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Impact of CO_2 emission taxation and fuel types on Arctic shipping attractiveness

Ali Cheaitou [a,*], Olivier Faury [b], Laurent Etienne [c], Laurent Fedi [d], Patrick Rigot-Müller [e], Scott Stephenson [f]

[a] *Department of Industrial Engineering and Engineering Management, College of Engineering, University of Sharjah, 27272 Sharjah, United Arab Emirates*
[b] *École de Management de Normandie, Métis Lab, 20 quai Frissard – 76600, Le Havre, France*
[c] *LabISEN, 20 Rue Cuirassé Bretagne, 29200 Brest, France*
[d] *KEDGE Business School, CESIT, Maritime Supply Chain Lab, Domaine de Luminy, 13288 Marseille, France*
[e] *Maynooth University, Maynooth, Ireland*
[f] *RAND Corporation, P.O. Box 2138, 1776 Main Street, Santa Monica, CA, United States*

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ABSTRACT

This study investigates the impact of hubs, CO_2 emission taxation policy, and bunker fuels on the economic and environmental attractiveness of the Northern Sea Route (NSR).

Twenty-eight years of historical ice data have been combined to define the uncertainty level of ice thickness and concentration and converted to risk indexes using POLARIS, a risk management tool. The shortest travel times have been defined using the risk levels and a time-dependent shortest path algorithm.

The results stress that the carbon tax is not antinomic with profit. Moreover, the use of hubs was not found to be economically advantageous for a majority of the examined scenarios. Furthermore, although it increases the overall emissions, this reduces the CO_2 emissions per container due to the rise in the shipping volumes. Demand elasticity to transit time and to freight rates shows that the choice of hubs significantly impacts the NSR's economic and environmental attractiveness.

1. Introduction

The Northern Sea Route (NSR) has been at the crossroads of emerging developments within the shipping industry on one side, and upcoming environmental regulations on the other side. First, Rosatom has created a partnership with DP World to manage containers by 2030, even if until now, except for COSCO, no specialized container transportation actor seems to be interested. Second, Aker Finnyard is working on a project of an ARC7 container vessel with a capacity of 8,000 TEUs. Thirdly, owing to the adverse environmental and health impacts of aerosol emissions from shipping (Delft, 2018), Heavy Fuel Oils (HFOs) will be banned from the Arctic by July 2024, with some exceptions until July 2029. Fourthly, the International Maritime Organization (IMO) regulating the shipping industry set an emission reduction target of 40 % as of 2030 and by 50 % as of 2050 relative to 2008 levels (IMO, 2020).

* Corresponding author.
E-mail addresses: acheaitou@sharjah.ac.ae (A. Cheaitou), ofaury@em-normandie.fr (O. Faury), laurent.etienne@yncrea.fr (L. Etienne), laurent.fedi@kedgebs.com (L. Fedi), Patrick.RigotMuller@mu.ie (P. Rigot-Müller), Scott_Stephenson@rand.org (S. Stephenson).

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Sailing in the Arctic raises several issues, such as the period of navigation, the environment, the risk represented by ice to vessel integrity and crew safety, the uncertainty of the planned schedule, and profitability (for a synthesis, see Theocharis et al., 2018; Lavissière et al. 2020). As ice presence can be difficult to predict, the length of navigation changes from one year to another or from one trip to another. Thus, to secure a longer period of navigation, two options exist: investing in vessels with higher ice-class and/or being escorted by an icebreaker.

Additionally, to mitigate the risk represented by ice, the Polar Code (IMO, 2014) that entered into force in 2017 (Fedi, 2019), has integrated the 'Polar Operational Limit Assessment Risk Indexing System' (POLARIS), a decision-making tool that assesses the risk that a given navigation area may represent to the vessel in function of its ice-class and the type of ice (IMO, 2016). Knowing that unsuitable speed is a key contributing factor to accidents (Marchenko, 2014a; 2014b), POLARIS also recommends a specific speed depending on the ice conditions.

In addition, underwriters may require shipowners to use a defined navigation pathway and icebreaker assistance, leading to higher transit costs. While all these parameters directly influence the cost of navigation, fuel cost is one of the most significant (e.g., Wang et al., 2021). Furthermore, the IMO approved Regulation 43A of MARPOL Convention Annex I that aims to definitively prohibit the use and carriage of HFO including Very Low Sulphur Fuel Oil (VLSFO) for all vessels sailing in the Arctic by July 2024, except for those engaged in safety operations (IMO, 2021). This new rule may reduce 'socio-economic and environmental damage costs' (Delf, 2018) while also raising bunker fuel expenditures for navigation. HFO is utilized in approximately 58 % of the total Arctic fleet, while distillate fuels such as Marine Diesel Oil (MDO) and Marine Gas Oil (MGO) account for 36 % (PAME DNV-GL, 2019). Nevertheless, until July 2029, HFO will continue to be permitted with the use of scrubbers or by burning VLSFO, as well as for ships with a double hull or those flying the flag of an Arctic coastal state that has ratified the MARPOL Convention. However, the related higher cost of VLSFO may have a negative impact on the economic profitability of the NSR.

Plus, the relevance of a tax on CO_2 emitted from ships has increased due to climate change, which has significant impacts for polar regions (Winther et al., 2014; Bai and Chircop, 2020). As demonstrated by Cariou and Faury (2015), such a tax may enhance the economic attractiveness of the NSR compared to the Suez Canal Route (SCR), by increasing the potential travel cost savings.

The aim of this research is to evaluate the impact of CO_2 emission taxation on the potential attractiveness of the NSR. In our model, we assess the influence that an environmental policy, namely a carbon tax, adopted by coastal states may have on NSR economic competitiveness. We consider that shipowners may set up different transportation strategies to maximize profits or to load as many containers as possible and enable a choice of a defined logistics setting or a type of fuel. Moreover, considering the risks related to Arctic navigation, we define vessel ability to sail based on the POLARIS risk assessment framework.

The innovative character of this study lies in a tridimensional approach, namely risk and uncertainty management, environmental considerations, and economic considerations. Beyond POLARIS requirements, the risks faced by vessels are computed based on the collection of historical ice thickness and concentration data including ice variability. This integrates the use of icebreakers depending on the optimal route along the NSR based on a time-dependent shortest path (TDSP) algorithm. Environmental parameters are represented by two different bunker fuels (HFO used with scrubber and VLSFO) and the Social Cost of CO_2 emissions. Finally, economic parameters result from the combination of both risk assessment and environmental elements.

Our analysis provides four main contributions to the existing literature. First, while most previous studies agree on the impact of ice conditions upon NSR attractiveness, none examine ways to counteract this risk by combining investment in ice-class vessels and specific logistics settings while also considering ice as a risk factor and using POLARIS as a risk management tool (Fedi et al., 2018b). Second, we provide the freight rate levels shipowners should apply to start generating profit depending on the logistics setting, the different ice conditions, and the environmental policy in effect. Third, we compute the NSR capacity to attract cargo depending on the combined freight rates and transit times. Fourth, we calculate the CO_2 emissions per loaded container depending on the freight rate charged, the logistics setting, the environmental policy, and the fuel type.

Following a literature review in Section 2, we present our profit model and business case in Sections 3 and 4 respectively. Section 5 focuses on the presentation of the main findings while Section 6 provides a discussion and concluding remarks.

2. Literature review

Despite the 40 % shortcut represented by the NSR versus the SCR, the inherent uncertainties and high costs of navigation along the NSR hinder the development of liner shipping (Verny and Grigentin, 2009). Currently, the transportation of cargo between European and Asian ports via the NSR remains scarce and container ships are almost nonexistent in the area (Gunnarson, 2021; Li et al., 2021b). Lasserre (2014), Zhang et al (2016), Koçak and Yercan (2021) and Cariou et al (2019) justified this situation on the grounds of economic considerations more than technical ones. First, due to the ice conditions, it is often difficult for vessels to adhere to a predefined schedule (Lasserre and Pelletier, 2011; Cariou et al., 2019; Lasserre, 2019; Cheaitou et al., 2020). Secondly, the NSR is not open all year long which implies using vessels in another trade or staying at the quayside during route closure. Thirdly, the period of navigation changes every year and is barely predictable (Stephenson et al., 2014; Li et al., 2021a). This unpredictability is due to changing ice conditions generating an ice coverage which may change from one year to another (Cheaitou et al., 2020). Fourthly, ice represents a direct threat to the vessel's structural integrity and the crew (Fedi et al., 2018a), and induces potential delays in case of 'ice besetting events' (Zhao et al., 2022). To mitigate this risk, the assistance of icebreakers is needed and may be imposed by underwriters (Fedi et al., 2018a) with a direct consequence on voyage cost (Zhao et al., 2022; Gritsenko and Kiiski, 2016; Furuiki and Otsuka, 2015) and thus on the profitability of such a journey (Lasserre, 2014). To address these issues, one of the solutions is to invest in an ice-class vessel. The advantages and drawbacks were highlighted by Cheaitou et al (2020) who demonstrated that this option showed some limits compared to a vessel with lower ice class especially regarding additional daily fuel consumption and capital cost. Cai et al (2020) concluded for their part that the ship's ice class did not significantly affect the NSR's economic advantages.

Moreover, the question of the economic impact of bunker fuel cost has been raised by academics such as Liu and Kronbak (2010), Zhu et al (2018), Cariou et al (2019), Cheaitou et al (2020), Ding et al (2020), Koçak and Yercan (2021), Jiang et al (2021), Jing et al (2021), Zhao et al (2022) for container ships and by Schøyen and Brathen (2011), Theocharis et al (2019; 2021), Cariou and Faury (2015), Lindstat and Eskeland (2016), Keltto and Woo (2019), Faury et al (2020) and Wang et al (2020) for bulk. Academics have agreed on the importance of bunker fuel costs to NSR economic attractiveness (Wang et al., 2021). Lasserre (2014) emphasized the fact that due to the extremely low temperature, a premium of one-third additional fuel must be added to NSR voyages. Despite the importance of fuel costs, as far as we know, few analyses have focused on this topic at the time of writing. Cheaitou et al (2020) compared both ice class 1A and 1AS vessels each fueled with Marine Gas Oil (MGO) or VLSFO. They stressed that when SO_x and CO_2 are taxed, MGO is more worthwhile. Cariou et al (2019) analyzed a vessel using either MGO or HFO and underlined those emissions per TEU along the NSR were higher than those along the SCR.

Further, several articles have questioned NSR competitiveness if CO_2 emissions were charged. Cariou and Faury (2015) demonstrated that this impact would be to the advantage of the NSR over the SCR, and that the cost saving rises with the average speed. Ding et al (2021) demonstrated that the cost saving between a navigation with a CO_2 tax and without it decreases when the container ship size increases. However, the NSR remains less costly. Both Lindstad and Eskeland (2016) and Zhu et al (2018) considered that the NSR can be a viable option but has a negative impact on emissions compared to the SCR. Yumashev et al (2017) insisted on the detrimental impacts on the environment related to NSR development and especially black carbon, CO_2 and other air pollutants whereas emissions would be concentrated at 80 % in the Norwegian and Barents Seas compared to the NSR and Northwest passage (Chen et al., 2022). Wang et al (2021) used two Social Costs of Carbon (50 and 125 USD) to define the economic impact of Global Warming Potential (GWP) on Arctic navigation, applied to two fuels and one with a scrubber (HFO). Their findings demonstrated the impacts that transit time, distance and cost may have on Arctic shipping.

In addition, Jiang et al (2021) stressed the impact of different factors upon the NSR's attractiveness using two hubs, one in Petropavlovsk and another one in Murmansk, and two types of ice class. Yet, their analysis is based on a fixed range of freight rates and one type of bunker fuel. Bennett et al (2020) suggested the creation of a "Central Arctic Ocean hub-and-spoke system" with transshipment hubs and Faury et al (2020) raised the question of whether two hubs at both extremes of the NSR may be economically viable.

Sailing in the Arctic represents a direct risk to the Arctic ecosystem from accidents and oil spills (AMSA, 2009; MARSH, 2014; Delft, 2018; Johannsdottir and Cook, 2019). Since the 2000 s, scholars have progressively paid more attention to vessel ability to sail in the Arctic via risk management tools such as the Canadian Arctic Ice Regime Shipping System (AIRSS) and more recently POLARIS. Regarding AIRSS, some authors evaluated its efficacity against ice damage (Timco and Kubat, 2001) through the vessel capacity to navigate in Canadian Arctic while considering ice conditions and ship ice class (Timco et al., 2005). Regarding POLARIS, Kujala et al (2016; 2019) estimated its usefulness on risk ice mitigation by identifying appropriate ice-class vessels for Polar waters. Other studies underlined the positive contributions of POLARIS on safe navigation and risk prevention. Stoddard et al (2016) showed that POLARIS was relevant for different stakeholders such as classification societies or underwriters, and for operational aspects, especially route planning, as corroborated by Lee et al (2021) who used POLARIS to determine the vessel optimal pathway in the Canadian and Russian Arctic. In the same vein, Fedi et al (2018b) highlighted the POLARIS system benefits as a decision-support tool at internal and external level, and its limitations from the perspective of human factors. Bergström et al (2022) confirmed POLARIS could prevent ice damages more comprehensively than AIRSS. Notwithstanding some limitations, the combined use of Polar Code provisions and POLARIS could prevent accidents in the Arctic (Fedi et al., 2020). Further, as key components of the "polarseaworthiness," the Polar Code and POLARIS together play a key role "in the shipping risk management of Arctic infrastructure projects" (Rigot-Muller et al., 2022). Finally, a recent comparison between POLARIS and AIRSS has concluded that even though POLARIS, as a modern regulatory framework, provides greater leeway to sail in severe ice conditions, AIRSS is rather "conservative" while allowing reduced transit time and fuel consumption (Browne et al., 2022).

Consequently, while numerous analyses deal with hubs, profit and cost analysis, the Social Cost of Carbon and POLARIS, none of them combine all these parameters to define the potential impact a Social Cost of Carbon may have on NSR attractiveness for shipowners, depending on changing ice conditions, different logistics settings constrained by "IMO 2020″ and the definitive ban of HFO by 2029. Our results could be beneficial for container liner operators in adopting sustainable transport strategies and to governmental bodies regarding environmental policies on CO_2 emissions from ships.

3. Profit model

Our model assesses the profitability of 1A ice-class vessels sailing along the NSR. To do so, the model compares four possible logistics settings to transport containers between Shanghai and Rotterdam using the NSR:

- Logistics setting 1 – two hubs: the ice class 1A vessel sails between Murmansk and Petropavlovsk with transshipment in both hubs. Feeder services are used between Rotterdam and Murmansk and between Shanghai and Petropavlovsk and vice-versa to complete the containers' trips.
- Logistics setting 2 – one hub in Murmansk: the ice class 1A vessel sails between Shanghai and Murmansk with transshipment in Murmansk. The remaining part of the containers' trip, i.e., between Murmansk and Rotterdam and vice-versa, is completed by feeder services.

- Logistics setting 3 – one hub in Petropavlovsk: the ice class 1A vessel sails between Rotterdam and Petropavlovsk with transshipment in Petropavlovsk. The remaining part of the containers' trip, i.e., between Petropavlovsk and Shanghai and vice-versa, is completed by feeder services.
- Logistics setting 4 – Direct: the ice class 1A vessel sails between Shanghai and Rotterdam without feeder services.

One assumes that the shipowner can decide to use Murmansk and Petropavlovsk simultaneously as hubs, or either of them separately, or sail directly between Shanghai and Rotterdam. When the liner company decides to use a hub, because the first/last part of each trip between the port of origin/destination and the hub is completed by a feeder, the feeder freight rate (cost) is considered in the calculation of the profit in addition to the revenue and the other costs (e.g. ice class 1A vessel operating costs, fuel cost,…).

As the ice conditions are highly variable, we suggest three ice thickness scenarios. To conform as much as possible to reality, we consider the ice-class container ship 1A *Venta Maersk* and compare it to a vessel with the same loading capacity and with a Triple-E vessel, commonly used along the SCR.

In the options where transshipment is used, the costs associated with feeder trips and transshipment are added to the model using average market rates. We also assume that the ice class 1A vessel uses only one logistics setting throughout the year.

3.1. Model input parameters

The following parameters have preset values and are used as inputs to the model and apply on the trip carried out by an ice class 1A vessel, excluding the feeder services (if any).

- d_0^d and d_F^d: first and last possible calendar day-of-departure of the year from Shanghai (or Petropavlovsk) for a trip that can be completed without the vessel being blocked, depending on the considered scenario. It is assumed that the first trip starts westbound and that vessels are assisted by icebreaker when necessary.
- V^{DS}: vessel design speed [knots].
- t_S^{C1}, t_S^{C2}: total standard transit time of the containers westbound and eastbound respectively, from the point of origin (Shanghai or Rotterdam) to the point of destination (Shanghai or Rotterdam) [days]. This transit time corresponds to the usual maritime lines passing through the Suez Canal for example.
- C_d^X: daily capital expenses corresponding to an ice class 1A vessel per day [USD/day]. This cost includes the scrubber cost when High Sulphur Fuel Oil is used.
- O_d^X: operational costs of an ice class 1A vessel, including crew, insurance, stores, lubricants, repairs, and maintenance, per day [USD/day].
- C_b^A, C_b^M: bunker fuel price per ton used for the auxiliary and main engines respectively [USD/ton].
- C^{SC}: social cost of one ton of emitted CO_2; i.e. Social Cost of Carbon (SCC) [USD/ton of CO_2].
- γ^{SCC}: a binary parameter that is equal to one if a carbon taxation policy accounting for the SCC (i.e., SCC) is in effect, and zero otherwise.
- E^f: carbon emission factor that represents the amount of CO_2 emitted by a ton of fuel and that depends on the type of fuel used [ton of CO_2/ton of fuel].
- $F^A, F^M(V)$: daily fuel consumption of auxiliary and main engines of an ice class 1A vessel [ton/day]. $F^M(V)$ is a function of the sailing speed V.
- ρ_S^1, ρ_S^2: standard/nominal market freight rate (selling price) charged to the shippers per TEU carried from the port of origin (Shanghai/Rotterdam) to the port of destination (Rotterdam/Shanghai) westbound and eastbound respectively [USD/TEU]. It corresponds to the usual market freight rate practiced by maritime lines and published on their websites (passing through the Suez Canal).
- ρ^1, ρ^2: selected freight rate (selling price) charged to the customers per TEU carried from the port of origin (Shanghai/Rotterdam) to the port of destination (Rotterdam/Shanghai) westbound and eastbound respectively [USD/TEU]. The value of this parameter is selected from a preset list of values.
- K: total carrying capacity of the vessel [TEU].
- α_S^1, α_S^2: standard/nominal utilization rate of the vessel's capacity westbound and eastbound respectively corresponding to a standard transit time and to a standard freight rate (selling price) [%].

3.2. Model calculated variables

The following parameters also apply on the trip carried out by an ice class 1A vessel, excluding the parts that are completed by the feeder services (if any), but their values are calculated based on the model inputs.

- R: total number of completed return trips per year between Shanghai (or Petropavlovsk) and Rotterdam (or Murmansk).

- V_r^1, V_r^2: average sailing speed of an ice class 1A vessel during trip $r = 1, \cdots, R$ while sailing on the NSR part of the route (area between Novaya Zemlya islands and the Bering Strait) westbound (Shanghai/Petropavlovsk to Rotterdam/Murmansk) and eastbound respectively [knots].
- V_r^3: average sailing speed of an ice class 1A vessel during trip $r = 1, \cdots, R$ while sailing in open water in both directions [knots].
- D_r^1, D_r^2: average NSR distance of trip $r = 1, \cdots, R$ westbound and eastbound respectively [nm].
- D_r^{31}, D_r^{32}: total average distance sailed by an ice class 1A vessel of trip $r = 1, \cdots, R$ in open water (outside the NSR zones) westbound and eastbound respectively [nm].
- t_r^{P1}, t_r^{P2}: total port time of trip $r = 1, \cdots, R$ westbound and eastbound respectively [days].
- t_r^1, t_r^2: total duration of the westbound and eastbound parts of trip r of an ice class 1A vessel respectively including sailing and port times [days]. This time excludes the feeder transit time.
- t_r^{F1}, t_r^{F2}: total feeder sailing time of the containers of trip r westbound and eastbound respectively, including the transshipment time [days]. They correspond to the time between the hubs and the ports of origin/destination and vice-versa. In the case of the non-use of a hub, the value of these parameters is equal to zero.
- t_r^{C1}, t_r^{C2}: total transit time of the containers of trip r westbound and eastbound respectively, from the point of origin (Shanghai or Rotterdam) to the point of destination (Shanghai or Rotterdam) [days].
- t_r: total duration of trip r including sailing and port times [days]. This time excludes the feeder transit time.
- d_r^{d1} and d_r^{d2}: day-of-departure of an ice class 1A vessel for trip $r = 1, \ldots, R$ westbound and eastbound respectively.
- C_r^{X1}, C_r^{X2}: capital expenses corresponding to an ice class 1A vessel for the westbound and eastbound legs of trip r [USD/trip].
- O_r^{X1}, O_r^{X2}: operational costs corresponding to an ice class 1A vessel for the westbound and eastbound legs of trip r [USD/trip].
- I_r^{B1}, I_r^{B2}: total NSR fees of trip r, westbound and eastbound respectively, including transit and pilotage fees, as well as the cost of the use of icebreakers if needed [USD/trip].
- B_r^{A1}, B_r^{M1}: total bunker fuel cost of the westbound leg of trip r for the auxiliary and the main engines respectively [USD/trip].
- B_r^{A2}, B_r^{M2}: total bunker fuel cost of the eastbound leg of trip r for the auxiliary and the main engines respectively [USD/trip].
- B_r^1, B_r^2: total fuel cost for both engines of an ice class 1A vessel for the westbound and eastbound legs of trip r respectively [USD/trip].
- C_r^{SCC1}, C_r^{SCC2}: Social Cost of Carbon corresponding to an ice class 1A vessel for the westbound and eastbound legs of trip r [USD/trip].
- C_r^i, π_r^i: total cost and profit respectively for the westbound ($i = 1$) and eastbound ($i = 2$) legs of trip r [USD/trip]. The cost includes capital costs, operational costs, bunker costs and NSR fees. Costs include only the ice class 1A vessel-related cost excluding the transshipment and the feeder-related ones (whenever applicable in case of use of hubs), while these costs are considered in the profit.
- C_y^i, π_y^i: total cost and profit respectively per year of the westbound ($i = 1$) and eastbound ($i = 2$) legs assuming that the ship sails continuously during the period when sailing is possible [USD/year]. The cost includes only the ice class 1A vessel-related cost excluding the transshipment and the feeder-related ones (whenever applicable in case of use of hubs), while these costs are considered in the profit.
- C_y, π_y: total cost and profit respectively per year in both directions for all the possible trips [USD/year].
- C_{TEU}^{T1}, C_{TEU}^{T2}: total feeder freight rate and transshipment cost per TEU westbound and eastbound [USD/TEU]. This cost depends on the chosen logistics option and is equal to zero if the option does not include any hub.
- C_{TEU}^{ri}, π_{TEU}^{ri}: total cost and profit respectively per TEU transported on the westbound ($i = 1$) and eastbound ($i = 2$) legs of trip r between the port of origin to the port of destination [USD/TEU].
- C_{TEU}^i, π_{TEU}^i: average total cost and profit respectively per TEU (port of origin to port of destination) transported westbound ($i = 1$) and eastbound ($i = 2$) based on all the trips of the year [USD/TEU].
- C_{TEU}, π_{TEU}: average total cost and profit respectively per TEU transported (port of origin to port of destination) based on all the trips of the year in both directions [USD/TEU].
- α_r^1, α_r^2: utilization rate of the vessel capacity for the westbound and eastbound legs respectively of trip r (selling price) [%]. These rates depend on the used freight rate and transit time.
- Q_r^1, Q_r^2: loaded quantity onboard an ice class 1A vessel for the westbound and eastbound legs respectively of trip r (selling price) [TEU].

It is worth noting that V_r^1 and V_r^2 are calculated as an average constant speed throughout each NSR-leg of the trip (in both directions) using the POLARIS system as explained in Section 3.6 and more precisely based on the Risk Index Outcome (RIO). These average sailing speeds depend on the day-of-departure (d_r^{d1}) of trip r from Shanghai (Petropavlovsk) for V_r^1 and d_r^{d2} from Rotterdam

(Murmansk) for V_r^2. Moreover, V_r^3 is assumed as equal to the vessel design speed.

3.3. Transit time and number of trips

We assume that the 1A ice-class vessel operates between Shanghai/Petropavlovsk and Rotterdam/Murmansk starting from the first day of the period during which navigation is possible, even with icebreaker assistance, until the last day of that period. A trip that starts in Shanghai also ends in Shanghai and a trip that starts in Petropavlovsk terminates in Petropavlovsk.

The duration of the westbound ($i = 1$) and eastbound ($i = 2$) legs of trip r are thereby calculated as follows:

$$t_r^i = \frac{D_r^i}{24 \times V_r^i} + \frac{D_r^{3i}}{24 \times V_r^3} + t_r^{Pi}, i = 1, 2 and r = 1, \cdots, R \tag{1}$$

In addition, the total trip time of an ice class 1A vessel is:

$$t_r = t_r^1 + t_r^2 \tag{2}$$

Therefore, based on the ice thickness scenario along the NSR, the day-of-departure of the eastbound leg of the first trip is calculated as follows:

$$d_1^{d2} = d_1^{d1} + t_1^1 \tag{3}$$

For any further trip $r = 3, \cdots, R$, the day-of-departure of the westbound leg is then calculated as follows:

$$d_r^{d1} = d_{r-1}^{d2} + t_{r-1}^2 \tag{4}$$

and the day-of-departure of the eastbound leg is then calculated as follows:

$$d_r^{d2} = d_r^{d1} + t_r^1 \tag{5}$$

Equations (3)-(5) are then used to determine the value of the total possible number of trips per year R so that R is the largest possible integer for which:

$$d_R^{d1} \le d_F^d and d_{R+1}^{d1} > d_F^d \tag{6}$$

A trip that cannot be completed (westbound and eastbound) due to heavy ice conditions is not counted. However, if only the westbound leg of the last trip can be completed, then that leg will be counted in the cost and profit calculations, and in this case R will be incremented by 0.5.

The total transit time, from the port of departure to the port of destination, of a container shipped westbound ($i = 1$) and eastbound ($i = 2$) respectively on trip $r = 1, \cdots, R$, including the feeder and transshipment time in case of the use of hubs is given by:

$$t_r^{Ci} = t_r^i + t_r^{Fi} i = 1, 2 and r = 1, \cdots, R \tag{7}$$

3.4. Cost calculations

The total costs of operating an ice class 1A vessel for the westbound ($i = 1$) and eastbound ($i = 2$) legs of trip $r = 1, \cdots, R$ are calculated as follows:

$$C_r^i = C_r^{Xi} + O_r^{Xi} + B_r^i + C_r^{SCCi} + I_r^{Bi}, i = 1, 2 and r = 1, \cdots, R \tag{8}$$

The total capital expenditures per trip are calculated in two different ways. The first case, referred to as the "Steady CAPEX" case, considers that the ice class 1A vessel is used for NSR navigation whenever navigation is possible and is used elsewhere when the NSR is not open for navigation due to ice conditions, i.e., the vessel is used year-round. Therefore, in this case, when navigation is not possible in the Arctic due to ice conditions, the vessel can be used on the SCR or on any other trade routes. For this case, the depreciation of the ship is assumed to occur over a period of 15 years and therefore the daily CAPEX is constant and is calculated as follows:

$$C_d^X = \frac{C^{AP}}{365 \times 15} \tag{9}$$

where C^{AP} represents the ice class 1A vessel capital cost, i.e., its original price. It also includes the scrubber cost in case of the use of a high sulphur content fuel.

The second method contemplates that the vessel is used only for the NSR trips throughout the year whenever sailing is possible and is therefore not used on other lanes when NSR navigation is not possible. This method is referred to as the "Changing CAPEX" case, for which the daily capital cost is calculated as follows:

$$C_d^X = \frac{C^{AP}}{\sum_{r=1}^{R} t_r \times 15} \tag{10}$$

The capital costs westbound ($i = 1$) and eastbound ($i = 2$) respectively of trip r are thereby calculated as follows:

$$C_r^{Xi} = C_d^X \times t_r^i, i = 1, 2 and r = 1, \cdots, R \tag{11}$$

The total operational costs westbound ($i = 1$) and eastbound ($i = 2$) respectively of trip r are then calculated as follows:

$$O_r^{Xi} = O_d^X \times t_r^i, i = 1, 2 and r = 1, \cdots, R \tag{12}$$

For each leg of trip r, the total bunker fuel cost per trip leg for both engines is the sum of the bunker fuel cost from the main and the auxiliary engines:

$$B_r^i = B_r^{Ai} + B_r^{Mi}, i = 1, 2 and r = 1, \cdots, R \tag{13}$$

with.

$$B_r^{Ai} = C_b^A \times t_r^i \times F^A i = 1, 2 and r = 1, \cdots, R \tag{14}$$

and.

$$B_r^{Mi} = C_b^M \times \left(\frac{D_r^i}{24 \times V_r^i} F^M(V_r^i) + \frac{D_r^{3i}}{24 \times V_r^3} F^M(V_r^3) \right), i = 1, 2 and r = 1, \cdots, R \tag{15}$$

where.

$$F^M(V) = \frac{S_{FOC}^M L^M P_S^M}{10^6} \times \left(\frac{V}{V^{DS}} \right)^3 \tag{16}$$

S_{FOC}^M is the specific fuel oil consumption of the main engine [in g/kWh], L^M the engine load of the main engine [in %], and P_S^M the power of the main engine [in kW]. As Wang and Meng (2012), we used the third power approximation.

The Social Cost of Carbon for the westbound ($i = 1$) and eastbound ($i = 2$) legs respectively of trip r are subsequently calculated as follows:

$$C_r^{SCCi} = \gamma^{SCC} \times C^{SC} \times E^f \times \left(t_r^i \times F^A + \frac{D_r^i}{24 \times V_r^i} F^M(V_r^i) + \frac{D_r^{3i}}{24 \times V_r^3} F^M(V_r^3) \right) \tag{17}$$

$$with i = 1, 2 and r = 1, \cdots, R$$

Finally, I_r^{Bi} is determined for each leg of trip r based on the RIO value of the day-of-departure of the westbound ($i = 1$) or eastbound ($i = 2$) leg of the trip dod_r^i.

The total cost of the ice class 1A vessel per year and for one direction (westbound or eastbound) is then the sum of the costs of all the trips of one year in that direction:

$$C_y^i = \sum_{r=1}^R C_r^i, i = 1, 2 \tag{18}$$

In addition, the total cost of the ice class 1A vessel per year in both directions is:

$$C_y = C_y^1 + C_y^2 \tag{19}$$

The total cost per transported TEU for leg i of trip r, including the transshipment and feeder freight rate if any, and assuming that the vessel sails with a loaded quantity of Q_r^i is as follows:

$$C_{TEU}^{ri} = \frac{C_y^i}{Q_r^i} + C_{TEU}^{Ti}, i = 1, 2 and r = 1, \cdots . R \tag{20}$$

The average total cost per TEU (port of origin to port of destination) transported westbound and eastbound respectively based on all the trips of the year is then:

$$C_{TEU}^i = \frac{\sum_{r=1}^R C_{TEU}^{ri}}{R} i = 1, 2 \tag{21}$$

Finally, the average total cost per TEU transported (port of origin to port of destination) based on all the trips of the year in both directions is:

$$C_{TEU} = \frac{C_{TEU}^1 + C_{TEU}^2}{2} \tag{22}$$

3.5. Demand and profit calculations

We use the same approach as in Cheaitou and Cariou (2017) to model the sensitivity of shipping demand to transit time and freight rate (selling price).

The transported quantity onboard the vessel for leg i of trip r is calculated as follows:

$$Q_r^i = Min\left(K; \left(K \times \alpha_S^i\right) \times \alpha_r^i\right) \tag{23}$$

where.

$K \times \alpha_S^i$ represents the nominal (standard) quantity that is loaded on the NSR for the nominal transit time defined by Lasserre (2014), i.e., $t_S^{C1} = t_S^{C2} = 22.4$ days, where $\alpha_S^1 = 70\%$ and $\alpha_S^2 = 45\%$.

Moreover, the impact of the transit time that varies based on the departure day of every trip, and of the freight rate is accounted for in α_r^i as follows:

$$\alpha_r^i = \left(\frac{t_S^{Ci} + \beta^i - t_r^{Ci}}{\beta^i}\right)^+ \times \left(\frac{\rho_S^i + \delta^i - \rho^i}{\delta^i}\right)^+ \tag{24}$$

where β^i represents the maximum additional transit time beyond which the shipping demand becomes equal to zero. This means that when the transit time is above a certain level (standard transit time + maximum additional transit time), the transport demand is then equal to zero. β^i was estimated based on the difference between the maximum transit time for all the possible trips in a direction and the nominal transit time and the values are $\beta^1 = 11$ days and $\beta^2 = 11.2$ days.

δ^i plays the same role for the freight rate and means the maximum additional freight rate above the standard freight rate above which the shipping demand becomes equal to zero. For the standard freight rates, we used the values provided by an international freight forwarder, i.e., $\rho_S^1 = 690$ USD/TEU and $\rho_S^2 = 665$ USD/TEU. The value of δ^i was calculated based on the maximum difference between the maximum considered freight rate and the standard freight rate for each direction and the results are $\delta^1 = 1146$ USD/TEU and $\delta^2 = 1144$ USD/TEU. The maximum considered freight rate for every direction was selected based on the results of the cost analysis and the NSR economic viability and are provided in Section 5.

The profit per TEU for leg i of trip r is calculated as follows:

$$\pi_{TEU}^{ri} = \rho^i - C_{TEU}^{ri}, i = 1, 2, and r = 1, \cdots, R \tag{25}$$

Moreover, the average total profit per TEU container transported (port of origin to port of destination) westbound ($i = 1$) or eastbound ($i = 2$) based on all the trips of the year in the considered direction is:

$$\pi_{TEU}^i = \rho^i - C_{TEU}^i, i = 1, 2 \tag{26}$$

The average total profit per TEU container (port of origin to port of destination) based on all the trips of the year (in both directions) is then:$\pi_{TEU} = \left(\frac{\rho^1+\rho^2}{2} - C_{TEU}\right)$ (27).

The total profit for leg i of trip r is calculated as follows:

$$\pi_r^i = \left(\rho^i - C_{TEU}^{ri}\right) \times Q_r^i, i = 1, 2, and r = 1, \cdots, R \tag{28}$$

The total profit of the ice class 1A vessel per year and for one direction (westbound or eastbound) is hence the sum of the profits of all the trips of one year in that direction:

$$\pi_y^i = \sum_{r=1}^R \pi_r^i, i = 1, 2 \tag{29}$$

Table 1
Risk Index Values (RIV).

Vessel Category	Vessel Class	Ice free	New ice	Grey ice	Grey white ice	Thin 1st year ice (1st stage)	Thin 1st year ice (2nd stage)	Medium 1st year ice < 1 m	Medium 1st year ice	Thick 1st year ice	2nd year ice	Light muti-year ice < 2.5 m	Heavy multi-year ice
Polar Class (Cat. A)	PC-1	3	3	3	3	2	2	2	2	2	2	1	1
	PC-2	3	3	3	3	2	2	2	2	2	1	1	0
	PC-3	3	3	3	3	2	2	2	2	2	1	0	−1
	PC-4	3	3	3	3	2	2	2	2	1	0	−1	−2
	PC-5	3	3	3	3	2	2	1	1	0	−1	−2	−2
Polar Class (Cat. B)	PC-6	3	2	2	2	2	1	1	0	−1	−2	−3	−3
	PC-7	3	2	2	2	1	1	0	−1	−2	−3	−3	−3
Ice-class	1AS	3	2	2	2	2	1	0	−1	−2	−3	−4	−4
	1A	3	2	2	2	1	0	−1	−2	−3	−4	−5	−5
	1B	3	2	2	1	0	−1	−2	−3	−4	−5	−6	−6
	1C	3	2	1	0	−1	−2	−3	−4	−5	−6	−7	−8
Cat. II	Not ice-class	3	1	0	−1	−2	−3	−4	−5	−6	−7	−8	−8

Source: Authors based IMO (2019).

Finally, the total profit per year for the ice class 1A vessel considering both directions is:

$$\pi_y = \pi_y^1 + \pi_y^2 \quad (30)$$

3.6. Sailing speed in ice and navigability period

The period of navigation in which the ice class 1A vessel can sail along the NSR is defined based on POLARIS Risk Index Outcome (RIO). This index is computed via the concentration of different types of ice the ship may encounter and its resilience capacity (Fedi et al., 2018b) as shown in Eq. (31). POLARIS is considered as a decision tool for deck officers to adapt the vessel speed and to decide on using the assistance of an icebreaker and plan the vessel journey to provide safe navigation (Fedi et al., 2018b).

$$RIO = (RIV_1.C_1) + (RIV_2.C_2)\cdots\cdots. + (RIV_n.C_n). \quad (31)$$

Here, RIV_n indicates the ability of the vessel to maneuver in a concentration C_n (tenths) of a specific ice type encountered by the vessel. We consider the relationship between the ice-class and the Polar Code based on DNV-GL Polar categories as shown in Table 1 (Arctic Today, 2019; DNV, 2018).

The RIO can vary between 30 and −80 but a vessel may not be allowed to sail at −10 as shown in Table 2 (IMO, 2019).

Combining our model with recommended speeds (IMO, 2019), we assumed that the vessel would sail at design speed of nineteen knots with a RIO = 30, at eight knots when RIO = 0 (icebreaker assistance required) (Cheaitou et al., 2020), and three knots when RIO = -10 (lowest steering speed) (Faury et al., 2020). Thus, using a regression in a similar way to the ice-thickness to speed relationship defined in (Faury et al., 2020), the vessel speed is defined as a function of the RIO value by equation (32) which integrates these three constraints of speed and RIO values and in which × stands for the RIO as seen in Fig. 1.

$$V = -\frac{1}{300}x^2 + \frac{7}{15}x + 8 \quad (32)$$

3.7. Route planning using time-dependent short path algorithm

Stephenson et al (2014) highlighted the fast-changing conditions of Arctic sea ice, especially during the freezing and melting season. These changes make the duration of these seasons uncertain and require high spatiotemporal resolution data to be modeled.

As explained, depending on their ice class (IC), the vessels react differently to the various types and concentrations of ice and thus must adapt their speed. In our analysis, we used the Arctic Circle area as a raster grid with fixed spatial resolution (12.5 × 12.5 km).

Each grid cell is filled with a daily statistical POLARIS RIO value for each ship's ice class. These statistical values depict various scenarios of historically observed POLARIS RIO within this grid cell. We contemplated three different scenarios:

- Low-access scenario which corresponds to the first quartile (25 %) of the POLARIS values.
- Median-access scenario (50 %) of the lowest POLARIS values.
- High-access scenario which corresponds to the third quartile (75 %) of the POLARIS values.

Using Equation (32), three speeds (V_{25}, V_{50}, V_{75}) are computed for each scenario and each time slice at daily time resolution. Grid cells are connected using eight directed edges (adjacent and diagonally) to generate a graph network. Grid cells located on land are discarded from the graph network. Daily travel times and icebreaker escort requirements are computed for each edge of the graph.

The time-dependent graph $G_T = (\Upsilon, \Theta, W)$ is a graph having an edge-transit time function $w_{i,j}(t,c)$ associated to the edge (v_i, v_j). We define the graph nodes $\Upsilon = \{v_i\}$, edges $\Theta = \{(v_i, v_j)\}$ and weights $W = \{w_{i,j}(t,c)\}$, for $1 \leq i,j \leq n$.

$w_{i,j}(t,c)$ is a periodic, discrete, piecewise linear function that returns the required travel time between node i and node j at time t for scenario c considering vessel characteristics (Ice Class, design speed). If the ice conditions are too harsh for the ship ice-class (POLARIS RIO $\langle -10$), then the function returns -1 indicating that the edge cannot be navigated at time t. When the POLARIS RIO is negative, an icebreaker escort is required.

An adapted version of the shortest path algorithm that considers the time-dependent edge weights was used to compute the shortest time route between Arctic locations. We also integrated the Dijkstra's time-dependent shortest path algorithm with the first-in, first-out (FIFO) assumption (Dehne et al., 2009; Jigang et al., 2011; Wang et al., 2019). The FIFO property of the graph ensures that on every edge, an earlier day-of-departure will lead to an earlier arrival (respectively a later departure will result in a later arrival). Waiting at a node during transit is not permitted in this algorithm and transit time of any edge at the lowest possible speed is always much lower

Table 2
Risk Index Outcome Criteria.

RIO_{SHIP}	Ice-classes PC1-PC7	Ice-classes below PC7 and ships not assigned an ice-class
RIO ≥ 0	Normal operations	Normal operations
−10 ≤ RIO < 0	Elevated operational risk	Operations subject to special consideration
RIO ≤ -10	Operations subject to special consideration	Operations subject to special consideration

Source: IMO (2019).

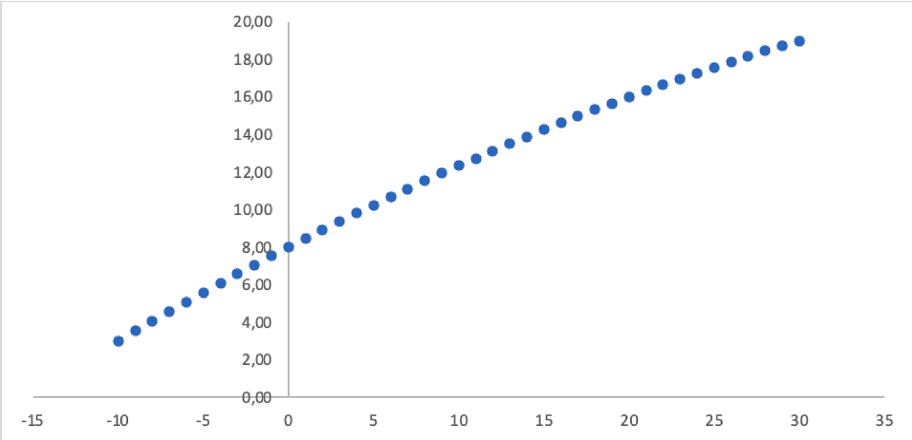

Fig. 1. speed of an ice class 1A vessel according to its RIO.

than waiting for one full day at the node.

The time-dependent shortest path between Arctic locations was computed iteratively for each day-of-departure (day 1 to 365) and each scenario (low-access, median-access, and high-access case) resulting in a matrix indicating, for each day-of-departure, whereas

Table 3
Economic and technical parameters.

	Venta Maersk in ice waters
C^{AP} [Mln USD][1]	38
C_d^X for the Steady CAPEX case without the scrubber cost [USD] [1]	6,941
O_d^X [USD]	6,121[6]
K [TEU] [1]	3,600
Standard loading factor Eastbound[2], α_S^2	45 %
Standard loading factor Westbound[2], α_S^1	70 %
Gross Tonnage [Ton] [1]	34,882
Design speed, V^{DS} [Kts] [1]	19
Main engine power, P_S^M [Kw] [1]	19,620
S_{FOC}^M [g/Kwh][1]	170
Main engine daily fuel consumption [Ton/Day][1]	
Auxiliary engine daily fuel consumption, $F^M(V)$, at design speed [Kw]	2,000
Auxiliary engine daily fuel consumption, F^A [Ton/Day]	3.5
Fuel cost, C_b^A and C_b^M, [USD / Ton] [1]	511
Fuel cost, C_b^A and C_b^M, [USD / Ton] [1] VLSFO	420
Time spent in port per trip per direction, t_r^{P1} and t_r^{P2} [days][2]	2
Suez Canal fees Eastbound [USD][3]	
Suez Canal fees Westbound [USD][3]	
Freight rate eastbound via the SCR, ρ^2 [USD/TEU]	665
Freight rate westbound via the SCR, ρ^1 [USD/TEU]	690
Transshipment fees for a TEU in each hub (if any), [USD/TEU][8]	120
Feeder freight rate for a TEU from Murmansk to Rotterdam and vice versa [USD/TEU] [9]	1,120 and 523
Feeder freight rate for a TEU from Shanghai to Petropavlovsk and vice versa [USD/TEU] [9]	349 and 566
Emission factor HFO, E^f [ton/ton]	3.113
Emission factor VLSFO, E^f [ton/ton]	3.206
Social Carbon Cost, C^{SC} [USD/ton]	100

Source: Authors (2022) based on:
[1] Clarksons (2019).
[2] Lasserre (2014).
[3] Suez calculator (2019).
[4] Coming from an interview with JF Cornille (Seafrigo - international freight forwarder).
[5] Retrieved from: https://www.wsj.com/articles/costly-bet-on-big-cargo-ships-comes-up-short-1433151181.
[6] Opex Survey (2017) and Erikstad and Ehlers (2012).
[7] Intervew of Rona Ayberk from BRS Genève.
[8] Yetkili et al. (2016).
[9] https://www.worldfreightrates.com/fr/.
[10] Cariou and Faury (2015).

the path between locations is possible, how much time and distance it will take and if an icebreaker escort is required.

These results are required to set up the following model parameters introduced in Sections 3.1 and 3.2:

- d_0^d and d_F^d: day-of-departure time window.
- V_r^1, V_r^2: average NSR sailing speed of an ice class 1A vessel during trip r.
- D_r^1, D_r^2: average NSR distance of trip r.
- t_r^1, t_r^2: total duration of the westbound and eastbound parts of trip r.
- t_r: total duration of trip r.
- I_r^{B1}, I_r^{B2}: total NSR fees of trip r, including the cost of icebreaker escort if needed.

In addition to the other economic parameters that rely on speed and sailing time.

4. Business case

Our business case considers two categories of vessels: a shuttle, an ice class 1A vessel sailing between hubs and/or destination depending on the logistics scenario, and the non-ice-strengthened feeder vessels connecting hubs to Rotterdam and Shanghai. Regarding the technical aspects of both types of vessels, we relied on the *Venta Maersk* (Table 3). The standard transit time is assumed to be 27 days (Maersk, 2019). The choice of Murmansk and Petropavlovsk as hubs can be explained by the fact that containers are already managed in these ports (The Ministry of Foreign Affairs of the Russian Federation, 2010). Following Jiang et al (2021), we estimated that the vessels spend two days at ports to load and unload containers and that the handling cost is 60 USD per TEU (Yetkili et al., 2016).

In accordance with Regulation 43A (IMO, 2021), HFO and VLSFO are allowed until 2029. Thus, we considered HFO with scrubber and VLSFO as possible fuels. Due to the extreme conditions, we applied a 33 % premium to the bunker cost (Lasserre, 2014). We considered that the Social Cost of Carbon is 100 USD per ton (Cariou and Faury, 2015; Zhu et al., 2018; Cheaitou et al., 2020).

Because of the trade imbalance, we assumed that the vessel will be loaded at 70 % and 45 % of its capacity westbound and eastbound respectively (Lasserre, 2014). Still, due to trade imbalance (Demirel et al., 2011), we integrated different freight rates depending on the direction. As it is not possible to sail independently year-round along the NSR, we examined two possibilities for the ship during closure: to use it on another trade (Steady CAPEX) or to wait, idle, for the opening of the NSR (Changing CAPEX). This

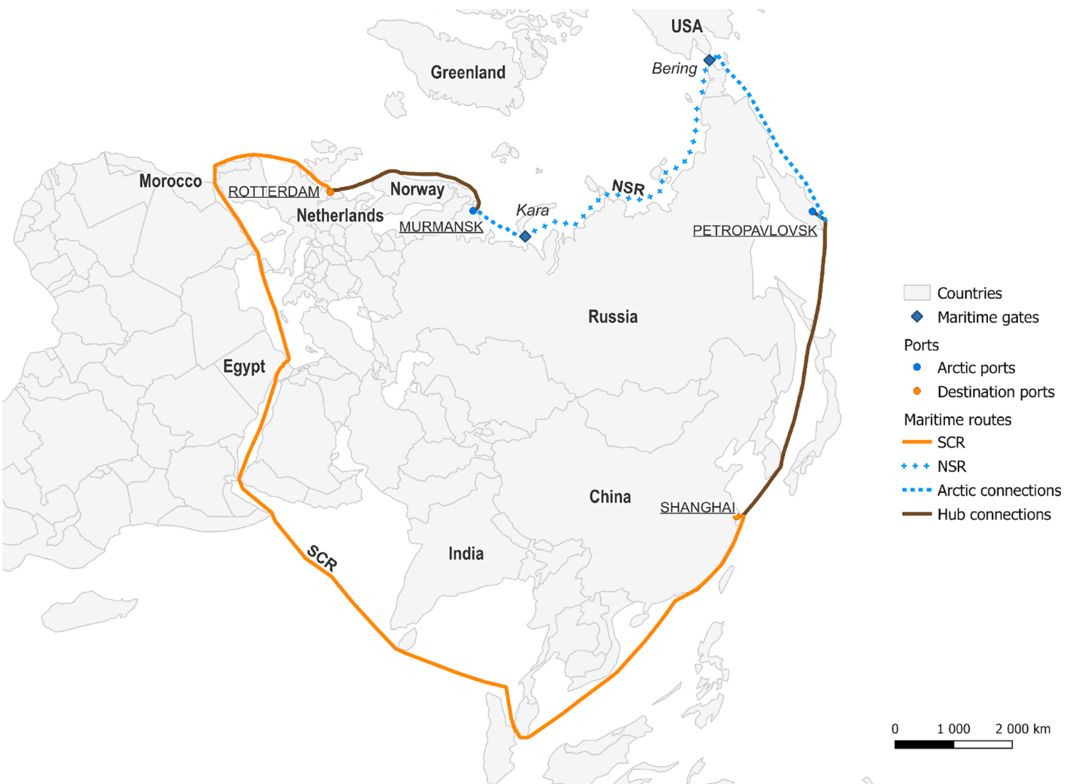

Fig. 2. Shipping route options. Source: Authors (2022).

assumption aims to demonstrate the possibility to generate profit without reorganizing existing trades; in other words, the NSR would be managed independently from other services.

As unsuitable speed is a major cause of incident and/or accidents (Marchenko, 2014a), we define the speed depending on the ship's RIO. To compute the RIO, we extracted data from the European Copernicus database, which provides access to a full range of data on ice conditions worldwide (von Schuckmann et al., 2016). In this analysis, we used the ARCTIC_REANALYSIS_PHYS_002_003 dataset (von Schuckmann et al., 2016) which provides gridded ice thickness and concentration at 12.5 km resolution over 28 years.

We extracted the daily ice conditions over 28 years for each year (365 days) between 1991 and 2019 and used the R^{IV} of an ice-class 1A vessel. Insofar as underwriters and the Polar Code provisions require a defined route when agreeing to insure ships (Fedi et al., 2018a), we determined a route between the Bering Strait and Murmansk, as illustrated in Fig. 2.Fig. 3a.Fig. 3b.Fig. 3c.Fig. 3d..

The R^{IV} is the basis for the speed computation of the ice class 1A vessel with technical specificities like the Venta Maersk in three ice conditions: "high-access", the "median-access", and the "low-access".

Finally, we integrated icebreaker assistance as another constraint imposed by underwriters. To define the costs I_r^{B1} and I_r^{B2}, we relied on the Northern Sea Route Administration (NSRA, 2018). Since fees are charged in Rubles, we considered an exchange rate of 0.0149109 Russian Rubles for one USD on 8 January 2019 (Xe, 2019) knowing that results can be generalized with any rate.

5. Results

The results stress the environmental impact a CO_2 tax may have upon NSR attractiveness as the number of shipped containers depends on the freight rate. VLSFO has a higher emission factor of CO_2 (Bilgili, 2021) with a difference of 0.093 ton of CO_2/ton of fuel and is more expensive than HFO (Ji and El-Halwagi, 2020); thus, the profit generated by the HFO is obviously higher than the profit generated with the use of VLSFO. However, as the number of shipped containers depends on the applied freight rate, our results show the following: which option generates the lowest amount of CO_2 per container, the range of freight rates that generate profit, the freight rate that produces the maximum profit or the minimum loss, and the amount of CO_2 emitted per container if the optimal freight rate is applied.

First, we define the price per container based on the cost depending on the climatic scenario and the navigation direction (eastbound or westbound). Secondly, we compute the number of containers loaded depending on the freight rate charged. Thirdly, we assess the amount of CO_2 emitted per container. To conclude, we determine which option shall be the most profitable or enables loading the highest number of containers as per the CAPEX strategy implemented by the shipowner.

5.1. Freight rate value

Our methodology generated a sample of 192 freight rates. The freight rates were computed based on the costs of scenarios combining different ice conditions, logistics settings, bunker fuels, CAPEX strategies (changing and steady CAPEX), navigation directions and whether SCC (i.e., a social carbon tax) is applied. The aim is to assess the shipowner's capacity to generate profit with a constraining environmental policy. Table 4a shows the different freight rates that have been computed according to the different configurations while Table 4b shows the minimum, median and maximum freight rates obtained as a function of the configuration including the navigation direction, the fuel used, the logistics setting, and the environmental policy, where a profit can be generated.

Table 4a sheds a light on the impact of the different exploitation strategies on the freight rate. First, the difference between the changing and the steady CAPEX strategies is more noticeable in the eastbound than in the westbound legs. This can be explained by the fact that the westbound legs of the trips load more containers than the eastbound legs, leading to a higher impact per container.

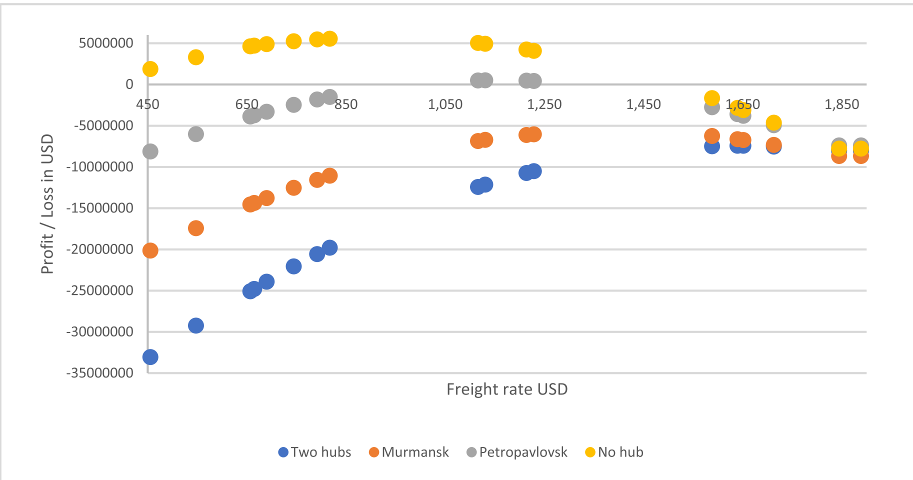

Fig. 3a. Profit and Loss generated with VLSFO in median access scenario without SCC.

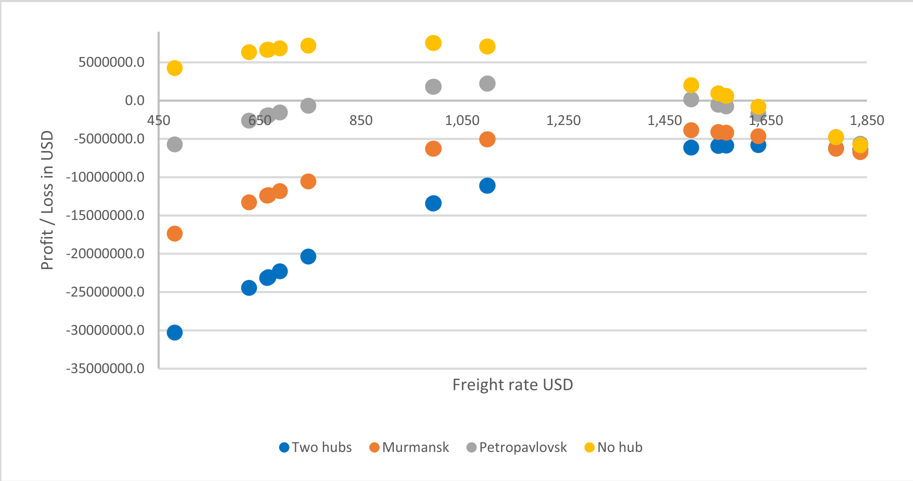

Fig. 3b. Profit and Loss generated with HFO in median access scenario without SCC.

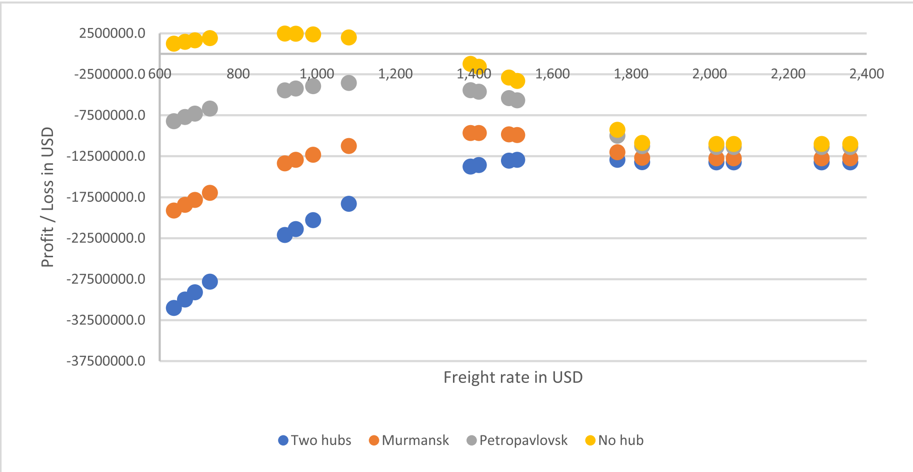

Fig. 3c. Profit and Loss generated with VLSFO in median access scenario with SCC policy.

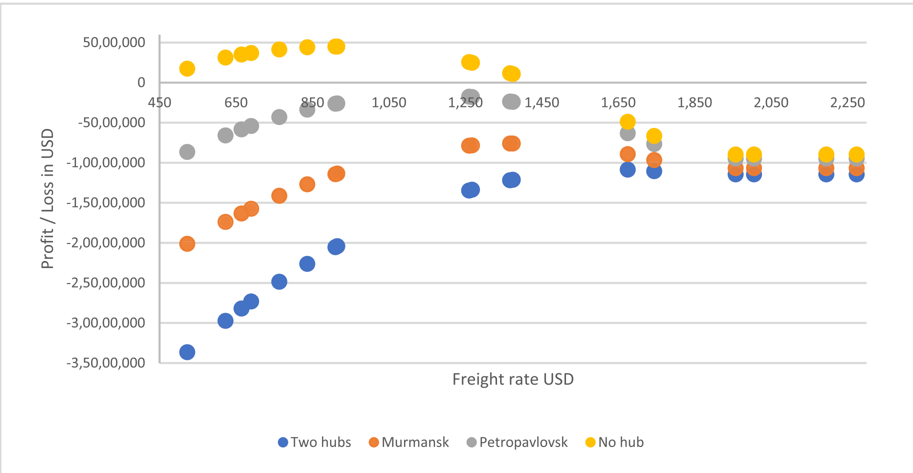

Fig. 3d. Profit and Loss generated with HFO in median access scenario with SCC.

Table 4a
Freight rate computed according to different configurations of navigation direction, ice conditions, logistics setting, environmental policy, fuel type, and CAPEX type.

Direction	Ice conditions	Logistic setting	Without SCC				With SCC			
			VLSFO		HFO		VLSFO		HFO	
			Cost per TEU Steady CAPEX - (USD)	Cost per TEU - Changing CAPEX (USD)	Cost per TEU -Steady CAPEX - (USD)	Cost per TEU - Changing CAPEX (USD)	Cost per TEUSteady CAPEX - (USD)	Cost per TEU - Changing CAPEX (USD)	Cost per TEUSteady CAPEX - (USD)	Cost per TEU - Changing CAPEX (USD)
Westbound	Low-access scenario	Two hubs	1,883	1,981	1,830	1,937	2,053	2,151	1,995	2,102
		Murmansk	1,568	1,679	1,482	1,604	1,746	1,857	1,655	1,777
		Petropavlovsk	777	894	700	828	952	1,141	869	997
		No hub	498	646	392	554	675	823	564	726
	Median-access scenario	Two hubs	1,845	1,889	1,790	1,837	2,018	2,062	1,958	2,006
		Murmansk	1,588	1,652	1,503	1,572	1,766	1,829	1,676	1,745
		Petropavlovsk	745	817	668	746	919	991	837	915
		No hub	456	547	347	447	637	728	523	623
	High-access scenario	Two hubs	1,833	1,869	1,776	1,815	2,009	2,045	1,947	1,986
		Murmansk	1,544	1,593	1,454	1,509	1,728	1,777	1,633	1,687
		Petropavlovsk	754	806	675	732	931	983	847	903
		No hub	467	526	358	422	649	708	535	599
Eastbound	Low-access scenario	Two hubs	1,684	1,842	1,600	1,773	2,332	2,491	2,241	2,414
		Murmansk	1,207	1,398	1,077	1,285	1,481	1,672	1,342	1,551
		Petropavlovsk	1,195	1,382	1081	1,285	1,458	1,645	1,336	1,541
		No hub	695	904	525	753	978	1,186	800	1,027
	Median-access scenario	Two hubs	1,640	1,713	1,557	1,636	2,286	2,359	2,195	2,274
		Murmansk	1,131	1,229	994	1,101	1,413	1,511	1,268	1,374
		Petropavlovsk	1,116	1,214	993	1,100	1,392	1,490	1,260	1,368
		No hub	657	792	482	629	947	1,082	764	911
	High-access scenario	Two hubs	1,606	1,663	1,519	1,581	2,258	2,314	2,162	2,224
		Murmansk	1,116	1,205	978	1,075	1,399	1,488	1,253	1,350
		Petropavlovsk	1,119	1,188	994	1,070	1,396	1,465	1,263	1,339
		No hub	656	743	482	577	944	1,032	762	857

Table 4b
Minimum, median, and maximum freight rates depending on the navigation direction, fuel type, logistics setting, and environmental policy.

		Without SCC				With SCC	
		Min	Median	Max	Min	Median	Max
Westbound	Two hubs - Westbound VLSFO	1,833	1,876	1,981	2,009	2,049	2,151
	Murmansk - Westbound VLSFO	1,544	1,591	1,679	1,728	1,771	1,857
VLSFO	Petropavlovsk - Westbound VLSFO	745	792	894	919	967	1,141
	No Hub - Westbound VLSFO	456	512	646	637	692	823
Westbound	Two hubs - Westbound HFO Scrubber	1,776	1,823	1,937	1,947	1,991	2,102
	Murmansk - Westbound HFO Scrubber	1,454	1,506	1,604	1,633	1,681	1,777
HFO Scrubber	Petropavlovsk - Westbound HFO Scrubber	668	739	828	837	886	997
	No Hub - Westbound HFO Scrubber	347	435	554	523	581	726
Eastbound	Two hubs - Eastbound VLSFO	1,606	1,674	1,842	2,258	2,323	2,491
	Murmansk - Eastbound VLSFO	1,116	1,206	1,398	1,399	1,485	1,672
VLSFO	Petropavlovsk – Eastbound VLSFO	1,116	1,192	1,382	1,392	1,462	1,645
	No Hub – Eastbound VLSFO	656	719	904	944	1,005	1,186
Eastbound	Two hubs - Eastbound HFO Scrubber	1,519	1,590	1,773	2,162	2,232	2,414
	Murmansk - Eastbound HFO Scrubber	978	1,076	1,285	1,253	1,346	1,551
HFO Scrubber	Petropavlovsk - Eastbound HFO Scrubber	993	1,076	1,285	1,260	1,338	1,541
	No Hub - Eastbound HFO Scrubber	482	551	753	762	828	1,027

Source: Authors (2022).

Second, the difference between the two strategies gets smaller as the ice conditions become lighter.

Looking at Table 4b, first, the enforcement of a tax on CO_2 emissions has a direct impact on the freight rate with an additional cost varying between \$141 USD and \$651 USD per TEU depending on the configuration chosen. Second, the use of HFO allows to save between \$49 USD and \$182 USD per TEU versus VLSFO. Third, in the case of westbound navigation, the impact of a SCC is lower on the freight rate than for eastbound navigation for both HFO and VLSFO.

In terms of profit, it appears that avoiding the use of hubs generates positive profits regardless of the chosen climatic scenario, fuel or environmental policy (Fig. 2a, b, c, d). A configuration with a hub in Petropavlovsk can lead to positive profits only if no environmental policy (SCC) is considered, but the option of a hub in Murmansk and the “two-hub” option are both unable to generate profits (Fig. 2a, b, c, d).

Using a polynomial regression of the curves represented in Fig. 2(a, b, c, d), we calculated the freight rate that would generate the highest profit or the lowest loss for every configuration. The results for the median access scenario are shown in Table 5.

As seen in Figure 3, the different fuels and logistics options can generate profit in a defined bracket of values. Table 6 stresses the equivalent of the freight rate in terms of CO_2 emissions per container. For example, in the low access scenario for the “No hub” logistics setting, vessels should be able to generate profit if the freight rate is between \$476 and \$1,374 USD which should generate an equivalent of 1.67 and 4.907 tons of CO_2 per TEU respectively. Moreover, Table 6 shows the amount of CO_2 emitted at the economic bound of each logistics setting depending on the ice conditions.

First, the amplitude of the profitable range in the case of VLSFO is smaller than in the case of HFO, mainly due to the additional cost represented by the use of VLSFO. Second, on the lower bound of the range, the use of HFO decreases the amount of CO_2 emitted, regardless of the SCC policy. This can be explained by the fact that the freight rate required to generate profit is lower than in the case of VLSFO, leading to a higher number of loaded containers. Third, on the upper bound of the range, the use of VLSFO decreases the amount of CO_2 emitted per container. This is explained by the fact that the upper bound is lower if the vessel is fueled with VLSFO than with HFO. As illustrated in Table 6, according to the freight rate policy applied by the shipowner, a lower or higher cost of bunker fuel should be used to limit the CO_2 emissions per container.

Table 5
Freight rate for the median-access scenario required to generate the minimum loss or maximum profit depending on climatic scenario, logistics setting, environmental policy, and fuel type.

		Without SCC		With SCC	
Ice conditions	Logistics setting	VLSFO	HFO	VLSFO	HFO
Low-access scenario	Two hubs	1,706	1,666	1,804	1,820
	Murmansk	1,396	1,383	1,363	1,376
	Petropavlovsk	1,110	1,118	1,085	1,084
	No hub	886	881	890	884
Median-access scenario	Two hubs	1,663	1,641	1,785	1,792
	Murmansk	1,398	1,397	1,346	1,365
	Petropavlovsk	1,137	1,158	739	738
	No hub	897	927	902	883
High-access scenario	Two hubs	1,650	1,634	1,778	1,775
	Murmansk	1,397	1,395	1,353	1,377
	Petropavlovsk	1,146	1,157	1,082	1,080
	No hub	906	928	902	885

Source: Authors (2022).

Table 6
The minimum and maximum amount of CO_2 emitted (ton) per TEU for the freight rate (range) that generates no loss.

Ice conditions	Logistics setting		Without SCC				With SCC			
			VLSFO Min/Max		HFO Min/Max		VLSFO Min/Max		HFO Min/Max	
Low-access scenario	No hub	Freight rate (USD)	476	1,374	354	1,503	738	1,056	564	1,266
		CO_2 emission (Ton/TEU)	1.670	4.907	1.548	6.654	2.039	2.881	1.707	3.848
Median-access scenario	Petropavlovsk	Freight rate (USD)	990	1,287	798	1,518				
		CO_2 emission (Ton/TEU)	2.091	3.243	1.651	5.509	–	–	–	–
	No hub	Freight rate (USD)	376	1,496	249	1,604	597	1,267	486	1,392
		CO_2 emission (Ton/TEU)	1.470	6.060	1.365	8.755	1.638	3.577	1.504	4.473
High-access scenario	Petropavlovsk	Freight rate (USD)	975	1,320	793	1,521	913	1,270	759	1,493
		CO_2 emission (Ton/TEU)	2.011	3.379	1.656	5.614	1.875	3.076	1.603	5.131
	No hub	Freight rate (USD)	375	1,493	260	1,596	477	1,462	388	1,582
		CO_2 emission (Ton/TEU)	1.490	6.039	1.434	8.761	1.556	5.536	1.497	8.240

Source: Authors (2022).

Nevertheless, these results must be put in perspective with the amplitude of the freight rate range in which a positive profit can be generated, which clearly advantages the HFO whatever the scenario and logistics setting (Table 7). The question of the amplitude is relevant as this enables shipowners to apply greater flexibility in terms of prices depending on the evolution of the freight rate along the SCR.

5.2. Environmental policy

Table 8 illustrates the impact a carbon tax may have on the number of containers loaded. In our model, the higher the cost of shipping one container, the fewer containers a company will load. However, Table 8 also emphasizes the number of containers loaded if the optimal freight rate is applied. In nine cases out of 12, the implementation of a SCC provides the opportunity to load the highest number of containers. Six out of nine cases use HFO and three use VLSFO. In other words, applying a SCC is not antinomic with a strategy aiming to load as many containers as possible even if implementing a CO_2 tax would increase costs and reduce the number of TEUs loaded.

Figs. 4a and 4b highlight the exponential evolution of CO_2 emissions as a function of the freight rate applied. Additionally, as mentioned earlier, an increase in the freight rate implies a decrease in the number of shipped containers and therefore a rise in the amount of emitted CO_2 per container. Figs. 4a to 4d confirm that the higher the freight rate, the higher the emissions per container; hence the least profitable option is the most sustainable one. This can be explained by the fact that as the freight rate increases, the attractiveness of the NSR decreases, and consequently, the number of loaded containers drops. Globally, the option with “two hubs” provides a more attractive curve in terms of emissions while avoiding hubs enhances the amount of CO_2 emitted per container. The attractiveness of the “two hubs” option is justified since this logistics setting allows loading the highest number of containers. This result stresses that by enabling an increased number of containers loaded, the use of hubs also decreases the CO_2 emissions per TEU.

Table 9 illustrates the impact a sustainable policy implemented by the coastal state or by the shipowner may have on the use of the NSR as a transit shipping lane from both economic and environmental points of view. We analyze the results of Table 9 in three parts as detailed in the following paragraphs.

5.3. HFO versus VLSFO without SCC

From an economic point of view, the use of HFO provides higher profit compared to VLSFO regardless of the environmental policy implemented. From an environmental perspective, without the implementation of a SCC tax, the use of HFO is more sustainable compared to the use of VLSFO since it generates a lower amount of emissions per TEU in the low access scenario. Moreover, in the median access scenario, it remains the case only if two hubs are used or if Murmansk is the single used hub. Furthermore, in the high access scenario, the same results are found only if two hubs are used. This is mainly explained by the freight rate variation. First, when the HFO or the VLSFO appears to be the most sustainable option, this is due to the level of the freight rate. When the imposed freight

Table 7
Amplitude of freight range in which a positive profit is generated.

Ice conditions	Logistics setting	Without SCC		With SCC	
		VLSFO	HFO	VLSFO	HFO
Low-access scenario	No hub	899	1,148	318	702
Median-access scenario	Petropavlovsk	297	720	–	–
	No hub	1,120	1,355	670	906
High-access scenario	Petropavlovsk	344	729	356	734
	No hub	1,117	1,336	986	1,193

Source: Authors (2022).

Table 8
TEUs loaded depending on climatic scenario, logistics setting, fuel type, and environmental policy.

Ice conditions	Logistics setting		Without SCC VLSFO	HFO	With SCC VLSFO	HFO
Low-access scenario	Two hubs	Optimal freight rate	1,706	1,666	1,804	1,818
		TEU loaded	1,041	1,380	204	102
	Murmansk	Optimal freight rate	1,396	1,383	1,363	1,376
		TEU loaded	4,424	4,554	4,764	4,623
	Petropavlovsk	Optimal freight rate	1,110	1,118	1,085	1,084
		TEU loaded	7,015	6,933	7,255	7,266
	No hub	Optimal freight rate	886	881	890	883
		TEU loaded	9,560	9,608	9,510	9,582
Median-access scenario	Two hubs	Optimal freight rate	1,663	1,641	1,785	1,792
		TEU loaded	2,984	3,390	752	617
	Murmansk	Optimal freight rate	1,398	1,397	1,346	1,365
		TEU loaded	7,106	7,126	7,968	7,651
	Petropavlovsk	Optimal freight rate	1,137	1,158	739	738
		TEU loaded	12,129	11,752	19,135	19,146
	No hub	Optimal freight rate	897	927	902	883
		TEU loaded	15,002	14,523	14,932	15,227
High-access scenario	Two hubs	Optimal freight rate	1,650	1,634	1,778	1,775
		TEU loaded	4,105	4,488	1,107	1,169
	Murmansk	Optimal freight rate	1,397	1,395	1,353	1,377
		TEU loaded	8,259	8,303	9,110	8,656
	Petropavlovsk	Optimal freight rate	1,146	1,157	1,082	1,080
		TEU loaded	15,036	14,805	16,462	16,515
	No hub	Optimal freight rate	906	928	902	885
		TEU loaded	19,015	18,551	19,097	19,434

Source: Authors (2022).

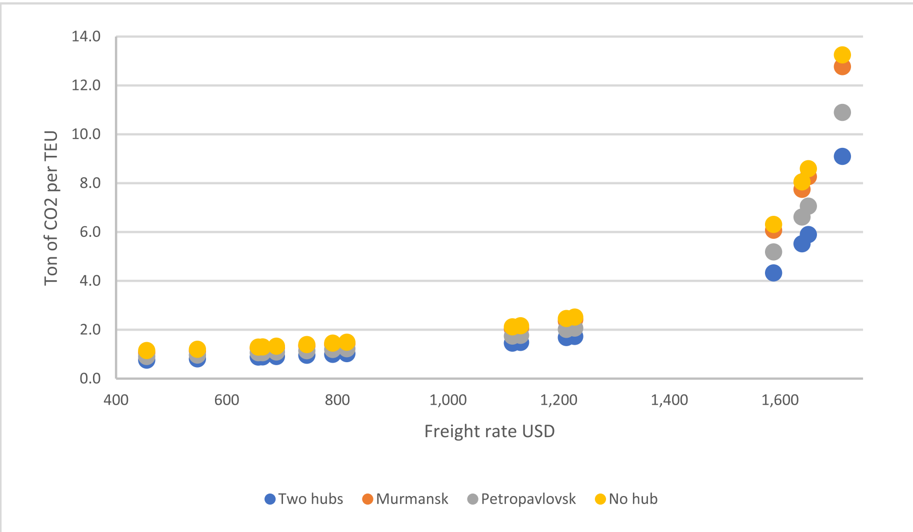

Fig. 4a. CO_2 emissions per TEU depending on the freight rate applied with VLSFO in median access scenario without SCC.

rate decreases, the number of loaded containers increases, leading to lower CO_2 emissions per container. The single exception lies with a freight rate of 1,110 USD, when Petropavlovsk is used as a hub. In this situation, the optimal freight rate is lower with VLSFO, but is not enough to counterbalance the higher emission coefficient of VLSFO compared to HFO. Thus, even if the use of VLSFO provides a lower optimal freight rate and thus more loaded containers, the option of HFO as a bunker fuel is more sustainable in terms of CO_2 emissions per container.

5.4. HFO versus VLSFO with SCC

In this case, the use of HFO in low access and median access scenarios is more sustainable in 50 % of the cases. Moreover, in the high access scenario, HFO is more sustainable in 75 % of the cases. This relatively favorable environmental result of HFO is due to the fact that VLSFO has a higher CO_2 emission factor. This higher emission factor has a direct impact on the optimal freight rate of VLSFO,

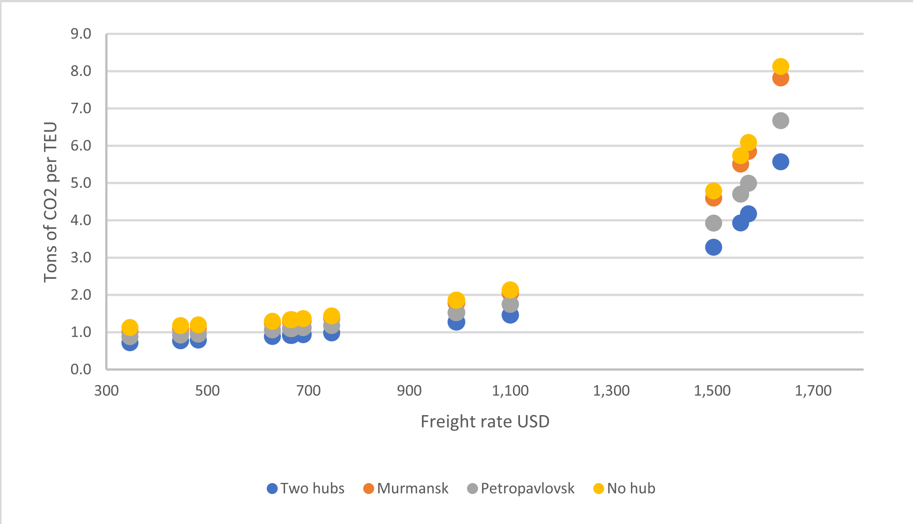

Fig. 4b. CO_2 emissions per TEU depending on the freight rate applied with HFO in median access scenario without SCC.

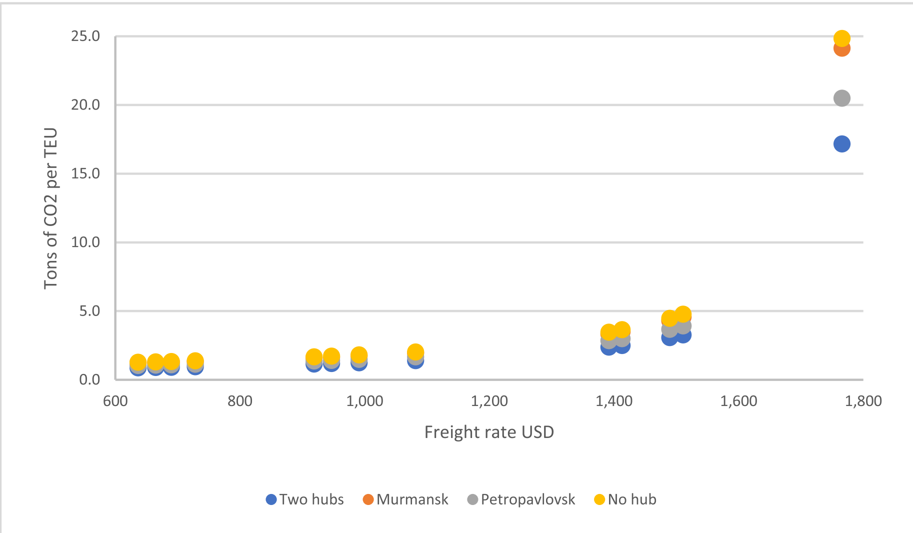

Fig. 4c. CO_2 emissions per TEU depending on the freight rate applied with VLSFO in median access scenario with SCC.

making this option less attractive as it is negatively impacted by both a higher emission factor and a higher cost.

5.5. "With SCC tax" versus "without SCC tax"

Fueling a vessel with VLSFO while avoiding SCC generates the highest profit except if the ice conditions are optimal and if Petropavlovsk or the "no hubs" option are used. In these cases, implementing a SCC tax generates higher profits.

In the low access and median access scenarios, when the vessel is fueled with VLSFO and without the use of a SCC tax, the case with two hubs and the case without hubs generate the highest profits and lowest emissions of CO_2 per container. This result can be explained by the absence of the SCC tax, which lowers the cost per TEU compared to the standard freight rate practiced through the SCR.

In the case of the "no hubs" option, the additional cost of the SCC tax is significant compared to both the cost of transportation via the SCR or via the NSR but without SCC. However, the use of Murmansk or Petropavlovsk as hubs gives the advantage to the implementation of a SCC tax. In this case, the model provides an optimal freight rate that is lower by 2.4 % and 2.2 % for Murmansk and Petropavlovsk, in the low access scenario, respectively, if a SCC tax is levied compared to the case without SCC. At the same time, the amount of loaded containers increases by 7.7 % and 3.4 % for Murmansk and Petropavlovsk respectively. In the case of the median access scenario, the percentages are −3.7 % and −35 % for the optimal freight rate and + 12.1 % and + 57.8 % for the number of containers loaded for Murmansk and Petropavlovsk respectively.

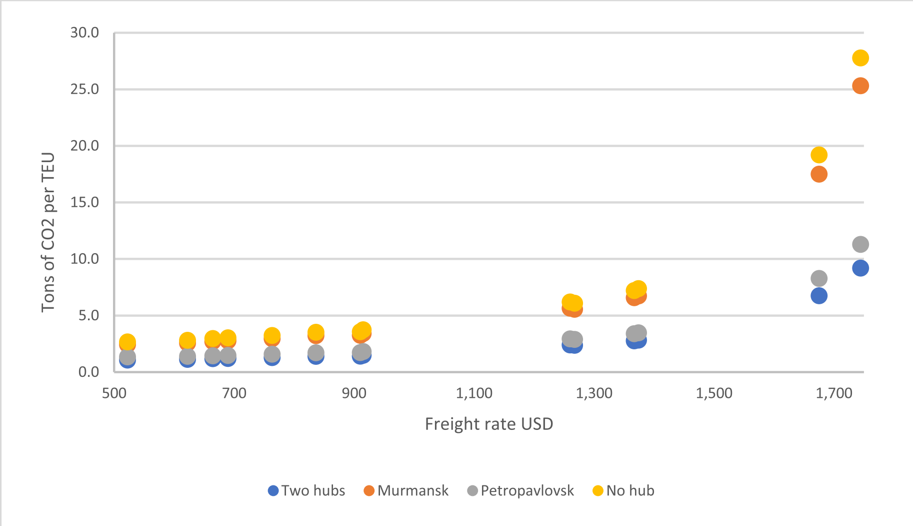

Fig. 4d. CO_2 emissions per TEU depending on the freight rate applied with HFO in median access scenario with SCC.

In the high access scenario, avoiding a SCC tax is more environmentally sustainable than the case in which a SCC is charged only if two hubs are used. In this case, the number of containers loaded is higher. However, when a SCC is charged, the optimal freight rate is lower than without SCC and thus the number of containers loaded is higher.

From an economic point of view, in the case of a high access scenario while using VLSFO, higher profits can be generated while paying an SCC tax if Petropavlovsk is used as a hub or if the company avoids the use of hubs completely. However, if HFO is used, higher profits may be generated while paying an SCC tax if no hubs are used. These results are the same for HFO when we compare the impact of a SCC tax on the environmental attractiveness of the NSR with the case without a SCC tax.

Consequently, depending on the logistics setting and the ice conditions, the implementation of an SCC tax may not necessarily have a positive impact on CO_2 emissions if the shipowner is looking for the highest profit or lowest loss. Table 10 sheds a light on the capacity of each option to generate profit or to minimize loss and/or limit CO_2 emissions. It appears that the option with two hubs has a higher cost per TEU than the optimal freight rate in the westbound direction.

Finally, the situation is more interesting for the eastbound leg, as the cost per TEU is lower than the optimal freight rate. First, using a vessel part of the year does not preclude charging the optimal freight rate. Second, a vessel fueled with VLSFO can also incur a cost per TEU that is lower than the optimal freight rate regardless of whether an SCC tax is charged. Third, the fact that the difference in the eastbound leg is more often at the advantage of the cost per TEU may suggest that the NSR can be useful for the transportation of empty containers between Europe and Asia as this direction is the one with the lowest loading rate (45 %).

6. Discussion

This research aims at evaluating the impact of CO_2 emission taxation on NSR attractiveness. Despite a highly constrained environment, we demonstrate that it is still possible to generate profit by navigating along the NSR using an ice class 1A vessel.

In contrast to Jiang et al (2021), we consider that the freight rate is set by the shipping company, and this has an impact on the number of containers loaded, i.e., on the shipping demand. Moreover, Jiang et al (2021) used the AIRSS based on monthly ice thickness and concentration while we evaluate the daily evolution of the ice conditions.

Additionally, one of the main issues faced by the economic development of the NSR is the difficulty of maintaining a fixed schedule for container liner operations (Zhao et al., 2022; Cariou et al., 2019; Lasserre, 2014; Schøyen and Bråthen, 2011) and recent studies have pointed out the suitability of hubs along the NSR (Bennett et al., 2020; Faury et al., 2020). Our results underline that using hubs facilitates loading more containers per year and enhances vessel productivity while also increasing costs. In addition, the use of hubs maximizes the number of journeys by the vessel during the period of possible navigation, as well as the number of journeys with short transit times (due to the distance saved), thus magnifying travel time savings relative to the SCR as indicated by existing literature (Faury and Cariou, 2016; Lin and Chang, 2018). However, from a profit perspective, with the tested freight rate values, the use of hubs would not be recommended.

Moreover, a carbon tax on ship emissions adversely affects investment in a high ice-class vessel with a greater engine power which would increase the amount of GHG emitted (Faury et al., 2020). While Cai et al (2020) affirmed the ship ice class does not greatly impact the NSR economic advantages, our analysis shows the shipping line can operate ice class 1A vessels with a logistics setting based on two hubs that optimizes loading capacity and meanwhile reduces the level of CO_2 emissions per TEU due to the increase in the volume of transported containers, although the overall amount of emissions increases.

The other issue highlighted by scholars is the difficulty of predicting ice conditions from one year to the next (Stephenson et al.,

Table 9
Economic and environmental results for the optimal freight rate under various scenarios.

Ice conditions	Logistics setting	Without SCC						With SCC					
		VLSFO			HFO			VLSFO			HFO		
		Optimal freight rate	Max Profit /Min Loss (000 USD)	Ton of CO_2 emitted / TEU	Optimal freight rate	Max Profit /Min Loss (000 USD)	Ton of CO_2 emitted / TEU	Optimal freight rate	Max Profit /Min Loss (000 USD)	Ton of CO_2 emitted / TEU	Optimal freight rate	Max Profit /Min Loss (000 USD)	Ton of CO_2 emitted / TEU
Low-access scenario	Two hubs	1,706	−4,968	28.988	1,666	−4,194	21.232	1,804	−8,060	147.922	1,818	−6,985	287.262
	Murmansk	1,396	−4,249	6.049	1,383	−3,006	5.706	1,363	−7,037	5.617	1,376	−5,662	5.621
	Petropavlovsk	1,110	−1,236	3.700	1,118	−122	3.635	1,085	−3,795	3.578	1,084	−2,597	3.469
	No hub	886	2,610	2.360	881	3,918	2.280	890	397	2.372	883	1,825	2.286
Median-access scenario	Two hubs	1,663	−7,414	17.436	1,641	−5,787	14.902	1,785	−12,746	43.629	1,792	−10,883	81.878
	Murmansk	1,398	−5,748	5.718	1,397	−3,690	5.537	1,346	−10,096	5.099	1,365	−8,109	5.157
	Petropavlovsk	1,137	370	3.280	1,158	2,259	3.287	739	−11,003	2.079	738	−8,456	2.018
	No hub	897	5,785	2.155	927	7,620	2.161	902	2,980	2.165	883	4,984	2.061
High-access scenario	Two hubs	1,650	−7,953	15.063	1,634	−5,993	13.777	1,778	−8,040	55.856	1,775	−5,938	52.894
	Murmansk	1,397	−5,426	5.581	1,395	−3,137	5.552	1,353	−5,801	5.060	1,377	−3,589	5.325
	Petropavlovsk	1,146	641	3.269	1,157	2,931	3.320	1,082	823	2.986	1,080	2,849	2.976
	No hub	906	7,201	2.188	928	9,600	2.243	902	7,729	2.179	885	10,196	2.141

Table 10
Difference between the optimal freight rate and the charged price to the shippers under various scenarios.

Direction	Ice conditions	Logistic setting	Without SCC				With SCC			
			VLSFO		HFO		VLSFO		HFO	
			Cost per TEU Steady CAPEX - (USD)	Cost per TEU - Changing CAPEX (USD)	Cost per TEU -Steady CAPEX - (USD)	Cost per TEU - Changing CAPEX (USD)	Cost per TEUSteady CAPEX - (USD)	Cost per TEU - Changing CAPEX (USD)	Cost per TEUSteady CAPEX - (USD)	Cost per TEU - Changing CAPEX (USD)
Westbound	Low-access scenario	Two hubs	(177)	(275)	(164)	(271)	(249)	(347)	(177)	(284)
		Murmansk	138	27	184	62	58	(53)	163	42
		Petropavlovsk	928	812	966	839	852	663	949	822
		No hub	1208	1060	1274	1112	1128	980	1254	1092
	Median-access scenario	Two hubs	(139)	(183)	(123)	(171)	(214)	(258)	(139)	(187)
		Murmansk	117	54	163	94	38	(25)	143	74
		Petropavlovsk	961	889	999	920	885	812	982	903
		No hub	1250	1158	1319	1219	1167	1075	1296	1196
	High-access scenario	Two hubs	(127)	(163)	(109)	(149)	(205)	(242)	(128)	(168)
		Murmansk	162	112	212	158	76	27	186	132
		Petropavlovsk	952	900	991	934	873	821	972	915
		No hub	1238	1180	1308	1244	1154	1096	1284	1220
Eastbound	Low-access scenario	Two hubs	22	(137)	66	(107)	(529)	(687)	(422)	(595)
		Murmansk	498	307	590	381	322	132	476	268
		Petropavlovsk	510	324	585	381	345	159	482	278
		No hub	1010	802	1141	913	826	617	1019	791
	Median-access scenario	Two hubs	66	(7)	109	30	(482)	(555)	(376)	(456)
		Murmansk	575	477	672	566	391	293	550	444
		Petropavlovsk	589	492	673	566	412	314	558	451
		No hub	1049	914	1184	1037	857	722	1055	908
	High-access scenario	Two hubs	100	43	147	86	(454)	(511)	(344)	(406)
		Murmansk	590	501	688	591	405	315	565	468
		Petropavlovsk	587	518	672	596	408	338	555	479
		No hub	1050	963	1185	1090	859	772	1057	962

Source: Authors (2022).

2014; Cheaitou et al., 2020). The recent obstruction of a vessel by ice in November 2021 (Staalesen, 2021) recalls the need for an accurate operational decision tool such as POLARIS, (Fedi et al., 2018b; Stoddard et al., 2016) as well as the necessity to use specific vessels designed for operations in this area (Rigot-Muller et al., 2022). In line with previous analyses (Kujala et al., 2016; Lee et al., 2021), our study confirms the relevance of POLARIS for preventing navigation risks along the NSR.

Furthermore, scholars have raised the issue of organizing trade with vessels leaving ports at unpredictable times (Schøyen and Bråthen, 2011). Whereas the existing literature agrees that distance savings are limited due to short navigation seasons leading to few trips per year (Zhu et al., 2018; Lee and Kim, 2015; Verny ang Grigentin, 2009), our analysis demonstrates the NSR's economic attractiveness and its capacity to generate profit if the vessel is not used on a yearly basis.

We also highlight the impact that environmental policies may have on NSR attractiveness. The use of VLSFO has an obvious negative impact on NSR economic competitiveness compared to HFO. Additionally, the implementation of a SCC policy constrains navigation along the Russian shores but does not necessarily imply an increase in the freight rate to generate more profit.

The literature stresses that maritime transportation represents one of the most significant sources of air pollution in the Arctic (Winther et al., 2014; 2017) that 'impacts on climate change, health and the environment' (PAME DNV-GL, 2019) which requires modifications to the current shipping patterns to mitigate (Chen et al., 2022). Since 2020, the IMO has required bunkers with a low quantity of sulphur or alternatively using HFO with scrubbers, and furthermore, HFO and VLSFO will be definitively banned in the Arctic as of 2029 (IMO, 2021; Bai and Chircop, 2020). According to Delft (2018), shipowners will comply with the HFO ban by using distillate fuels (MDO/MGO), while Liquified Natural Gas (LNG) as another alternative fuel to HFO is the most promising fuel option following the 2029 prohibition (Deniz and Zincir, 2016; PAME DNV-GL, 2019). Nevertheless, this raises the question of necessary investments in LNG and other transport infrastructure along the NSR. At the time of this writing, the 'large-scale investments' required to develop the NSR and the Russian Arctic where transport facilities are poor (Zisk, 2015) could be jeopardized by the war against Ukraine started in March 2022. While Rosatom (the state-owned nuclear company) has committed to further invest USD 18 billion in the NSR development for oil and gas by 2030 (Dobson, 2022), some doubts remain for the future of container shipping in this area as it involves international players and thus, foreign investments. Preliminary studies have already shown a significant decline (–22 %) in investments and M&A in Russia for the first quarter of 2022 compared to 2021 (OECD, 2022). Additionally, in this specific geopolitical context, we may see an increase in 'sustainable development divestment' (UNCTAD, 2022), and it is unclear if Russia will actually comply with the 2029 HFO ban.

In summary, the main contribution of this paper is the implementation of a model that combines different important aspects of the Arctic shipping system, including logistics settings, economic analysis, carbon taxation policies, and risk management in a novel way, under different climatic scenarios.

From a practical perspective, its main contribution is an inventory of quantitative results that may inform decision-making by shipping companies and governments regarding Arctic shipping operations, and in particular the environmental policies to be adopted.

7. Conclusion

This article has considered the impacts of CO_2 emission taxation on the NSR attractiveness for container liner shipping through a tridimensional approach including environmental and economic parameters and risk management. Despite the additional cost generated by transshipment, the use of hubs can improve vessel productivity and appears to counteract the impact of Arctic ice conditions on navigation. Indeed, using hubs increases the number of journeys during this period without using a vessel with a higher ice-class that is usually synonymous with a higher daily fuel consumption and related emissions. Although the overall amount of emissions may increase, as more containers are loaded, the amount of CO_2 emitted per container decreases which makes the NSR more environmentally friendly in relative terms. Finally, our analysis has also emphasized that the NSR can be a viable option if the vessel used for sailing along the Russian shores is not used year-round.

Our article highlights that an environmental policy is not antinomic with profit when dealing with Arctic navigation. The implementation of hubs decreases the amount of CO_2 per container but also counteracts the ice variation. Additionally, hubs offer inhabitants the possibility to settle by the creation of economic activities that are not dependent on raw materials. This issue is already being addressed by Russian authorities as they are updating numerous ports and connecting some of them with the rest of the national network. At the same time, they are building resistant and modern icebreakers able to assist vessels on a yearly basis, thus counteracting the challenges of remoteness that vessels may face. However, to make the use of hubs more economically viable for shipping companies, states may need to financially support the development and use of these hubs in order to reduce feeder and transshipment costs.

From the shipowners' perspective, if some container shipping companies have declined to sail along the NSR due to ecological considerations, we stress that the use of POLARIS and icebreakers may possibly mitigate potential risk occurrence to the fragile Arctic environment. From an economic standpoint, our analysis demonstrates that the ice-class 1A container ships can be profitable in the Arctic under some operating conditions. Such vessels also emit the lowest amount of CO_2, for a type of propulsion equivalent, compared to higher ice-class vessels, which are more expensive and have more powerful engines.

Finally, we acknowledge two main limitations relating to categories of the GHG analyzed and vessels used. We only evaluated CO_2 emissions as CO_2 remains the primary GHG emitted. SO_x emissions have not been integrated in line with the IMO 2020 regulations that reduced the sulphur threshold to 0.5 % and that came into effect in January 2020. Second, we considered "low" ice-class vessels such as class 1A since this ship type is the most used by shipowners. Third, we assumed a fixed value for the fuel price that corresponds to the situation before the COVID-19 pandemic. The model is flexible enough to accommodate other fuel price values, such as the high current prices, which would reduce the profit of the operations and increase thefreight rates that shipping companies charge to their customers since fuel price is an important component of the overall shipping cost. Future research will incorporate the evaluation of the fuel price volatility, additional emissions and ice-class vessels. Consideration of the effect of different financial subsidies provided by governments to Arctic shipping stakeholders, as well as the impact of other environmental policies, would also be promising avenues for future research.

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CRediT authorship contribution statement

Ali Cheaitou: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Olivier Faury:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing. **Laurent Etienne:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Laurent Fedi:** Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Patrick Rigot-Müller:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Scott Stephenson:** Conceptualization, Investigation, Writing – review & editing.

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.

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