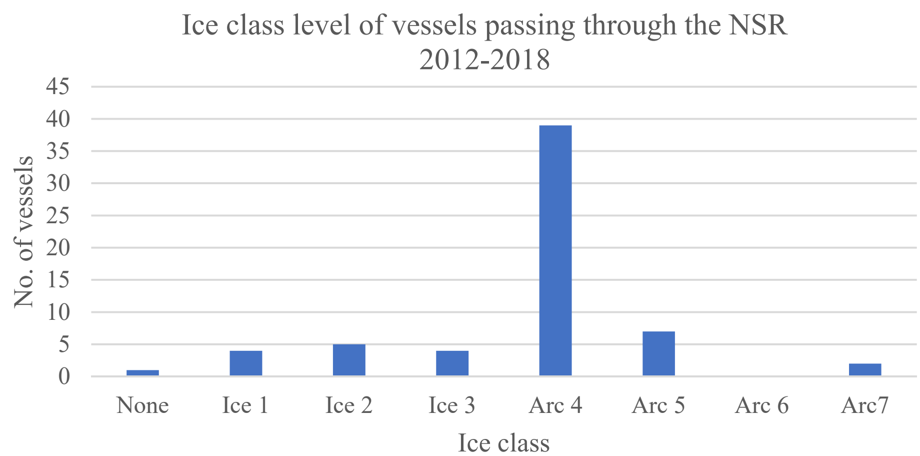

Fig. 5. The number of vessels and their corresponding ice classes which have transited through the NSR between 2012 and 2018, out of 62 ships, 39 Arc 4 ships passed through. The data used to produce Fig. 5 was sourced from CHNL Information office (2021).

Table 1
The R^2 values and p-values, combined with the number of observations.

Model	R^2	p-value*	Number of observations
Ice strengthened newbuild power	0.9902	0	5595

*All variables had a p-value of zero or equivalent.

$$E_{HFO,2-stroke,k,t} = P \times T_{t,k} \times L \tag{4}$$

$$sfc_{load} = sfc_{base} \times (0.455 \times L^2 - 0.71 \times L + 1.28) \tag{5}$$

$$FC_{HFO,2-stroke,k,t} = sfc_{HFO,2-stroke} \times E_{HFO,2-stroke,k,t} \tag{6}$$

$$FC_{i,j,k,t} = \frac{sfc_{i,j}}{sfc_{HFO,2-stroke}} \times FC_{HFO,2-stroke,k,t} \tag{7}$$

$$AuxFC_{i,j,k,t} = \frac{sfc_{i,j}}{sfc_{HFO,4-stroke}} \times AuxFC_{HFO,4-stroke,k,t} \tag{8}$$

$$BoilerFC_{i,j,k,t} = \frac{sfc_{i,j}}{sfc_{HFO,2-stroke}} \times BoilerFC_{HFO,k,t} \tag{9}$$

The baseline energy consumed ($E_{HFO,2-stroke,k,t}$) is in kilowatt hours (kWh). The vessel's energy consumed is calculated by multiplying the installed power of the vessel P, determined either by WSM or from Eq. (3) with the engine load factor given by L, the time in hours that the vessel is operating at sea ($T_{t,k}$), given route k during year t. The time at sea is extracted from the IMO third GHG study (Smith et al., 2014). Eq. (5) is also extracted from the third GHG study and is used to model the main engine specific fuel consumption (SFC) based off the assumed engine load (Smith et al., 2014). It is assumed that the additional power requirement for the ice class vessel can be accommodated through extra engine cylinders. In the experiments outlined in Section 4.0 the engine load factor is assumed to be 51% which is the average load factor of the reference vessel for that type and size (IMO, 2020). The base ship's energy consumption assumes an HFO/2-stroke combination, the same goes for the baseline fuel consumption $FC_{HFO,2-stroke,k,t}$ at the corresponding route and year. The energy consumed is assumed to remain the same regardless of fuel or engine used.

The variable $FC_{i,j,k,t}$ is the main engine fuel consumption with i and j representing the fuel and engine. The base auxiliary fuel consumption $AuxFC_{HFO,4-stroke,k,t}$ can be calculated using Eq. (6) by substituting in the corresponding values. The boiler consumption can be found by multiplying the consumption rate in tons per day by the annual time it is operating for in days. The base auxiliary and boiler specific fuel consumption/tons per day, as well as the time spent at sea are acquired from WSM and the 3rd GHG study respectively (Calleya et al., 2017; Smith et al., 2014). Fuel costs can then be calculated by multiplying the fuel consumed with the corresponding fuel price at that point in time.

$$C_{ME,i,j,k,t} = FC_{i,j,k,t} \times p_{i,t} \tag{10}$$

$$C_{Aux,i,j,k,t} = AuxFC_{i,j,k,t} \times p_{i,t} \tag{11}$$

$$C_{Boil,i,j,k,t} = BoilerFC_{i,j,k,t} \times p_{i,t} \tag{12}$$

The outputs $C_{ME,i,j,k,t}$, $C_{Aux,i,j,k,t}$ and $C_{Boil,i,j,k,t}$ represent the fuel costs of the main engine, auxiliary engine and boiler with i, j, k and t retaining the same meaning as in Eqs. (4)–(9). The input variable $p_{i,t}$ is the fuel price of a specific fuel and time and was obtained from internal datasets (UMAS et al., 2019).

3.3. Commercial profile

It is assumed that these operations fall under a time-charter relationship, as this arrangement mitigates the financial risks posed by market volatility. This means that the shipowner is responsible for the operating and capital costs, whilst the charterer is accountable for the voyage costs (Stopford, 2008) (see Table 2).

In terms of how Table 2 applies to the model architecture, the charterer is responsible for all the constituent costs under the 'voyage expenses' heading, and the shipowner is accountable for the costs under the 'capital expenses' and 'operating expenses' headings.

3.3.1. Capital costs

Annuities are commonly used in the literature to model the capital cost of ships (Furuichi and Otsuka, 2015; Ørts Hansen et al., 2016; Raucci et al., 2017a). However, annuities only form one component of the capital cost and the vessel's asset value will vary with

Table 2
The breakdown of the different types of expenses and their constituent cost pools. The structures are sourced from Stopford (2008).

Capital expenses	Operating expenses	Voyage expenses
Annuity instalments	Crewing fee	Fuel costs
Depreciation cost	Maintenance fee	Port dues
Debt repayment	Insurance fee	Route tariffs
Interest payment		Charter rate expenses
Dividends		Ice breaking fees

different engines and fuels.

$$V = UC_j \times P_{inst} \tag{13}$$

where V is the value of the ship, UC is the unit cost in ($/MW) with engine j and P_{inst} is the installed power of the vessel. The deposit and annual instalments can be determined from the value of the ship. Once the value of the vessel has been ascertained, the constituent capital cost components can be found. It is assumed that the shipowner finances most of the ship's purchase through a bank loan.

$$DP_{i,j} = V \times \frac{D}{100} \tag{14}$$

$$C_{AC,i,j} = \frac{\left(V - DP_{i,j}\right) \times R}{1 - (1 + R)^{-m}} \tag{15}$$

$$C_{DPA,i,j} = \frac{DP_{i,j}}{t} \tag{16}$$

$$C_{Dep,i,j} = \frac{V_{i,j}}{t} \tag{17}$$

$$C_{Cap,i,j} = C_{AC,i,j} + C_{DPA,i,j} + C_{Dep,i,j} \tag{18}$$

where $DP_{i,j}$ is the down payment for the ship with fuel i and engine$j$, V is the value determined previously and D being the assumed down payment percentage. The variable R is the loan interest rate (assumed to be 7%), m is the amortisation period (assumed to be 15 years), t is the ship's useful life (25 years) and $C_{AC,i,j}$ is the annual annuity payment to the bank (Ørts Hansen et al., 2016; Stopford, 2008). Furthermore, $C_{DPA,i,j}$ is the downpayment annualised over the vessel's useful life, with, $C_{Dep,i,j}$ represents the depreciation cost (assuming straight line depreciation). Lastly, $C_{Cap,i,j}$ is the total annual capital cost.

Different fuels will have different gravimetric and energy densities, furthermore the engines that correspond with different fuels will also have efficiencies which vary, meaning that fuel storage size and SFC will change with the main operating fuel. With less dense fuels, more fuel storage space is required to keep the same level of energy compared to a residual fuel oil (the traditional base fuel). To accommodate increases in fuel storage space, cargo space will have to be reduced unless the maximum range of the ship (in terms of distance) is reduced (Raucci et al., 2017b, 2015). It is assumed in this article that the vessel range remains the same for all operating fuels, so cargo carrying capacity is reduced.

The term dwtloss/MWh refers to the loss in deadweight tonnes per megawatt hour of fuel stored by the vessel, relative to an HFO/2-Stroke combination. Considering a MDO/Diesel electric combination, the deadweight loss is an absolute value of 0.03 t/MWh relative to the same ship design with an HFO/2-Stroke combination, this is due to differences in engine efficiencies and fuel energy content. More details of the concept can be found in Raucci et al. (2017b). In this case, the ship is assumed to carry enough fuel to complete exactly one trip around the Suez Canal. If the ship's displacement remains constant, an ice strengthened ship will also incur a loss in cargo carrying capacity due to the additional weight needed to operate in icy conditions. A regression model was constructed to convert the gross tonnage (gt) of 1A ice class ships into deadweight tonnage.

Table 3
The values below indicate how the SFC will change according to the vessel's engine type and how the fuel storage alters the cargo capacity of the vessel. The concept and data is adapted from Raucci et al. (2017b); Raucci et al. (2015).

Engine	SFC ratio	dwt loss (t/MWh)
Fuel Oil/2-stroke diesel	1.0000	0
Fuel Oil/4-stroke diesel	1.0526	0
Marine Diesel Oil (MDO)/Diesel electric	1.1053	0.03
4-stroke liquefied natural gas (LNG) internal combustion engine (ICE)	0.9053	0.09
Hydrogen fuel cell	0.3421	0.26
Ammonia fuel cell	2.4000	0.06
LNG fuel cell	0.8842	0.09
Ammonia ICE	2.0579	0.06
Hydrogen ICE	0.5789	0.43

Table 4
The R^2 values and p-values, combined with the number of observations.

Model	R^2	p-value*	Number of observations
Ice Wet bulker deadweight	0.9964	0	602

*All variables had a p-value of zero or equivalent.

$$ln(dwt_{ice}) = 0.18117 + 1.0345 \times ln(gt) - 0.078023 \times Cat_{ice} \tag{19}$$

The variable gt is the gross tonnage of the reference vessel, which is assumed to be the same for both ice class and open water vessels. The other variables dwt_{ice} and Cat_{ice} take the same meaning as in Eq. (3). The reduction of deadweight from Table 3 is in addition to any reductions from ice strengthening.

3.3.2. Operating, voyage expenses and profit

Before profit can be determined, the operating and voyage expenses must be acquired. Operating expenses consist of insurance, maintenance and crew fees and they were assumed to vary with the ship's value - determined by Eq. (13). Aside from fuel costs, voyage expenses constitute fees, tariffs and the charter rate expense. Information on distances, fees and tariffs can be found on the relevant authorities websites or from other studies (Agencies, 2018; Buixadé Farré et al., 2014; Faury and Cariou, 2016; Furuichi and Otsuka, 2015; Omre, 2012; Ørts Hansen et al., 2016; S&P Global Platts, 2019; Yokohama, 2013). The operating expenses were otherwise calculated using the same equations and values as in Ørts Hansen et al. (2016). Voyage expenses were calculated by summing the constituent cost components.

$$C_{IB,k,t} = gt \times p_{IB} \times n_{k,t} \tag{20}$$

$$C_{IP,k,t} = T_{k,t} \times p_{IP} \times n_{k,t} \tag{21}$$

$$C_{Tariff,k,t} = gt \times p_k \times n_{k,t} \tag{22}$$

$$C_{Port,k,t} = gt \times p_{Port} \times n_{k,t} \tag{23}$$

$$C_{V,i,j,k,t} = C_{ME,i,j,k,t} + C_{Aux,i,j,k,t} + C_{Boil,i,j,k,t} + C_{IB,k,t} + C_{IP,k,t} + C_{Tariff,k,t} + C_{Port,k,t} \tag{24}$$

With $C_{IB,k,t}$ representing the total annual icebreaker escort cost, p_{IB} is the icebreaking fee, $n_{k,t}$is the number of times the vessel transits down route$k$ in a given year t (Lasserre, 2014; Ørts Hansen et al., 2016). The icebreaker price is extracted from Zhang et al. (2016b). Similarly, $C_{IP,k,t}$ is the annual ice pilot fee and the variable $T_{k,t}$ is the time spent (in days) in the Arctic component of the corresponding route and year. The ice pilot price is extracted from Furuichi and Otsuka (2015). Annual tariff costs are given by $C_{Tariff,k,t}$ and p_k is the route tariff per gt (Furuichi and Otsuka, 2015). Port dues are given by $C_{Port,k,t}$ with p_{Port} equal to the port fee and lastly $C_{V,i,j,k,t}$ is the total voyage cost for the ship design.

$$R_{owner,t} = 365 \times min(TC_{i,j,k,t}) \tag{25}$$

$$FR_{i,j,k,t} = \frac{C_{V,i,j,k,t} + 365 \times TC_{i,j,k,t}}{dwt \times n_k} \tag{26}$$

$$PV_{i,j,k,t} = \frac{R_{owner,t} + B \times (minFR_{i,j,k,t} \times dwt \times n_{k,t} - C_{V,i,j,k,t} - R_{owner,t}) - C_{Cap,i,j} - C_{Op,i,j}}{(1+r)^t} \tag{27}$$

To close the time-charterer system, the shipowner and charterer's profits are merged together as in Raucci et al. (2017a) and discounted to reflect the time value of money. The annual time charter rate and charterer's freight rate was calculated for each ship design and each cross section, with the minimum value for both being selected to apply for that type and size and that year. This is to ensure a fair comparison across all the ship designs and reflect the decisions that operators would have to make to stay competitive. The variable $PV_{i,j,k,t}$ is defined as the profit's present value for the matching ship design. The discount rate r was chosen to be 3%, which is equal to the discount rate used for the chosen social costs from Shindell (2015a) in Section 3.6.

Where $TC_{i,j,k,t}$ is the time charter rate of an open-water ship design, with fuel i, engine j and route k at the corresponding year, it was interpolated using internal datasets. The variables $C_{Cap,i,j}$ represent the capital cost calculated in Eq. (18) and $C_{Op,i,j}$ is the operating cost which is calculated in the same way as in Ørts Hansen et al. (2016). The cargo capacity dwt is the deadweight tonnage. The variable $FR_{i,j,k,t}$ is a break-even freight rate calculated by dividing the total voyage expenses plus annual charter fee by the amount of annual transport work. It is assumed to be the freight rate for the commodity being transported, as for$R_{owner,t}$ the variable corresponds with the shipowner's revenue. A freight rate is calculated for each compatible ship design. To compare the profits of the ship designs the minimum calculated freight rate is used in Eq. (27), the minimum is selected as it is assumed that the same commodity is being transported for the same ship type and size, regardless of the operating fuel. Under a competitive market, the lowest freight rate is assumed to be the market rate as the charterer who charges a higher freight rate is unlikely to attract significant demand for the same activities.

For a time-charter arrangement, the shipowner's revenue is equal to the time charter rate multiplied by the number of days the ship is used for, which in this case is assumed to be a year (365 days). Lastly, $C_{V,i,j,k,t}$ is the total voyage cost.

The variable B is the market barrier factor, representing the information asymmetry between owner and charterer (Rehmatulla, 2014). In this case, $B = 1$ thereby assuming perfect information symmetry. Eq. (27) can be reduced further.

$$PV_{i,j,k,t} = \frac{(min(FR_{i,j,k,t}) \times dwt \times n_{k,t}) - C_{V,i,j,k,t} - C_{Cap,i,j} - C_{Op,i,j}}{(1+r)^t} \tag{28}$$

The discounting is relative to 2020 which is when t is set to equal zero. The emissions for each ship design can also be acquired simply by multiplying the fuel's corresponding emission factors with the design's annual fuel consumption.

$$Em_{ME,i,j,t,s} = FC_{i,j,t} \times EF_{i,s} \tag{29}$$

$$Em_{Aux,i,j,t,s} = AuxFC_{i,j,t} \times EF_{i,s} \tag{30}$$

$$Em_{Boil,i,j,t,s} = BoilerFC_{i,j,t} \times EF_{i,s} \tag{31}$$

$$Em_{i,j,t,s} = Em_{ME,i,j,t,s} + Em_{Aux,i,j,t,s} + Em_{Boil,i,j,t,s} \tag{32}$$

The emission factor (in tons per ton) for a given fuel and species is given by $EF_{i,s}$ with $Em_{ME,i,j,t,s}$ $Em_{Aux,i,j,t,s}$ and $Em_{Boil,i,j,t,s}$ correspond with main engine, auxiliary and boiler emissions for a ship with s being the species. Eqs. (4)–(9) yield the fuel consumption values.

3.4. Policy compatibility

The projected emissions for each species can be calculated for a baseline HFO powered vessel with a 2-stroke engine. If the emissions (relative to the baseline ship's emissions) was found to be less than the policy target then that ship design was found to be incompatible.

$$ComPol_{t,s} = 1 - Pol_{t,s} \tag{33}$$

$$ComEm_{i,j,t,s} = Em_{HFO,2-stroke,t,s} \times ComPol_{t,s} \tag{34}$$

$$Ves_{i,j} = \begin{cases} Em_{i,j,t,s} < ComEm_{i,j,t,s} Ves_{i,j} = 1 \\ Em_{i,j,t,s} > ComEm_{i,j,t,s} Ves_{i,j} = 0 \end{cases} \tag{35}$$

where Pol_S is the emission reduction target set by policy, $ComPol_s$ is the maximum proportion of emissions which can be emitted relative to the baseline. The baseline emissions are assumed to be the emissions produced by an HFO/2-stroke combination and $Em_{HFO,2-stroke,s}$ represents this. The variable $ComEm_{i,j,s}$ is defined as the maximum amount of emissions which can comply with policy. Lastly, $Ves_{i,j}$ is the vessel design for a given fuel and engine type. The policies implemented by the model effectively function as an ECA and are technology agnostic. The binary value of 1 and 0 corresponds to compatible and incompatible designs respectively, this process can be used for all vessel designs to build a compatibility matrix for all ship designs. Whilst the model only considers policies which result in reductions of emissions, other non-emission related measures such as the IMO 2020 Sulphur cap and the Arctic HFO ban are considered (IMO, 2019a, 2016a). It is assumed that Low Sulphur Heavy Fuel Oil (LSHFO) is compliant with both policies (IMO, 2019b).

3.5. Upscaling activities and emissions

The ship design which maximises the PVs whilst remaining compatible with input policies is assumed to be the design which maximises profits. The corresponding route where profit maximising activity takes place is the maximising route.

$$MaxVes_{i,j,k,t} = max(PV_{i,j,k,t}) \tag{36}$$

The output $MaxVes_{i,j,k,t}$ is the vessel design which maximises profits, with $i, j,$ and$k$ being the fuel, engine and route which also maximises profits during the equivalent year. Assuming that at the initial time (2020) a certain amount of trade takes place, it is possible to estimate the number of ships of IMO type and size using Clarksons data based on how that trade grows, and what proportion of global trade takes place between Europe and Asia (Clarksons, 2020). The number of ships are assumed to grow proportionally and linearly.

$$n'_{m,n,0} = \left(\frac{X_0}{Y_0}\right) \times n_{m,n,0} \tag{37}$$

$$n'_{m,n,t} = \left(\frac{X_t}{X_0}\right) \times n'_{m,n,0} \tag{38}$$

where $n'_{m,n,0}$ is the number of ships trading between Europe and Asia for a given IMO size and type, X_0 is the volume of trade taking place between Europe and Asia at the initial time, Y_0 is the volume of global trade taking place and $n_{m,n,0}$ is the number of ships operating globally for a size and type at the initial time (2020). The variable $n'_{m,n,t}$ represents the number of ships operating between Europe and Asia at time t, and X_t is the trade taking place between Europe and Asia at the same time. The number of ships can then be multiplied to find out the total number of emissions which take place at time t on the route and used to estimate the climatic effects. The model can then be rerun for each IMO size and category to obtain a fuel mix for the entire Europe-Asia trade.

$$TotEm_{k,t,s} = n'_{m,n,t} \times Em_{i,j,t,s} \tag{39}$$

where $TotEm_{k,t,s}$ are the total emissions for a given species being emitted on a given route k at time t.

Table 5
Damage values for considered pollutants. Data is adapted and sourced from Shindell (2015a, 2015b), Zhu et al. (2018).

			Species							
		Region	CO_2	CH_4	N_2O	SO_x	NO_x	$PM_{2.5}$	BC	CO
2020 $/tonne	2020	Global	129	6758	54,560	59,830	85,412	36,103	415,400	942
		Arctic	129	6758	54,560	59,830	85,412	10,831	2,146,233	942
	2035	Global	166	8711	68,355	73,625	110,980	49,632	554,900	1231
		Arctic	166	8711	68,355	73,625	110,980	14,890	2,866,983	1231
	2050	Global	205	11,408	83,700	91,760	131,440	65,714	731,600	1612
		Arctic	205	11,408	83,700	91,760	131,440	19,715	3,779,933	1612

3.6. *Damage costs*

The damage estimates are obtained from Shindell (2015a) who includes the climatic effects of different species and damages to human health. A range of values is presented which depends on the discount rate used, with a low discount rate apportioning higher damage from GHGs in the longer term and vice versa for high discount rates. For this article, the results from the intermediate discount rate (3%) was chosen to match the intermediate RCP4.5 scenario for sea ice thickness. It was assumed that the intermediate damages bisect with the estimated damages using low and high discount rates. Therefore, there's an assumption that the damages increase linearly with the carbon price and that their relation to carbon dioxide damages remain fixed.

With respect to the differences between Arctic and Global damages, only the BC damage was changed. It was changed according to the ratio between its 20-year specific Arctic GWP and global GWP (6200/1200), as for the GHGs, they are well-mixed gases and so their impact is not dependent on geographic location (IPCC, 2013). Despite the cooling effect of both SO_x and NO_x, the damages weren't reduced as they contribute to poor human health and other environmental effects (IPCC, 2013a; Shindell, 2015a). Nonetheless, the $PM_{2.5}$ Arctic and Suez values are adapted from Zhu et al. (2018) and Korzhenevych et al. (2014) and in both instances, the cost changes as the geographic source of emissions influences the effects of the species. For estimating upstream damages, the values are assumed to be equal to the Suez costs.

The use of damage values can be controversial due to their seemingly subjective nature, but the absolute error of using them in this case is less than assuming a default value of zero (Marten and Newbold, 2012). This point is especially important with respect to the Arctic, where it is very difficult to accurately quantify the damage from short lived climate forcers and where confidence levels on certain forcing estimates are low (IPCC, 2013a).

4. Model outputs

For the outputs section a reference Handymax Wet Bulker of IMO size 4 was chosen since its size can comply with the NSR restrictions (Ørts Hansen et al., 2016). A size 4 Wet Bulker corresponds with ships that have a deadweight between 20,000–59,999 deadweight tonnes (Smith et al., 2014). The Whole Ship Model assigns a deadweight of 46,249 tonnes for a size 4 wet bulker and for an ice strengthened ship using Eq. (19), the deadweight was reduced to 43,089 – a consequence of having an increased lightweight. Further details can be found in the appendix. The selection also enables a comparison with Schøyen and Bråthen (2011) and Faury and Cariou (2016). Several behavioural and policy scenarios were constructed to test the model. Absolute validation is difficult due to the lack of empirical data on Arctic shipping cash flows and operations, and so to validate the model its outputs were compared against results from other studies. Several behavioural and policy scenarios were constructed to test the impact of policy on Arctic commercial viability.

The navigable period for the ice strengthened vessel was the first variable to be constructed and is compared against different studies. The navigable period represents the length of time that the NSR is theoretically open for an ice strengthened vessel in an RCP4.5 scenario. This study predicts that the NSR navigable season will extend from 3 months to 6 months which aligns with the predictions determined in other studies. This prediction is used to ascertain how accessible the NSR is when considering behavioural Scenario 2, since in Scenario 1 it is assumed that the vessel operates year-round through the Arctic with icebreaker (IB) assistance and in Scenario 3, Arctic routes aren't considered. A value with 1 significant figure is predicted due to the monthly resolution of sea ice data used. Nonetheless, the alignment with values obtained from other studies points to a robust estimate.

The results for the TSR's navigable period are characterised by a sudden loss of ice and increase in the navigable period. This trend was discovered in Melia (2016); Smith and Stephenson (2013); Stephenson and Smith (2015). This may be due to the climate mechanisms which sustain Arctic summer sea ice extent malfunctioning as the tipping point is passed. Nonetheless, caution is advised

Table 6
Description of behavioural scenarios.

Behavioural scenario	Description
1	Year-round Arctic operations with icebreaker assistance
2	Vessel is Arctic bound when ice thickness is below 0.8 m and Suez bound in other instances.
3	Year-round Suez operations

Table 7
Description of policy scenarios.

Scenario name	Policy scenario	Justification
Business as usual (BAU)	IMO 2020 Sulphur cap and HFO ban. A 50% reduction of operational GHG emissions in 2050.	A minimalist interpretation of the IMO initial GHG strategy, and hence the status quo.
Arctic zero emission ECA	IMO 2020 Sulphur cap and HFO ban. A 50% reduction of operational GHG emissions in 2050. An Arctic zero emission ECA is applied in 2035.	As shown in Fig. 2, there is a high chance that above 2° warming the Arctic summer sea ice tipping point will be passed. Due to less shipping activity taking place in the Arctic relative to the world, there is less inertia to impose an Arctic zero emission ECA relative to a global one. This follows a trend for designating ECA's under MARPOL Annex VI (IMO, 2019c).

Table 8
Results for the NSR navigable period against results of other studies.

	Year*	This study	(Khon et al., 2017)	(Melia, 2016)	(Stephenson and Smith, 2015)
NSR Navigable period (months)	2020	3	2.6	4.2	5
	2050	6	3.4	6.3	7.1

*The years obtained from other studies may not pertain to the exact year but will pertain to the same period (e.g. the results which correspond with 'Mid-century' is matched with 2050).

Table 9
TSR navigable period for an 1A vessel.

	Year	Current study
TSR Navigable period (months)	2020	0
	2050	5

when interpreting the results of a single model, as the navigable period varies with model output (Khon et al., 2017; Stephenson and Smith, 2015). The fuel consumption and other associated costs are also compared against other values.

The Suez result is in line with the result from the 3rd IMO GHG study, which deploys automatic identification system (AIS) based techniques to calculate the average fuel consumption for each ship type and size, however the result from the GHG study is not route

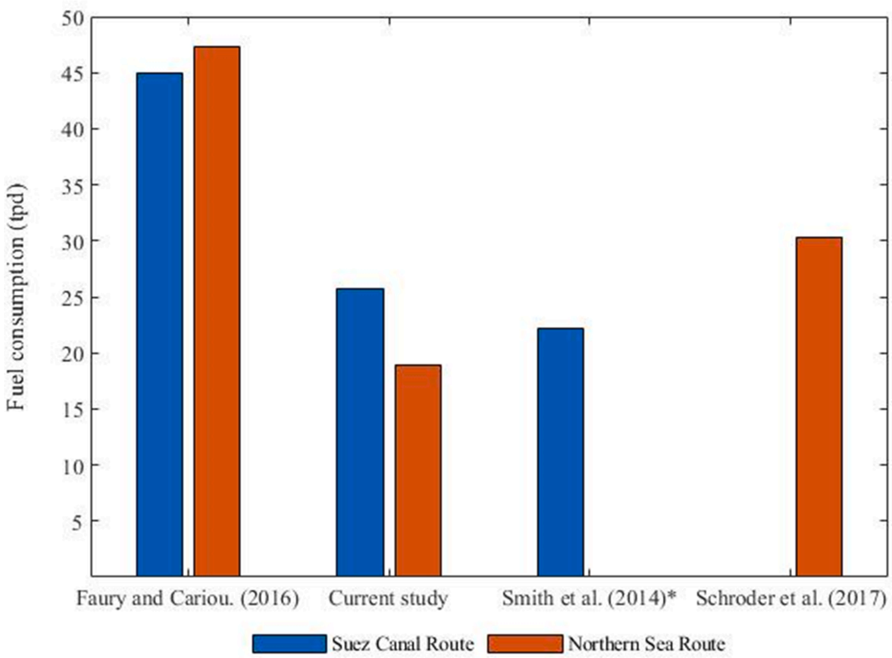

Fig. 6. Fuel consumption (Tonnes per day) for an Arc 4 (1A) Wet Bulker using a LSHFO/2-Stroke fuel transiting between from Mongstad to Mizushima is compared with tpd used or produced by other studies. *The Third IMO GHG study doesn't include specific fuel consumption data for ships transiting through the Suez route but the average fuel consumption for ships of the same size and type across the world.

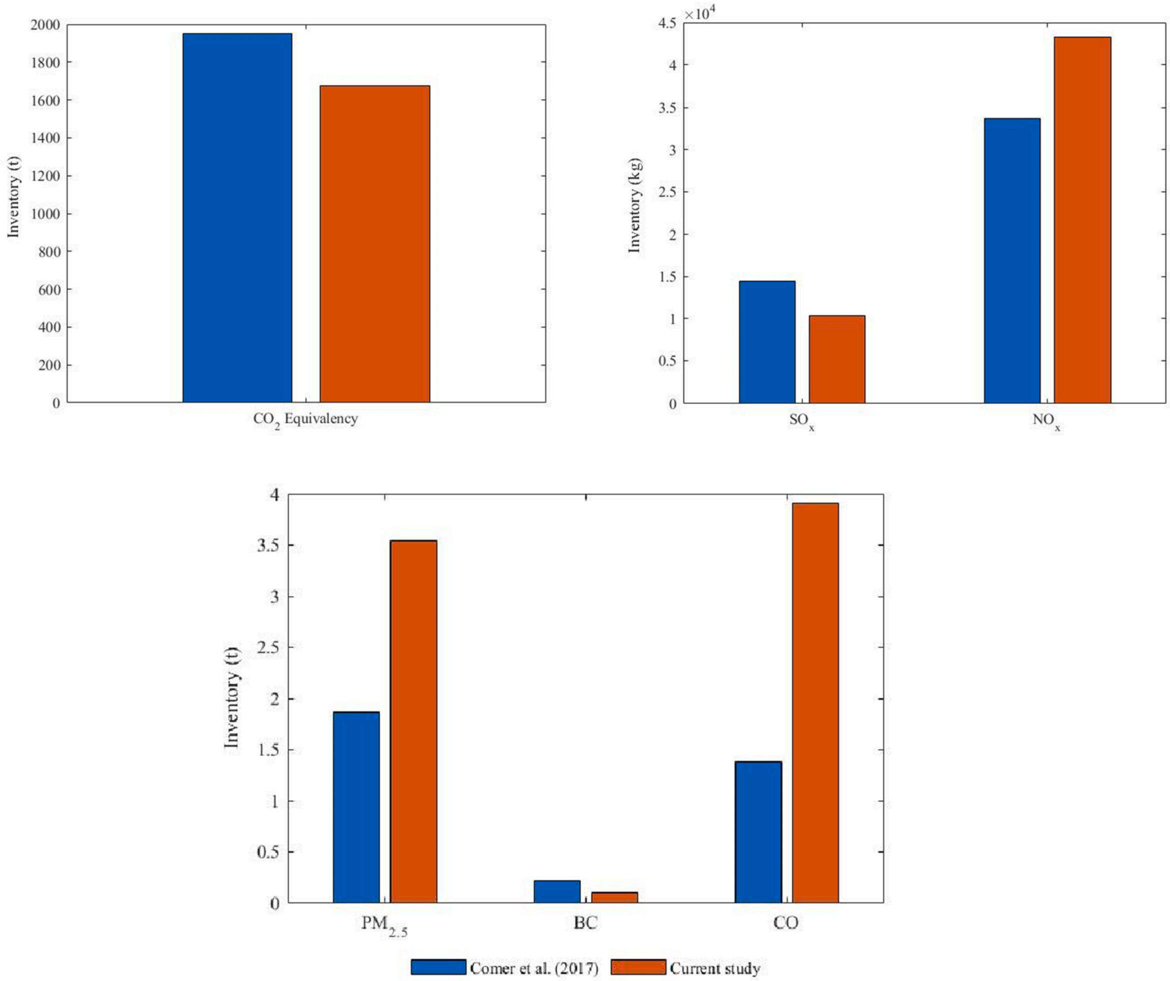

Fig. 7. (a)–(c) Average emission inventories for different species for a 1A Wet Bulker using a LSHFO/2-Stroke fuel-engine combination transiting through the Northern Sea Route between Mongstad and Mizushima - it is compared with a study which uses AIS based methods (Comer et al., 2017).

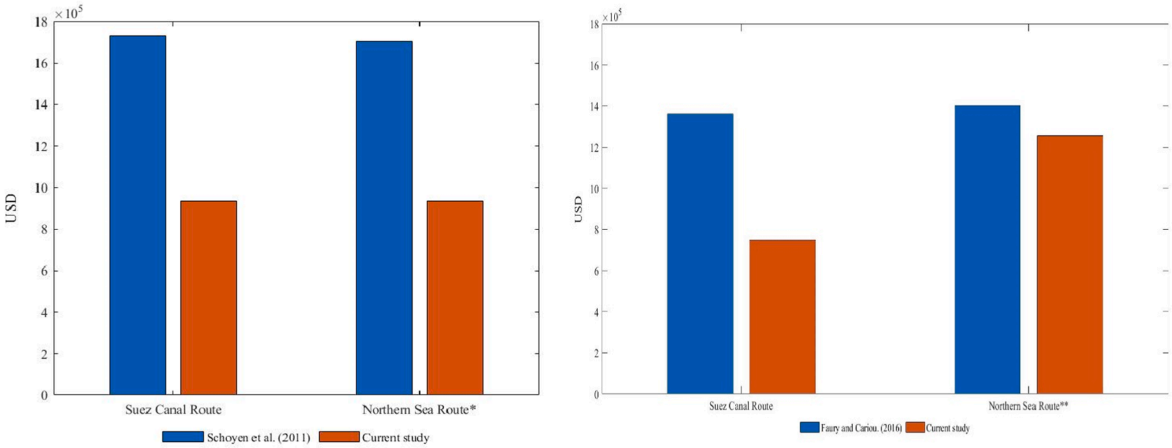

Fig. 8. (a) and (b) The chart comparing cost per voyage from Mongstad to Mizushima is on the left and the chart comparing cost per month for the same voyage is on the right.

specific (Smith et al., 2014). Compared to the Suez results from other studies, the fuel consumption is lower than other studies and this is due to the engine in the current study being assumed to have a comparatively lower static load (0.51) than with other studies. For example, in Faury and Cariou (2016) the stated fuel consumption in tpd is stated to be the fuel consumption at design speed, this explains the Suez result from the present study corroborates with just over a half of what was used in Faury and Cariou (2016). With respect to the Arctic result, the engine load varies from 0.51 when the ship requires icebreaker assistance or is passing through ice the fuel consumption lowers further, influencing the fuel consumption, hence the slightly lower result. The result is less than what is used in Faury and Cariou (2016) but for the same reason stated previously. The Arctic result is less than what was reported in Schröder et al. (2017) but that is due to the reference vessel in the current study being half the size of the vessel in Schröder et al. (2017), hence the power specifications and energy demand in the present study's reference vessel will be smaller.

The results from the Arctic route are explored further, the projected emissions per voyage using the NSR is compared with the results from Comer et al. (2017) which uses an AIS based method to estimate emission inventories in the Arctic. The GHGs are aggregated together under CO_2 equivalent per tonne using 20-year GWP values and the values are in close agreement with each other and the same can be said for when SO_x and NO_x values are compared with one another. There is a significant difference with respect to PM and CO emissions, but their absolute error is in the order of tonnes which isn't significant enough to influence the overall result. The discrepancies between the results are due to emission factors (EFs) varying with the engine load, small differences in fuel consumption estimations. Nonetheless, the close agreement between two results produced from different methods points to a robust estimation for not only Arctic fuel consumption but Arctic shipping emissions.

The costs of Arctic and Suez voyages are predicted to be less than that of other studies. The capital and operating expenses are included in the cost per voyage and cost per month estimates for both Suez and NSR estimates. The smaller prediction from the present study is due to a lower fuel consumption being modelled and also lower fuel prices, this is especially relevant for Fig. 8a as the study Schøyen and Bråthen (2011) predates the 2014 oil price crash. In terms of comparing with the cost per month with Faury and Cariou (2016) a similar pattern occurs where due to the lower modelled fuel consumption, a relatively lower cost is predicted and this appears to be proportional with the assumed engine load. Nonetheless, in Faury and Cariou (2016) it is stated that capital costs are not included in the analysis, whereas in the present study it is and this means that the additional capital expense incurred from owning an ice class vessel would result in a smaller difference between the studies. Furthermore, the NSR result is taken from Scenario 1, which means Arctic related tariffs such as ice pilot fees and icebreaking tariffs will be higher relative to seasonal Arctic operations, this also leads to the difference between the results to reduce further.

The results show that under a BAU policy scenario, transiting through the NSR during the summer and then the Suez during the winter is the most profitable enterprise relative to year-round NSR and Suez transits. Due to the introduction of the IMO initial GHG strategy in 2050, the fuel switches to an internal combustion engine/Ammonia combination as this fuel is the most profitable alternative which complies with the GHG reduction target. The key driver for Scenario 2 being the most profitable is due to the number of voyages (transport work) that the vessel can undertake in the same space of time relative to exclusively using the Suez and Arctic routes, despite the added costs of navigating the Arctic route. Whilst Arctic accessibility increases, the increase is not enough to warrant year-round NSR operations with an ice class of 1A under this RCP scenario. Nonetheless, this may not hold for RCP pathways with higher warming narratives or for ships with heavier ice strengthening and this area warrants further study.

Several assumptions are made regarding the different designs, behaviours and routes to produce the results shown in Table 10. With respect to alternative fuels, all ships have the same installed power, displacement, volume and fuel storage capacity and the speed of the ship does not change as a consequence of changes to fuel or ice strengthening. The ice class variant also has the same geometry as its

Table 10
Commercial cross section for the maximum profits in the years 2020, 2035 and 2050 for the BAU scenario.

Variable	Scenario 1*			Scenario 2*			Scenario 3		
Year	2020	2035	2050	2020	2035	2050	2020	2035	2050
Charter rate ($/d)	13,781	13,781	15,772	13,781	13,781	15,772	13,781	13,781	15,772
Freight rate ($/t)	31.16	29.09	32.28	31.16	29.09	32.28	31.16	29.09	32.28
Deadweight (t)	42,778	42,778	42,606	42,778	42,778	42,606	46,249	46,249	46,106
Fuel	LSHFO/2-Stroke	LSHFO/2-Stroke	ICE/Ammonia**	LSHFO/2-Stroke	LSHFO/2-Stroke	ICE/Ammonia**	LSHFO/2-Stroke	LSHFO/2-Stroke	ICE/Ammonia**
Annual operating expense ($)	1,252,962	1,252,962	1,298,128	1,270,495	1,252,962	1,276,374	1,244,052	1,244,052	1,281,621
Total annualised capital cost ($)	474,580	474,580	879,306	631,690	474,580	684,369	394,745	394,745	731,387
Total voyage expense ($)	4,552,205	3,271,532	3,599,413	3,408,752	3,968,270	3,591,901	2,096,454	2,540,617	2,326,428
Number of voyages	5	5	6	5	7	7	4	4	4
Profit ($)	385,705	1,222,788	2,459,841	1,646,112	3,014,794	4,075,328	2,029,819	1,201,986	1,605,444

*These vessels were ice strengthened and the results apply to the Northern Sea Route.
**The ammonia is produced through renewable electrolysis.

open water variant but a different installed power. In terms of charter and commodity rates, the base time charter rate is exogenous to the model and it is assumed to vary directly proportionally with the asset value of each ship design. The minimum value across all the compatible ship designs for commodity rates and time charter rates was then found and applied to all ship designs in profit calculations, and so these rates are independent of the route taken. It is assumed that in terms of cargo carrying capacity, the ship is fully loaded for both legs. With respect to assumptions about the Scenarios, it is assumed that for Scenarios 1 and 2 when escorted by an icebreaker in a convoy it can operate through all ice conditions. In terms of the routes, no NSR tariff is applied to the vessel when operating through the TSR as it is outside the Russian exclusive economic zone (EEZ), but it still incurs icebreaking costs which is disaggregated from the overall tariff cost (refer to Eq. (24)). It is assumed that the NSR tariff is separate from ice pilot and icebreaking expenses. The Suez route involves no external tolls aside from the Suez Canal fee.

As the Arctic becomes more accessible, the relative profitability increases for Scenario 2 and this is paramount with a BAU policy

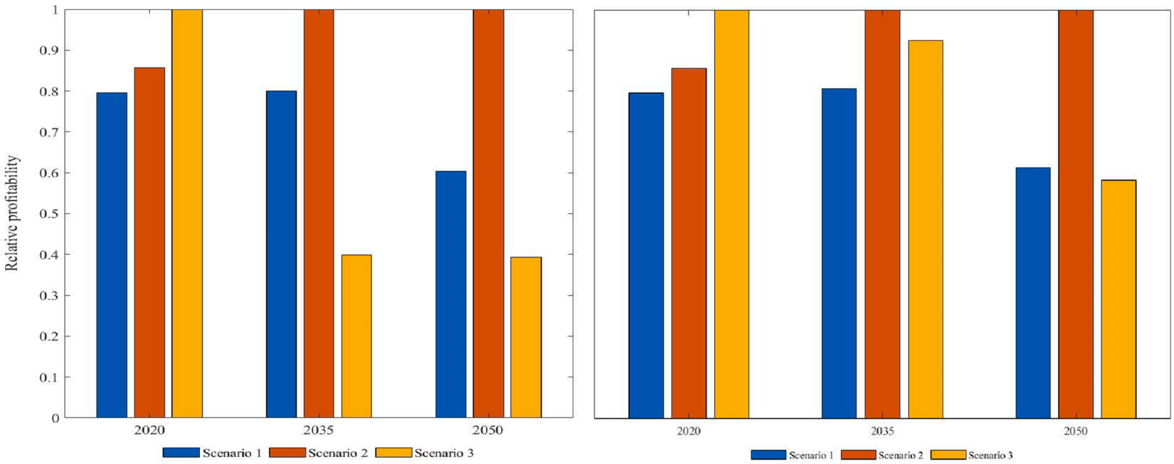

Fig. 9. (a) and (b) Graphs containing the financial profits relative to the maximum profit was constructed using the described behaviours (Scenarios 1–3) for the BAU and Arctic zero emission ECA (left and right respectively).

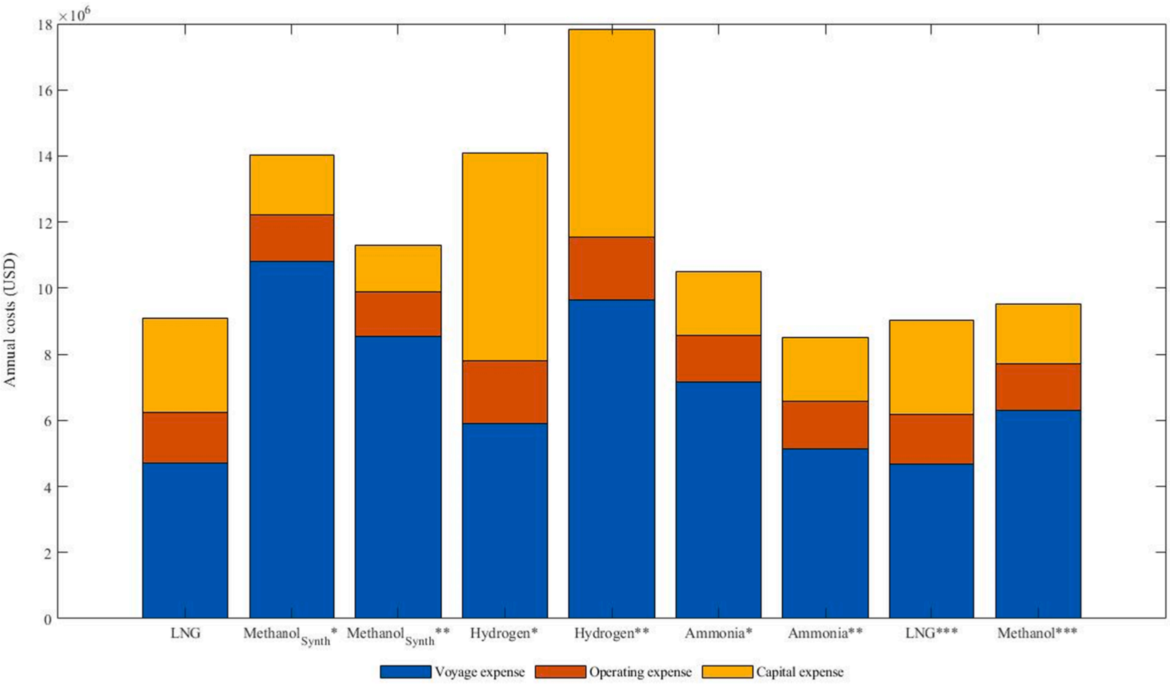

Fig. 10. The annual voyage, operating and capital expenses for zero emission fuel cells stacked on top of one another. The total costs from 2035 under an Arctic zero emission ECA, for each fuel are compared with one another. *The fuel was produced from steam methane reduction (SMR) with carbon capture storage (CCS). **The fuel was produced using electrolysis used from renewable electricity ***The fuel was produced from bio feedstocks. Methanol$_{Synth}$ refers to synthetic methanol, where the syngas used to produce methanol is derived from CO_2 rather than CO.

scenario. The other scenarios decline in their relative profitability and this is due to an increasingly lengthy Arctic season, enabling more transits to take place with a reduced amount of sea ice to impede the transits. The longer Arctic season means that less ice combined with a shorter route means that a larger volume of transits can take place within the same amount of time relative to the Suez Canal Route, and this offsets the additional Arctic related tariffs such as icebreaking fees. As the profitabilities are relative and the profit for Scenario 2 increases by the largest amount relative to the other scenarios in each cross section, the relative profitability for the other scenarios decline. With respect to the Arctic zero emission ECA policy scenario, 2020 follows the same projection as the BAU scenario and for 2035 Scenario 2 becomes the most profitable operation. However, the relative profitability of year round Suez bound ships is higher than it is under a BAU scenario and this is due to the Arctic ECA forcing Arctic ships to adopt zero emission technologies. In this case, the most economically compliant technology is a green ammonia combined with a fuel cell. By 2050 however the technology matures, and this is reflected in the fuel price of ammonia which then contributes to the increase in relative profitability. This comes concomitantly with a more accessible Artic, as lower costs leads to a larger profit (Lloyd's Register, 2019).

The nearest competitor is an LNG fuel cell ship design, however its large capital and operational cost offset the slight reduction in voyage costs relative to green ammonia. Therefore, a green ammonia fuel cell retains the lowest cost amongst all the other zero emission vessels. The Arctic zero emission scenario is explored further and the emissions damages from a LSHFO/2-Stroke ship transiting through the Suez Canal was compared with an NSR bound green ammonia fuel cell powered ship using the values from Table 5.

The environmental costs of a LSHFO/2-Stroke powered ship significantly outweigh the damages from the zero-emission vessel (ZEV). The damages associated with the ZEV are due to upstream and not operational emissions. Even though the fuel is green ammonia, which is produced through renewable electricity, there will still be emissions associated with constructing a renewable electricity generation and transport grid. Nonetheless, the net effect of the LSHFO ship's activity is still significantly negative. The main damage constituent for both operational and upstream emissions are from both NO_x and SO_x with the damages per ton shown in Table 5. The result demonstrates the significant social cost of utilising residual fuel oil. The results were decomposed further into ($\$kWh^{-1}$) to illustrate a more direct comparison. It is assumed that there are no direct emissions emanating from the production of green ammonia, however as the production location influences the feasibility of ammonia production it is recognised that there are upstream emissions associated with the transportation of green ammonia (Lloyd's Register, 2019).

Naturally residual fuel oil incurs a lower financial cost per kWh consumed as this fuel is energy dense and relatively cheap, however the social costs significantly offset the extra monetary costs of using an ammonia fuel cell ship. When incorporating externalities from emissions, the total cost per kWh when using LSHFO is roughly 9 times that of using a green ammonia fuel cell ship. The large damages associated with a LSHFO/2-Stroke ship's emissions emanate from operating emissions. When the externalities are excluded, the monetary cost per kWh of a green ammonia fuel cell is almost twice that of a LSHFO/2-Stroke powered ship. The results in Fig. 12 compound the illustration in Fig. 11 and demonstrate the significance and influence of incorporating damages from emissions on results and it suggests that this activity incurs an expensive societal cost.

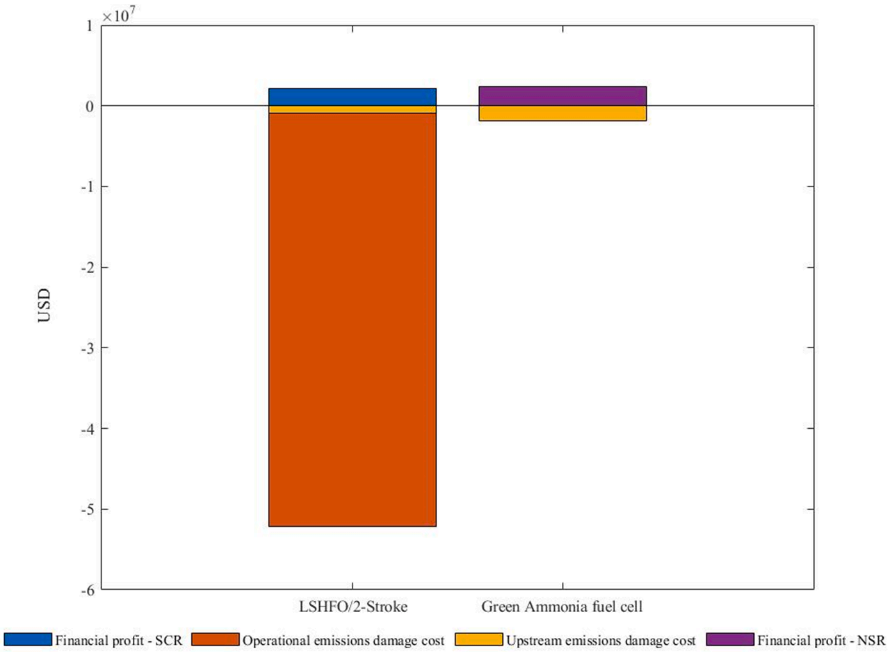

Fig. 11. Annual financial profit against annual social costs of air pollution for a LSHFO/2-Stroke powered ship against a green ammonia fuel cell powered ship in 2035 and under the Arctic zero emission ECA scenario.

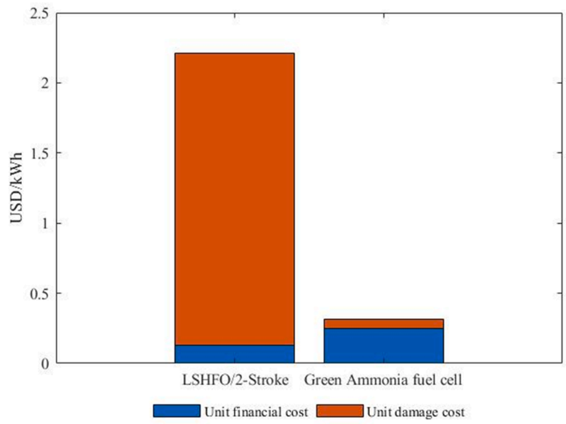

Fig. 12. The financial and damage cost per kWh for LSHFO/2-Stroke and a green ammonia fuel cell.

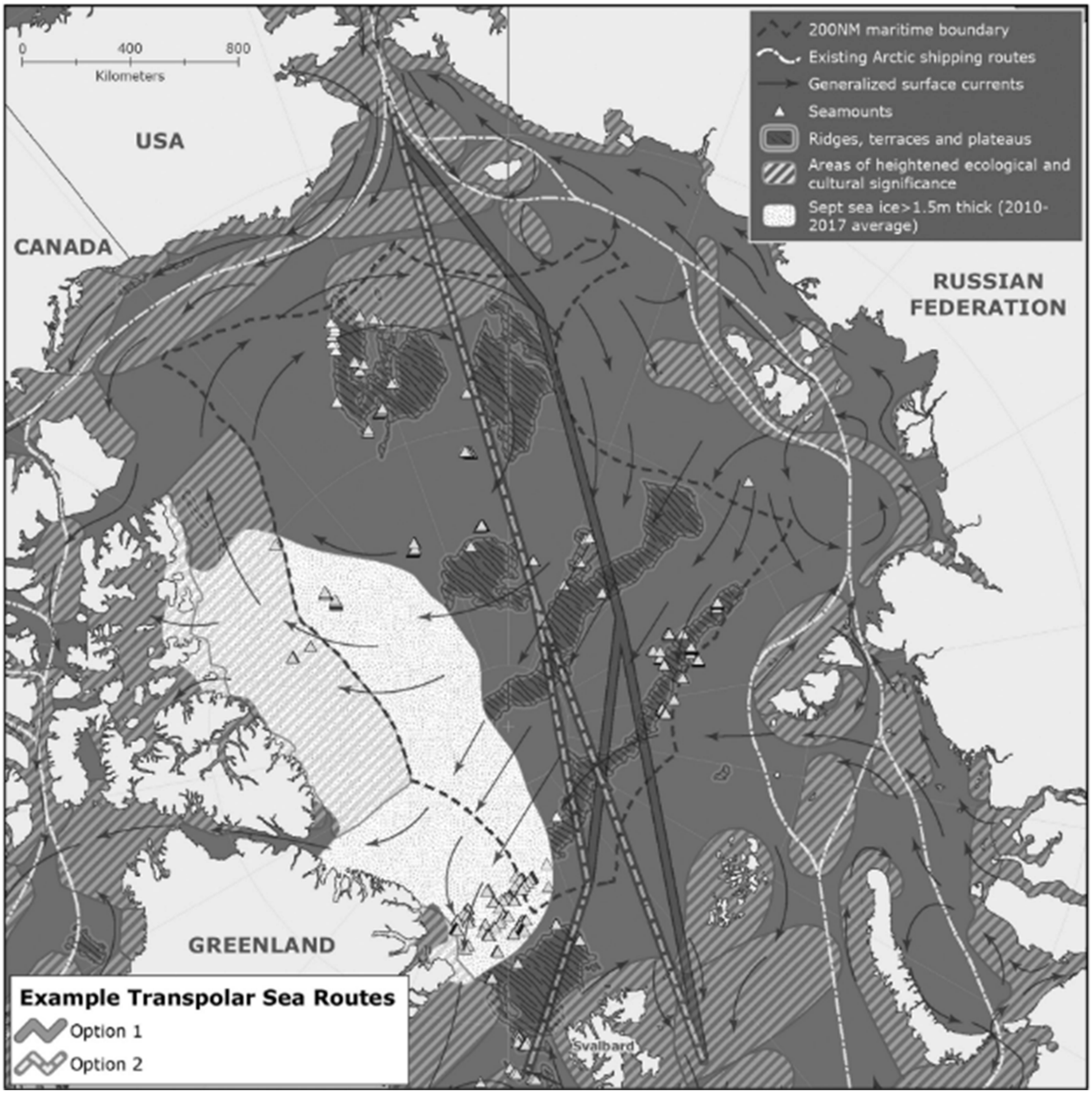

Fig. 13. The TSR super-imposed on the Arctic ocean and how it runs through environmentally/culturally significant areas. Sourced from: Stevenson et al. (2019).

5. Discussion

The construction of the model hinged upon unifying core concepts in Arctic shipping under profit maximisation theory. Through accounting of social costs, externalities can be incorporated into any economic analysis and used to quantify what the risks of market failure are, in addition to the net losses incurred by society. This also leads to the implicit incorporation of an economic cornerstone, that people face trade-offs – in this case, the Arctic sea routes may enable an increased volume of trade but also accelerate the ice melt (Mankiw and Taylor, 2011). This point is evidenced through the results in Table 10 which shows that by 2035, it becomes profitable for ships using residual fuel oils to transit through the NSR but when considering the damage per kWh illustrated in Fig. 12 in tandem, it is clear to see that the direct damage from emissions will be significant.

Whilst the evidence presented in Fig. 9a, 9b, 11 and 12 show that under an Arctic zero emission ECA policy a sustainable outcome is reached – ships powered by green ammonia fuel cells will transit through the NSR. When the damages from Figs. 11 and 12 are taken into account, it is clear that in terms of costs emanating from emissions, ammonia fuel cells are a more sustainable option. If the Arctic becomes accessible, more sustainable technologies should be incentivised and encouraged to be adopted. Nonetheless, there are many underlying modelling uncertainties and environmental consequences which aren't considered by this model. Issues such as noise pollution, climate perturbations and by how much shipping through the Arctic outside of emissions will push the summer sea ice to its tipping point should be explored (Alvarez et al., 2020; Stevenson et al., 2019; Yumashev et al., 2019). These areas must be researched and pursued with greater fidelity before a consensus on the costs and benefits of Arctic shipping can be reached. Thus, the results in Figs. 9a, b, 11 and 12 highlight the complexity of the issues currently facing policymakers (see Fig. 10 and Fig. 13).

The results from other studies have been used to corroborate the findings from the current model, however the incorporation of environmental costs as in Zhu et al. (2018) adds a new dimension to the cost analysis of Arctic shipping. Nonetheless, using an economic profit maximisation framework is not without its own drawbacks, it is very difficult to quantify the damages produced by emissions from Arctic shipping and the costs plus methods behind their calculation are often subject to debate (Nordhaus, 2014). In the case of the damages used in this study, a large cost is attributed to SO_x and NO_x emissions due to their impact on human health and these costs are significantly higher than the costs used in Zhu et al. (2018). Whilst SO_x and NO_x emissions take place at sea and far away from populated areas, it also argued by the author of the damage cost estimates that the variance from the discount rate is greater than the variance from geographic source of emissions (Shindell, 2015b, 2015a). In this case however, spatial variation between the costs will help inform local policymaking decisions. Nonetheless, there is a trade-off between comprehensiveness and simplicity (Shindell, 2015b). A great effort must be expended to define the value of an opportunity or social cost and where the boundaries for what constitutes a societal cost and what doesn't are drawn (Parkin, 2016). For example, the damages outlined in Table 5 consist of damages resulting from emissions, they do not include other forms of pollution or effects on biodiversity and culturally significant areas (shown in Fig. 13).

The cultural and ecologically significant areas are illustrated in Fig. 13. This model doesn't account for costs emanating from loss of Artic biodiversity or culturally significant areas. Nonetheless, the main aim of this study was to propose and develop a more complete modelling framework. This method provides a platform for testing of different policy instruments and scenarios, which can analyse and balance the economic trade-off between the financial and environmental costs and economic gains of Arctic shipping. This proof-of-concept justifies the argument for a broader approach and reinforces the argument for methods that include policy, emissions and energy considerations.

6. Concluding remarks

By treating microeconomics, policy, fuels and emissions as co-dependencies, the researcher can rigorously assess the dynamics within Arctic shipping. Leveraging the groundwork laid by previous research both within Arctic shipping and beyond, a more complete approach is developed and used to build a model architecture. The techno-economic architecture captures the complexity of Arctic shipping operations and encompasses sea ice, commercial operations, alternative fuels and policy, enabling a rigorous assessment on how these areas interact with one another and the commercial viability of Arctic shipping. Through the inclusion of different variables, a platform for the identification of influential variables which the commercial feasibility and environmental risks posed to the Arctic may be sensitive to can be better evaluated.

The model was tested under a BAU policy scenario and with a zero emission ECA applied in the Arctic region. The reference vessel was a Handymax wet bulker and it was found that under both policy scenarios, a behaviour tantamount to summer Arctic and winter Suez transits becomes the most profitable enterprise in 2035 and again in 2050 due to the Arctic sea ice decline. Under the zero emission ECA scenario a zero-emission green ammonia/fuel cell ship design was shown to be the most economically viable design option. Whilst this is a sustainable outcome, there are still some modelling uncertainties which need to be addressed and studied more thoroughly.

Combining the evidence from this study, that the Arctic will become economically feasible in the future, with the analysis of damages from emissions it can be concluded that there is a need for environmental policy to prevent a net societal loss from emissions. At present the model only addresses costs emanating from emissions and ignores other forms of pollution or other damages such as noise and losses to biodiversity and socio-culturally significant areas, hence the damage costs may be an underestimate. Furthermore, there is an added layer of complexity as GHGs contribute to Arctic specific damages through causing Arctic sea ice to decline, regardless of its geospatial source of emissions. This suggests that restricting policy to an Arctic area may not be enough to inhibit the sea ice decline due to the low volume of activity taking place there, Through capturing the dynamics between policy, fuels, economics and emissions, new factors such as fuels and costs of emissions significantly influence the results relative to findings in other studies. It is hoped that the framework will be adopted and used to assist policymakers in the future.

6.1. Future work

Future work will entail comparing the model with empirical data. This task will enable the identification of variables and concepts which influence Arctic shipping's commercial viability, so that they may be incorporated and investigated with greater fidelity. We aim to pursue this investigation with state-of-the-art data (e.g. CMIP6 sea ice predictions) and explore the sensitivity of Arctic shipping commercial feasibility to different policy scenarios and other identified parameters. This will yield a better understanding of the commercial and environmental opportunities, challenges and uncertainties in Arctic shipping. Moreover, further research can be directed towards the incorporation of other environmental factors such as noise pollution and other Arctic specific damages such as losses to biodiversity and socio-cultural significant sites.

CRediT authorship contribution statement

Lambert Joseph: Writing – original draft, Writing – review & editing, Visualization, Investigation, Formal analysis. **Thomas Giles:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Rehmatulla Nishatabbas:** Writing – review & editing, Supervision, Conceptualization, Funding acquisition. **Smith Tristan:** Supervision, Methodology, Funding acquisition, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. We would also like to thank those whose comments and feedback have contributed to the development of this framework. We are grateful to the EPSRC for the Ph.D. funding that made this research possible.

Appendix A. Vessel specifications

Table A1
The size and type of the reference ship defined according to IMO categories.

IMO type	IMO size
7	4

Table A2
The open water vessel's energy consumption specifications. These outputs are obtained from the holistic ship design model WSM (Calleya et al., 2017).

Design speed (kts)	Main Engine Specific fuel consumption (gkWh^{-1})	Main Engine Installed Power (kW)	Auxiliary engine SFC (gkWh^{-1})	Auxiliary engine power (kW)	Boiler consumption (tpd)
13	178	5961	211	1324	1.74
14	178	7659	211	1324	1.74
15	176	10,194	211	1324	1.74
16	175	13,420	211	1324	1.74
17	178	17,767	211	1324	1.74

Table A3
The ice strengthened variant's energy consumption specifications.

Design speed (kts)	Main Engine Specific fuel consumption ($gkWh^{-1}$)	Main Engine Installed Power (kW)	Auxiliary engine SFC ($gkWh^{-1}$)	Auxiliary engine power (kW)	Boiler consumption (tpd)
13	178	6962	211	1324	1.74
14	178	8764	211	1324	1.74
15	176	11,475	211	1324	1.74
16	175	14,903	211	1324	1.74
17	178	19,508	211	1324	1.74

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