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Generalized transport costs in intermodal shipping: the context of the Northeast Passage

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Abstract

Intermodality is regarded as one way of achieving more sustainable transport solutions. To make intermodal transport the preferred solution among shippers, it must be attractive according to the concept of generalized transport costs. An extended model for generalized transport costs is developed which includes elements important for comparing maritime transport solutions in the Artic. This framework forms the basis for a principal discussion on the conditions that make one transport solution preferable to another within the context of maritime logistics. This model is then applied to the context of the Northeast Passage to discuss the necessary requirements for making an intermodal transport solution attractive relative to the current main route from Northeast Asia to Northwest Europe through the Suez Canal. Even though intermodality could be preferable in principle, current solutions cannot compete with either Arctic routes using unimodal solutions with high ice-class vessels or with the Suez route. Due to uncertainty and limited empirical evidence, a sensitivity analysis is conducted, focusing on the variables with the greatest impact on the result. Policymakers and stakeholders can consider the findings to improve transport competitiveness via the Northeast Passage.

Keywords: Intermodal transport, Generalized transport costs, Arctic shipping, Northeast Passage, The Northern Sea Route

Introduction

Modern society relies on global trade, but an overarching problem is the pollution related to transporting goods (The General Assembly of the United Nations 2017). Transportation systems, from infrastructure development to vehicle operations, have environmental impacts ranging from local effects due to noise and emissions to global effects on climate change (Rodrigue 2020). To achieve global climate goals while meeting growing demand, the transport of consumer goods will have to significantly reduce the corresponding greenhouse gas emissions (Bové and Swartz 2016). As a response to these challenges, a rising number of multinational corporations from a variety of industries move towards sustainable supply chains (Villena and Gioia 2020). Freight transport policies have aimed to accommodate the growing demand sustainably (European Commission 2022). A body of academic literature has emerged as a response to the political desire to establish environmentally friendly solutions.

According to Ricci and Black (2005), freight intermodality is increasingly considered a major potential contributor to managing the sustainability problems of the European transport sector. The main advantage is the opportunity to exploit benefits related to transport modes by combining them in a way that produces a less costly and more energy-efficient alternative than an unimodal solution (Hanssen et al. 2012). However, despite considerable investments in dedicated infrastructure, and increasing awareness of the many benefits with respect to economic and environmental factors that a higher intermodal market share would generate, hardly 10% of the total volume of freight movements in Europe is carried out by intermodal options. The majority of transport work is still carried out by road transport (Ricci and Black 2005).

A number of actors influence the choice of a transport solution of which exporting firms and transport firms play main roles (Hanssen and Mathisen 2011). Transport cost, reflected in the price for the transport firm, is argued to be the most important aspect in the transport choice decision (Marcucci and Danielis 2008; Punakivi and Hinkka 2006). Nevertheless, the demand for different types of freight traffic is influenced not only by price but also by other characteristics such as time usage and damage probability that can be converted to pecuniary values. Time has a price because it has an alternative use (Becker 1965). From the sea freight point of view, time can play a big role depending on the type of cargo, particularly for expensive goods and time-sensitive goods. These features of transport services require a focus on generalized transportation costs, comprising pecuniary valuation of elements such as time costs in addition to price (Button 2022). Consequently, to make a specific transport solution preferred, it is necessary to reduce generalized transport costs to a lower level relative to other transport alternatives. Assuming that the transport market is comprised of rational behaviour from fully informed transport purchasers, the reduction of generalized costs for a transport solution will improve its attractiveness in the market. Hence, this makes the generalized cost concept well suited for the purpose of comparing the attractiveness of maritime transport solutions in this study. Admittedly, the generalized cost concept is not without weaknesses such as setting pecuniary values on parameters and inferring how they influence the demand (e.g. Wardman and Toner 2020).

Evidently, the variety in characteristics between types of goods means that an improvement in transport quality does not affect all types in the same way (e.g. Button 2022). Hence, this means that an improvement leading to reduced time usage would be more important for fresh products than frozen products, and reduced damage cost is most important for high-value goods. Maritime transport competitiveness is generally assumed to be low mainly due to the low travel speed. However, Suárez-Alemán et al. (2015) have proven with specific examples that once a generalized cost methodology is put in place, these results may change when assessing the advantages of low unit price due to economies of scale, high punctuality and low damage cost.

Drawing on the variety of experiences with the generalized freight cost concept, we aim for an application to maritime logistics with particular emphasis on the potential for the route over the Northeast Passage (NEP). The NEP has attracted substantial international interest over the past years, due to the benefit of a shorter sailing route between the North Atlantic and the North Pacific. Most studies addressing this route have been empirical and have not discussed the differences from a theoretical perspective (e.g.

Sibul and Jin 2021). The steady development towards a lighter ice situation has made trans-arctic transports more feasible (Moe 2020). However, there is currently a shortcoming in the integration of the NEP in the larger transport chain between these two regions. Moreover, in the short term, this route will probably not be developed in terms of transit shipping due to the Russian/Ukrainian armed conflict which has inflicted extra sanctions and unwillingness to operate in Russian territories.

Currently, most transport volumes within maritime trade are directed towards a few transport corridors such as the Suez Canal, the Malacca Strait and the Panama Canal (Kiiski 2017), which all, to some degree, have shortcomings related to capacity restrictions, political and piracy risks, infrastructural requirements and long distances for detour alternatives. The recent incident in March 2021, with the containership Evergreen blocking the Suez Canal for around a week, is a reminder to consider resilience in global trade by analysing alternative maritime corridors such as the NEP. Besides diversification, sustainability is another driver, the significantly shorter route has the potential to also decrease the negative impact of transport if sufficient considerations are taken to avoid damage to the vulnerable nature in the Arctic.

In the existing literature, NEP has mostly been considered the same as the Northern Sea Route (NSR), which is, in fact, a route stretching from Novaya Zemlya to the Bering Strait and an integrated part of the NEP. A variety of topics relevant to the NSR as a transit route have been addressed including viability for commercial shipping (Kiiski 2017; Pruyn 2016; Zhao et al. 2022), costs of operations (Furuichi and Otsuka 2018; Pruyn and van Hassel 2022; Sibul and Jin 2021), profitability (Jiang et al. 2021; Lasserre 2019) and commodity segments (Gunnarsson 2021; Leypoldt 2015). Milaković et al. (2018) established several possible future operational models for transit shipping along the NSR and concluded that the most probable of the analyzed operational models is a combination of ice-strengthened vessels and independent ice-going cargo vessels. Quantitative investigations of various determinants for the profitability of container shipping via the NEP for different shipping modes and ice-class ships were done by Jiang et al. (2021). Nonetheless, while the aforementioned studies provide valuable insights from various perspectives to our knowledge, none of them considers unimodal and intermodal transport solutions for NEP transit from a theoretical perspective.

In this study, we develop a generalized transport cost model for intermodal transport solutions, taking into consideration the characteristics of shipping over the NEP. The conceptual model is applied to give a principal discussion on the attractiveness of unimodal and intermodal navigation concepts for shippers of containers between Northeast (NE) Asia and Northwest (NW) Europe. We pay particular attention to an alternative inter-maritime solution where intermodality is understood as using several types of vessels in line with a concept developed by Milaković et al. (2018). The well recognized generalized cost concept is extended to include aspects of intermodal maritime transport in the Arctic by incorporating elements of cost and speed by use of ice breakers, uncertainty in damage costs related to ice conditions and the consideration of parameters for different ice classing of vessels.

Since the intermodal solution in this context is hypothetical, the results are further enlightened by a sensitivity analysis addressing the most important variables. The findings could assist decision-makers and maritime operators in making more accurate assessments of the value of investments aimed at improving the competitiveness of transport via the NEP.

The paper is structured as follows: Sect. "Context: Container shipping over the NEP" accounts for the context of container shipping via the NEP. Sect. "Theoretical framework" reviews the theoretical framework of generalized transport costs and elaborates on the conditions under which intermodal alternatives are preferred to unimodal solutions in the context of shipping in the Arctic. In Sect. "Methodology", we consider methodology and suggest an application of the generalized cost framework to reflect the characteristics of different transport solutions over the NEP. Finally, conclusions and implications are given in Sect. "Conclusion and implications".

Context: container shipping over the NEP

The NEP considers a sea route from Europe to the Pacific Ocean along the Arctic Ocean coasts of Norway and Russia (Kovalenko et al. 2018). We put particular focus on the NSR section of this route due to the existing special climatic and legislative issues. The NSR refers to the whole sea area in the Russian Arctic between the islands of Novaya Zemlya and the Bering Strait crossing the Kara Sea, the Laptev Sea, the East Siberian Sea, and the Chukchi Sea). The distance from east to west is approximately 3000 nautical miles (nm) (~ 5,600 kms) (Ragner 2000).

For the liner shipping market, a year-round service plays a key factor. According to Stopford (2008), the main principle of liner shipping is to provide a fixed service, at regular intervals, between named ports, and offer transport to any goods in the catchment area served by those ports and ready for transit by their sailing dates, whether containerships are filled or not. A review by Theocharis et al. (2018) stated that in most studies assuming a year of operation, Arctic routes tend to be either uncompetitive or show mixed results, especially for liner shipping (Lasserre 2015; Liu and Kronbak 2010; Zhao et al. 2016).

Under the current winter navigational and climatic conditions, operations, including the NSR, can serve mainly as seasonal alternatives for a limited period of about five months rather than offering regular access to ships on an annual basis (Theocharis et al. 2018). In general, sailing along the NSR is allowed in the summer/autumn navigation season without ice-breaker (IB) assistance if ice conditions are favorable (clean water in all zones) and/or the vessel has an appropriate ice-class (Northern Sea Route Administration 2020). Only the vessels with the highest ice-class grading can sail independently in different ice conditions over the entire year. Currently, the absence of containerships with the highest ice-classes (Clarkson 2021) does not allow for the route to be used year-round for container shipping.

Another constraint, that stands out for container shipping, is the draft restrictions, meaning that the largest container ships – which today can carry over 20,000 twenty-foot equivalents (TEU) and provide economies of scale – cannot be used unless they sail far north of the main NSR route into deeper waters, where ice conditions are much more difficult (Gunnarsson and Moe 2021). Pruyn (2016) noted a lack of hydrographic data for the NSR area. This increases the risk of grounding, and there is currently no insurance coverage for ships sailing on the NSR, while the chances of damage to the hull are large, which increases repair costs for the vessels. Security is a major issue since there is not enough ice-breaking capacity and minimal search and rescue (SAR) coverage (Lárusson 2010). Poorly developed infrastructure and the seasonality of work of some ports in the water area of the NSR also limit commercial potential (Kiiski 2017).

The legal status and political uncertainties in the Arctic region are other obstacles to the development of commercial international shipping along the NEP (e.g. Kiiski 2017; Pruyn and van Hassel 2022). The governance of Arctic shipping is fragmented. For instance, the legal framework regulating navigation along the NSR is largely based on the United Nations Convention on the Law of the Sea and the International Maritime Organization doctrines, but it is de facto regulated by the Russian Federation (Kiiski 2017). The recent geopolitical turns resulting from the Russian–Ukrainian international armed conflict led to sanctions against the Russian state and private businesses. This change in international relations also affects the Arctic space within the sovereignty of Russia, which includes part of the NSR (Hermann et al. 2022).

All aspects mentioned above can negatively influence the potential of transit shipping and could be reasons for never seeing successful shipping along the NEP via the NSR. However, for this paper, we assume that these issues are solvable and that shipping along the NEP is possible.

Theoretical framework

The intermodal concept

An alternative to the occasional unimodal transit shipping solution currently operating the NEP would be a scheduled intermodal transport solution. Intermodality involves using at least two different modes on a trip from origin to destination through a multimodal transport chain, which permits the integration of several transportation networks (Rodrigue 2020). As a consequence, Rodrigue (2020) suggests that intermodality enhances the economic performance of a transport chain by using modes in the most productive manner.

Considering this as a starting point, we use a theoretical concept for a possible future operational model for transit shipping through the NEP developed by Milaković et al. (2018). The concept illustrated in Fig. 1 outlines the principles of an intermodal liner transportation network design between markets in Europe and the Far East. In network theory, this kind of model is classified as a dog-bone system with hub-and-spoke

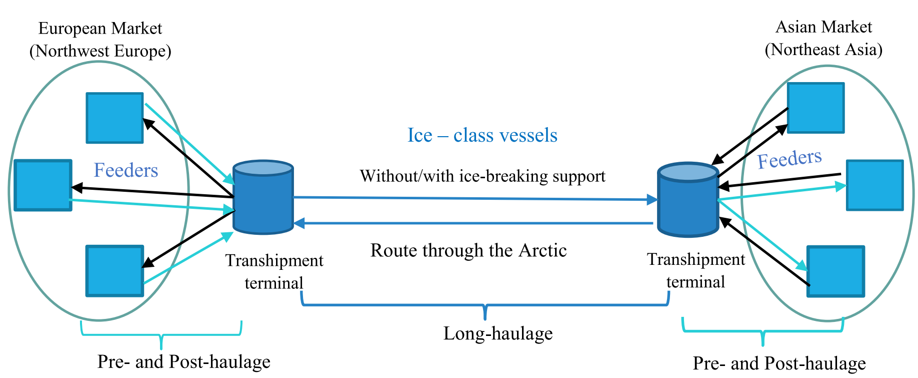

Fig. 1 Intermodal transport solution for year-round transit shipping through the NEP. Adapted from (Milaković et al. 2018)

networks at the ends. According to Button (2022), this system has the advantages of potentially collecting a sufficiently large volume to obtain sufficient frequency and exploiting economies of scale and economies of density. Since it is supposed to use two types of vessels with different properties on the route, we consider the application of this concept to the NEP context as an intermodal solution. The principle of shipping in the intermodal solution may allow for viable year-round container shipping. The intermodal transport solution in Fig. 1 includes processes of pre- and post-haulage, transhipment in intermodal terminals and long-haul shipment.

The costs of pre- and post-haulage are important for the attractiveness of intermodal transport solutions since they could account for as much as 40% of the total costs (Macharis and Bontekoning 2004). Within the framework of the considered intermodal transport solution, pre- and post-haulage include only the transport of containers by feeders to and from the transhipment terminals on free waters. Transhipments at terminals are a key aspect of that. For the current investigation, only feeder services are considered with terminals available at each end of the Arctic leg of the trip.

For long-haul shipment in an intermodal transport chain, the predominant modes of transport are rail, inland waterway, short sea transport or sea transport, where units are consolidated and economies of scale are applied (Bergqvist and Behrends 2011). Considering the special requirements for shipping on the NSR described in Sect. "Context: Container shipping over the NEP", higher ice-class vessels are preferred for long-haul shipment between transhipment terminals since they might be able to sail the route without IB support for large parts of the year. However, we cannot absolutely state that these vessels will not need IB support since weather conditions could require this in some zones of the NSR in the winter season. The sensitivity of ice-class on the success of the route will be considered, as the costs of the vessel must be balanced with costs for IB support. Different ice-classes lead to different operational allowances.

The model

A model for generalized transport costs will be established to take into consideration such variables as price costs, time costs and damage costs for possible unimodal and intermodal transport solutions combining the usage of the different ice-class vessels over the NSR. Compared to a traditional intermodal model, the special features of Arctic maritime transport require concerns of elements such as ice-breaker support and characteristics of vessels with different ice-class. The first type of vessel is a traditional freight transport solution without ice-class. Such vessels are not able to serve the long-haul distance of the northern route between Asia and Europe and may therefore only take the role of feeders in the post- and pre-haul phases of the transport solution. Second, are the medium ice-class transport vessels which could operate at long haul distance with the support of IB. Finally, there is a type of high ice-class transport vessel that could operate without IB support during the main part of the year. In the following, we will first define the model for generalized transport costs based on the specification by Janic (2007) and Hanssen et al. (2012) and then apply it to discuss possible transport solutions.

Let us assume that the generalized transport costs per unit of freight transported for a purchaser of transport services, G, can be given by the following function:

$$G(D) = P(D) + H \cdot T(D) + R \cdot Q(D) \; where \; \partial P/\partial D, \partial T/\partial D, \partial Q/\partial D > 0 \quad (1)$$

The generalized transport cost in (1) is the sum of three elements. First, pecuniary costs, P, are primarily related to price for the transport service. Second, the time cost is the product of time costs per hour, H, and transport time, T. Here transport time corresponds to total transit time from origin to destination and comprises both sailing time and transshipment time. Finally, damage cost is the product of the probability for damage, Q, having the restriction $0 < Q < 1$, and the cost if damage occurs, R. These three elements will be discussed in more detail later in this section. It is assumed in (1) that P, T and Q, and thereby also G, are positively related to transport distance measured in for example nautical mile (nm), D. When H and R are independent of the transport distance, then $H \cdot T = HT(D)$ and $R \cdot Q = RQ(D)$ represent total time cost and expected damage cost, respectively, for transport of one unit of freight at a distance of D.[1]

The definition of generalized transport cost in Eq. (1) includes only costs relevant to the transport company (private costs). If the perspective of welfare economics is taken, it would be relevant to also consider external costs (Button 2022). The internalization of all external costs in the generalized transport costs would make private economic and welfare economic costs equal. In such a case the most attractive transport solution for the private actors would also be the optimal solution for society as a whole. A higher focus on environmental issues and attitude campaigns could make transport companies more aware of the costs they impose on others. This can be formalized by extending the generalized transport costs in (1) by an element addressing external costs (see e.g. Zhu et al. 2018). Alternatively, regulators could work towards internalizing the environmental costs so they become part of the generalized costs and thereby for the decision on which route to use.

The relationship between generalized freight costs and the demand for freight transport, X, is negative as defined in (2). In our context of sea transport of containers, an appropriate measure for X might be TEU. The parameter α_0 is independent of generalized costs, while α_1 represents the reduced demand when generalized costs increase by one pecuniary unit.

$$X = \alpha_0 - \alpha_1 G \text{ where } \alpha_0, \alpha_1 > 0 \quad (2)$$

The costs for the transport firm, C, is directly related to the amount transported, X, and the transport distance, D, as defined in (3). Despite the weakness of treating all transport services as a homogenous product, common output measures are related to the TEU or a measure of weight in combination with transport distance (Pels and Rietveld 2007).[2] Parameters β_1 and β_2 in (3) are coefficients for the number of TEU, indicated by X, and the number of TEU per distance unit, XD, respectively. Other costs which are independent of the number of TEU, and transported distance are considered by the

[1] The transport distance represented by D is longer than the linear distance by air. According to Mathisen (2008) the distance sea is 20% higher compared to that of linear distance.

[2] In scheduled passenger transport the distance costs typically relates to route- or vehicle kilometers. Additionally, a measure indirectly related to distance is the number of vehicle hours in operation.

parameter β_0. Marginal costs do, according to $\partial C/\partial X = \beta_1 + \beta_2 D$, increase linearly with transport distance.

$$C = \beta_0 + \beta_1 X + \beta_2 XD \text{ where } \beta_0, \beta_1, \beta_2 > 0 \tag{3}$$

Pecuniary costs and transport distance

Let us first focus on variable P in Eq. (1) corresponding to the price for the transport purchaser. Costs are an important basis for setting prices for transport services, particularly in markets where competition is high such as freight transport (Mathisen et al. 2015). The setting of prices for freight transport is to a larger extent than public passenger transport characterized by negotiations. The lower standardization of prices implies that characteristics of market and demand have considerable influence on prices. It can for example be more expensive to buy transport services for the same type of goods from A to port B than to port C being further away if the market for A to C is more price elastic than A to B. Consequently, prices do not necessarily increase linearly with distance even though this assumption is made on marginal costs. It is, however, most common that prices increase concavely with distance. At least for passenger transport longer trips are more price sensitive than shorter trips (Button 2022). The relationship between pecuniary cost (price) and distance is indicated in Eq. (4) for the three types of vessels accounted for above; non-ice-class feeders, denoted f, ice-class vessels with IB support, denoted v, and high ice-class vessels, denoted h, able to operate without IB support during favorable conditions.

$$\begin{gathered} P_f = \gamma_{0f} + \gamma_{1f} D^{\theta} \text{ (feeder)} P_v = \gamma_{0v} + \gamma_{1v} D^{\theta} \text{ (ice} - \text{class)and} \\ P_h = \gamma_{0h} + \gamma_{1h} D^{\theta} \left(\text{high ice} - \text{class}\right) \end{gathered} \tag{4}$$

where $\gamma_{0i}, \gamma_{1i} > 0, i = f, v, h$ and $0 \leq \theta \leq 1$.

The parameters γ_{0i} in (4) refer to distance independent cost typically related to canal fee, ice- breaker support and loading and unloading at terminals. We are unable to give a clear ranking between the three types of vessels and assume that $\gamma_{0h} = \gamma_{0v} = \gamma_{0f}$. It might, however, be that $\gamma_{0h} > \gamma_{0v} > \gamma_{0f}$ if ice-class vessels require specialized equipment or other attention.

It follows from (4) that $\partial P_i/\partial D \geq 0$ and $\partial^2 P_i/\partial D^2 \leq 0$ for $i = \{f, v, h\}$. This concavely increasing relationship is valid when $0 \leq \theta < 1$ and implies that the increase in price by transporting the goods an additional unit of distance diminishes with respect to the distance the goods are transported. Hence, the parameter θ ensures that not only linear relationships are considered. Assuming that prices are based on costs, then such tapering rates are reasonable since terminal costs and fixed charges are distributed over longer distances (Ballou 2004) and are in line with the reasoning of economies of scale. However, the value of theta is likely close to 1 since important costs related to crew and fuel are relatively constant over distance. A value of $\theta = 1$ implies a linear relationship between price and distance, while $\theta = 0$ renders the price independent of transport distance (uniform rate). Empirical evidence suggests that the relationship between price and distance is generally less steep for transport by sea relative to other transport modes (Ballou 2004).[3]

With respect to the distance-dependent cost, it is reasonable to consider traditional freight vessels as the most cost-efficient. Due to higher weight and lower freight capacity relative to size, it is reasonable to assume that ice-class vessels have higher marginal costs per unit of freight per distance unit on waters free from ice than conventional feeders (Grigoriev and Uvarov 2016). This raise in costs increases with ice-class implying that $\gamma_{1h} > \gamma_{1v} > \gamma_{1f}$. The need for IB support further increases the costs per unit of distance. This implies that both γ_{1h} and γ_{1v} increases.[4] Under normal conditions, we can conclude that $\partial P_h/\partial D > \partial P_v/\partial D > \partial P_f/\partial D$. The parameter restrictions in (4) imply that price per nautical mile decreases with distance, $\partial(P_i/D)/\partial D < 0$. When distance moves towards infinity, then the price per nautical mile, (P_i/D), approach 0 if $\theta < 1$ and γ_{0i} if $\theta = 1$.

Time costs and transport distance

It is assumed that the relationship between time and distance for transport is linear for all three vessel categories as presented in Eq. (5).

$$\begin{aligned} T_f &= \tau_f + \frac{D}{S_f}(\text{feeder}) \\ T_v &= \tau_v + \frac{D}{S_v}(\text{medium ice} - \text{class}) \\ T_h &= \tau_h + \frac{D}{S_h}(\text{high ice} - \text{class}) \end{aligned} \tag{5}$$

In (5) the total transport time and the speed of the vessels are defined by T_i and S_i, respectively, where $i = \{f, v, h\}$. The parameter τ_i is positive and represents time usage for loading and unloading the goods and is independent of transport distance. We do not have any indication of differences in distance-independent time use between types of vessels meaning that $\tau_f = \tau_v = \tau_h$.

Evidence indicates that speed is positively related to ice-class because these ships have considerably higher engine power and can operate at a higher optimal cruising speed. According to Solakivi et al. (2018) ice-classed vessels have an approximately 10–15 per cent higher design speed than the non-ice-classed because of their additional power. On the other hand, evidence suggests that the length of a vessel might influence speed to a larger extent than ice-class. Hence, large feeders might have speed advantages. However, even though vessels often will run independently of ice-breakers it might be that speed must be reduced to comply with convoy regulations. Consequently, it is impossible to rank speed between modes, but if $S_h < S_v < S_f$ is the case then the relationship between time and distance in (5) is steepest for high ice-class and least steep for feeders.

[3] Ballou (2004) addresses prices for a number of transport modes. Starting from lowest, the ranking of average freight price per ton-mile is water, pipe, rail, truck and air.

[4] Under particular conditions where high ice-class vessels are able to operate without IB support the medium ice-class vessels might be most expensive if IB is sufficiently expensive. In such a case we would not be able to give a clear ranking in costs between the three categories.

However, due to a lack of inconclusive evidence we assume in the following that parameters for speed are identical for the three categories.

The speed can vary substantially between parts of the transport network. In the Arctic region, speed is particularly sensitive to weather conditions. For example, severe ice conditions would reduce the speed of high ice-class vessels able to operate alone and induce waiting time for IB support. Consequently, the increasing slope between time usage and transport distance becomes steeper. In line with this reasoning, there is a cost related to the uncertainty in time usage. We do, however, assume that the uncertainty is independent of the type of vessel and we, therefore, treat all categories according to expected transit time.

Time usage is often assigned a monetary value by economists (see e.g. the literature dating back to Becker (1965) and particularly for transport it is evident that time costs make up a large part of total costs (Button 2022). Time costs have been widely studied in the transport literature and are found to vary greatly between contexts (see e.g. Ho et al. 2016; Rodrigue 2020). It is not our aim to discuss the valuation of time costs and we, therefore, assume in this model that time costs per hour, H, is equal for all types of transport modes and independent of transport distance, but only dependent on the goods transported. The value of H for a commodity can be estimated by considering the value per unit (TEU), the interest rate per hour and, if relevant, the deterioration costs per hour. The deteriorating costs vary considerable between commodities from negligible (e.g. sand) to vital for fresh products.

The relationship between time costs and trip distance is defined in (6) by combining time costs per hour by the time usage defined in (5).

$$\begin{aligned} HT_f &= \mu_{0f} + \mu_{1f}D \text{ (feeder)} \\ HT_v &= \mu_{0v} + \mu_{1v}D \text{ (medium ice} - \text{class)} \\ HT_h &= \mu_{0h} + \mu_{1h}D \text{ (high ice} - \text{class)} \end{aligned} \quad (6)$$

In (6) $\mu_{0i} = H \times \tau_i$ and $\mu_{1i} = H/S_i$ where $i = \{f, v, h\}$. The distance independent time costs are represented by μ_{0i}, while μ_{1i} is interpreted as the increase in time costs when the transport distance increases by one unit (nm). If $\tau_f = \tau_v = \tau_h$ then $\mu_{0f} = \mu_{0v} = \mu_{0h}$. If $S_h < S_v < S_f$ as discussed earlier, then $\mu_{1f} < \mu_{1v} < \mu_{1h}$ but this is uncertain. An increase in time costs per hour, H, makes the relationship steeper between total time costs and trip distance and increases the differences in time costs between the transport modes.

Damage costs and transport distance

There is a probability of damage both when loading and unloading goods at the terminal and during transport. The probability varies between transport modes and is a factor the shipper should recognize before making a carrier selection (Ballou 2004). When comparing with other transport modes it is argued by Ballou (2004) that the overall loss and damage is least for sea transport and higher for truck and train. Carriers are obliged to move freight using reasonable care to avoid loss and damage. The responsibility is relieved for causes not within the control of the carrier and insurance contracts enable the firms to pay a certain amount to avoid the value of *R*.

The relationship between expected damage costs and distance is defined in (7). For simplicity, a linear relationship is given for the probability of damage in the interval from 0 to 1. Normally, the probability distribution of risk would be given by a strictly positive concave function implying that probability increases but at a diminishing rate.

These damage costs are part of the generalized costs for the firm buying transport services (private costs) and will always be lower than welfare economic costs (social costs) related to an accident. For certain types of goods, such as perishable goods, it is reasonable to assume that the value of goods decreases with distance. In such cases, the cost in case of damage and the corresponding social cost will be reduced at longer distances. Damage costs could be severe also for the transport mode and not only the commodities. Moreover, the commodities will often be covered by insurance which could give some empirical estimates of the monetary values of this variable.

$$\begin{aligned} RQ_f &= \rho_{0f} + \rho_{1f}D(\text{feeder}) \\ RQ_v &= \rho_{0v} + \rho_{1v}D(\text{medium ice} - \text{class})RQ_h = \rho_{0h} + \rho_{1h}D\left(\text{high ice} - \text{class}\right) \end{aligned} \tag{7}$$

In (7) the distance-independent element, ρ_{0i}, relates to expected damage costs occurring at terminals and during loading and unloading. The distance-dependent element, ρ_{1i}, represents an increase in expected damage costs when transport increases by one unit of distance. The ρ-values increase both with the probability of damage and the value of the goods. Assuming that time at the terminal is equal for all vessels, the distance-independent damage costs are $\rho_{0f} = \rho_{0v} = \rho_{0h}$. The distance-dependent element might differ between types of vessels. However, since we assume that feeders are not operating in icy waters and that the ice-breaker support is used by high ice-class vessels only when conditions are adverse, we can assume that $\rho_{1h} > \rho_{1v} > \rho_{1f}$. The IB support plays a main role here as part of maritime preparedness infrastructure implying that damage costs might be highest for ice-class vessels operating alone.

Generalized transport costs and transport distance

A full expression for generalized transport costs for each transport solution is derived by inserting (4) (monetary cost), (6) (total time costs) and (7) (expected damage costs) into (1) as defined in (8).

$$\begin{aligned} G_f &= \omega_{0f} + \gamma_{1f}D^\theta + (\mu_{1f} + \rho_{1f})D \ (\text{feeder}) \\ G_v &= \omega_{0v} + \gamma_{1v}D^\theta + (\mu_{1v} + \rho_{1v})D \ (\text{medium ice} - \text{class}) \\ G_h &= \omega_{0h} + \gamma_{1h}D^\theta + (\mu_{1h} + \rho_{1h})D \ (\text{high ice} - \text{class}) \end{aligned} \tag{8}$$

In (8) the distance-independent part of generalized costs is represented by $\omega_{0i} = (\gamma_{0i} + \mu_{0i} + \rho_{0i})$ where $i = \{f, v, h\}$. According to previous assumptions $\omega_{0h} > \omega_{0v} > \omega_{0f}$. The relationship between generalized transport costs and distance increase concavely when $\theta < 1$. It has previously been defined that all distance-dependent elements for transport are increasing with the ice-class level which again implies that generalized transport costs increase more steeply with respect to distance for higher ice-class. However, provided that IB support makes a sufficiently large part of the generalized freight costs, the ranking between medium and high ice- class could be different during seasons where a medium ice-class vessel requires IB support while a high ice-class vessel does not.

The assumptions on parameter values do not provide an unambiguous conclusion on how the types of vessels are ranked according to the concept of aggregated generalized freight costs. If price is assumed to increase linearly with distance, $\theta = 1$, then a parameter $\omega_{1i} = (\gamma_{1i} + \mu_{1i} + \rho_{1i})$ representing all distance-dependent elements can be used to simplify the notation of (8) for generalized costs for the entire trip as shown in (9) where $\widehat{D}$ is total distance from origin to destination.

$$\begin{aligned} &G_f = \omega_{0f} + \omega_{1f}\widehat{D}\,(\text{feeder})\; G_v = \omega_{0v} + \omega_{1v}\widehat{D}\,(\text{medium ice} - \text{class}) \\ &G_h = \omega_{0h} + \omega_{1h}\widehat{D}\,\left(\text{high ice} - \text{class}\right) \end{aligned} \tag{9}$$

where $\omega_{0i} = (\gamma_{0i} + \mu_{0i} + \rho_{0i})$ and $\omega_{1i} = (\gamma_{1i} + \mu_{1i} + \rho_{1i})$ for $i = \{f, v, h\}$

Generalized freight costs for intermodal transports

The discussion has focused on the relationship between generalized costs and distance for unimodal transport solutions. When allowing for more than one transport mode the transport chain is characterized as intermodal. An important question is whether an intermodal transport solution is preferred to unimodal transport for a purchaser of transport services aiming to minimize generalized transport costs. Let us assume that a container needs to be transported from the origin to its final destination with a total distance of $\widehat{D}$. An alternative is the use of an ice-class vessel. The generalized costs in this case when assuming linear relationships are defined in (10) for an ice-class vessel needing IB support for the long-haul distance.

$$G_v = \omega_{0v} + \omega_{1v}D_1 + \omega_{1v}(D_2 - D_1) + \omega_{1v}\left(\widehat{D} - D_2\right) \tag{10}$$

The container can alternatively first be transported by feeders to a terminal at a distance D_1, then by medium ice-class vessels for the long-haul distance $(D_2 - D_1)$ and finally reloaded to feeder again to the final destination, $\widehat{D}$. Handling costs for loading the container (handling at the terminal) from the feeder to the ice-class vessel at D_1 and back to feeders at D_2 are equal and defined by L. Higher value of L would make the intermodal transport solutions less attractive. Note that these handling costs extend beyond the distance-independent costs related to loading and unloading containers defined as part of ω_{0i}. The generalized transport costs for this intermodal transport solution using feeders and ice-class vessels, G_{Int}, is defined in (11).

$$G_{Int} = \left(\omega_{0f} + \omega_{1f}D_1 + L\right) + \omega_{1v}(D_2 - D_1) + \left(L + \omega_{1f}\left(\widehat{D} - D_2\right)\right) \tag{11}$$

Based on the discussion above, the ranking of transport solutions depends on many variables and intermodality is not necessarily the preferred alternative in all situations. For illustrative purposes, the intermodal transport solution combining feeders and medium ice-class vessels is presented in Fig. 2 as having the lowest generalized transport costs. The ranking of $G_{Int} < G_v$ presented in Fig. 2 relies mainly on two conditions.

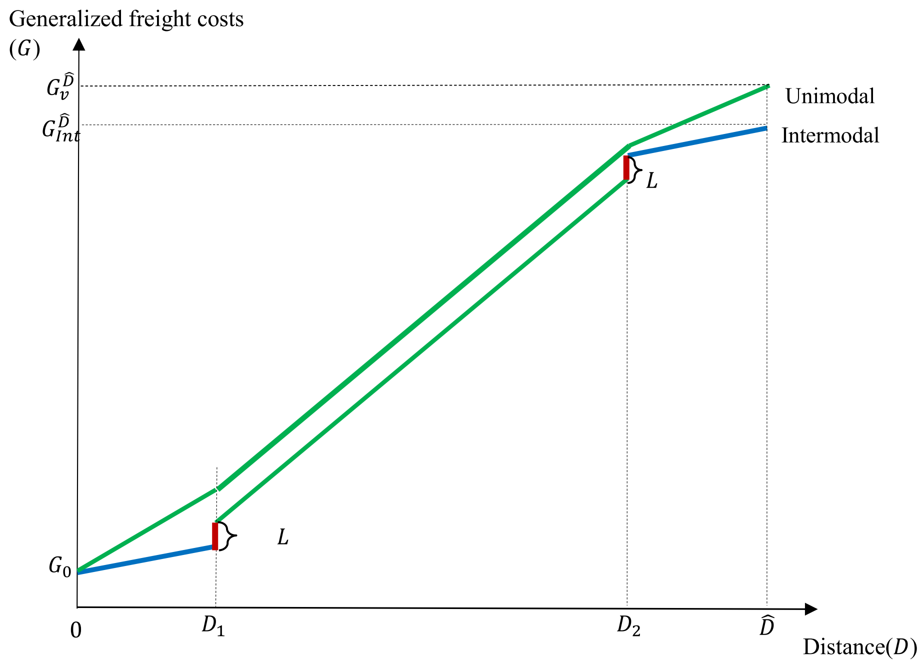

Fig. 2 Generalized freight costs for intermodal and unimodal transport solutions. Adapted from Hanssen et al. (2012)

First, the sum of pre-haulage and loading at the terminal is lower than costs for the ice-class vessel over the distance D_1. The case is similar for the post-haulage (last element to the right in (10)). Second, for the intermodal transport solution, the long-haul distance is carried out by the use of medium ice-class vessels with IB support implying that the slope is ω_{1v} and equal for G_{Int} and G_v (indicated by the green line) over the interval $(D_2 - D_1)$. The costs for IB support is here distributed over the interval from D_1 to D_2 a trip where these services are required. This implies that the cost per distance unit increases and the slope becomes steeper in this distance interval.[5]

By studying the general costs of feeder distances more closely we can specify the condition for arriving at $G_{Int} < G_v$. We do not need to consider the constant and the long-haul element since these are equal in the two transport solutions. Hence, it can be demonstrated that the condition is $2L < (\omega_{1h} - \omega_{1f})\left(D_1 + \widehat{D} - D_2\right)$. This means that two times the loading costs at the terminal must be lower than the difference between the distance-dependent parameters multiplied by the sum of the pre- and post-haulage distance. Consequently, an increase in loading cost at terminals can be compensated only by increasing the difference between feeders and ice-class vessels in the slope of the generalized cost curve given that the distance for pre- and post-haulage is constant. From (1) it is clear that this difference can be related to price (based on costs), time costs or damage cost and the effect is largest for the longest distance of D_1 and $(\widehat{D} - D_2)$. If we for simplicity assume equal distances for pre- and post-haulage so that

[5] IB costs are charged in different ways and if they are regarded as a fixed amount, it could alternatively be more included as an increase in the constant term. In practice they vary according to size of vessel, ice-class, navigation period and number of zones.

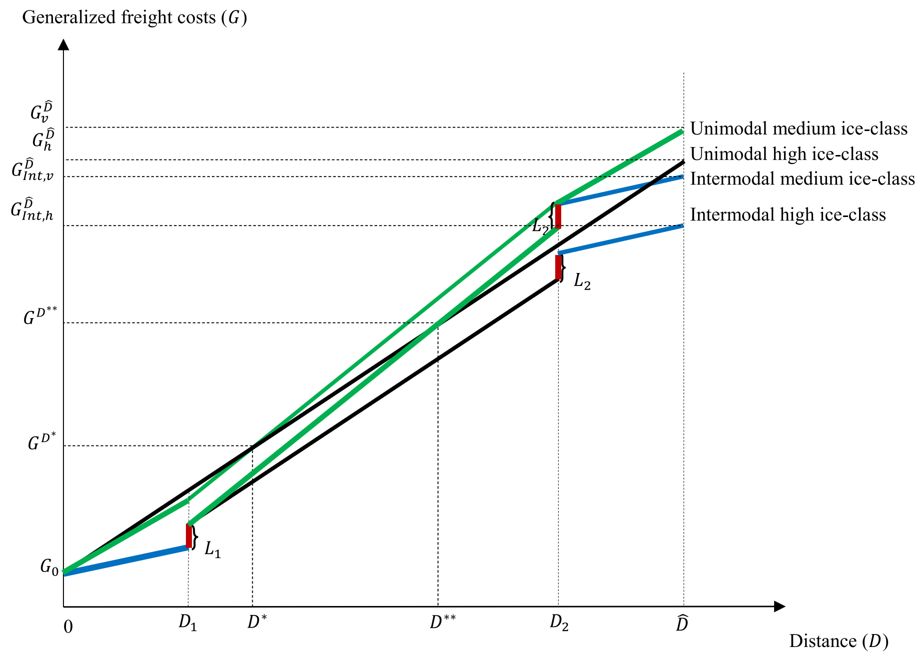

Fig. 3 Principal draft of the relationship between generalized freight costs and distance for different transport solutions. Adapted from Hanssen et al. (2012)

$D_1 = \left(\widehat{D} - D_2\right) = D$, then the condition can be simplified to $L < (\omega_{1h} - \omega_{1f})D$ with the same interpretations as above. Moreover, it should be noted that distances could differ between transport solutions. A unimodal solution would be expected to pick up and deliver cargo at multiple ports which would imply an increase in transport distance compared to the intermodal solution having a long-haul distance between two transshipment hubs. However, in order to enable comparison we assume in our model that distances for transporting one TEU are the same for all transport solutions.

Extended application of the model

This generic model can be modified in many ways. It is for example possible to allow different loading costs at terminals at D_1 and D_2 denoted L_1 and L_2, respectively. Let us now consider that high ice-class vessels do not require IB support for the long-haul distance. A situation is illustrated in Fig. 3 where a high ice-class vessel (h) can operate the long-haul distance without IB support. Hence, G_h is represented by a linearly increasing relationship with distance as specified in (12) which implies constant speed and damage probability over the entire distance interval. In this situation, we clearly see the differences in slope in the interval from D_1 to D_2 for a medium ice-class vessel requiring IB support and the high ice-class vessel.

$$G_h^{\widehat{D}} = \omega_{0h} + \omega_{1h}\widehat{D} \tag{12}$$

Figure 3 illustrates a situation where the medium ice-class vessel need IB support, while vessels with high ice-class can operate without IB support. Now, medium ice-class vessels have the highest distance-dependent costs meaning that $\omega_{1h} < \omega_{1v}$. A situation is illustrated in Fig. 3 where $G_v^{\widehat{D}} > G_h^{\widehat{D}} > G_{Int,v}^{\widehat{D}} > G_{Int,h}^{\widehat{D}}$ meaning that generalized freight costs for the entire trip are highest for a unimodal solution with medium ice-class vessels requiring IB support and lowest for the intermodal solution combining feeders and high ice-class transport without the need for IB support.

In the principal draft in Fig. 3, the possible relationships for G_{Int} (blue line) and G_v (green line) are similar to Fig. 2 except that we now specify the combination between feeders and medium ice-class vessels by the notation $G_{Int,v}$. The linear representation of generalized freight costs for the high ice-class vessels G_h (black line) implies that the slope is steepest during pre- and post-haulage, and least steep over the long-haul distance. These two contradictory effects imply that the curves will intersect if the long-haul distance $(D_2 - D_1)$ is sufficiently long. Consequently, G_h is highest from distance 0 and will not be the preferred alternative for short transport distances. The intersection between the medium ice-class vessel and the high ice-class vessel takes place at the distance D^* with the corresponding generalized freight cost of G^{D^*}. At D^{**} the unimodal high ice-class transport solution intersects with the intermodal transport solution at the corresponding $G^{D^{**}}$. The feeders in combination with high ice-class vessels, $G_{Int,h}$, takes advantage of having the least steep slope under all parts of the trips and is therefore the best alternative for all distances.

In addition, to the conditions on loading costs and differences in slopes discussed in relation to Fig. 2, it is evident that the long-haul distance has an impact on the ranking $G_v^{\widehat{D}} > G_h^{\widehat{D}} > G_{Int,v}^{\widehat{D}} > G_{Int,h}^{\widehat{D}}$ in Fig. 3. Moreover, the ranking relies heavily on the parameter values selected. It is for example likely that potential damage costs are considerably higher for high ice-class vessels travelling without IB support since consequences could be severe if an incident occurs in remote waters (Dalaklis and Baxevani 2018). This is at least a sound assumption for the arctic context where ice-breakers not only make the route possible to traverse but also act as supply bases and as part of the infrastructure for emergency preparedness.

The four alternatives illustrated in Fig. 3 can be compared to the traditional route passing through the Suez Canal. The Suez route is operated by considerably larger vessels exploiting the economies of scale. Hence, operating costs per TEU will be lower compared to the smaller vessels running the NEP route. On the other hand, the Suez route has a longer transit time which favours the NEP route in terms of distance-dependent costs. Finally, the Suez route includes a number of transhipments which increases both costs, time use and probability for damage. Consequently, when comparing the generalized costs the effects pull in different directions for the two alternatives. In the future, the NEP route might be an attractive alternative if the advantages can be exploited to a degree that they more than outweigh the cost advantages related to economies of scale in the use of large vessels at the Suez route.

Methodology

This section starts with the presentation of the main assumptions and corresponding parameter values to be used in the application of the generalized cost model. Ideally, a full estimation would require detailed empirical evidence on all elements of the generalized costs, but such data are not currently available to us. Still, we believe that our numerical examples demonstrate that the model has practical application and that the results provide insight into the cost elements in the specific market. Then estimations of change in generalized costs for each transport alternative are provided. The section is completed by a sensitivity analysis of factors that are particularly important for the attractiveness of the NEP transport route.

Possible application for transport over the NEP

To compare the NEP transport solutions, the generalized costs per carried TEU for transport will be compared using the model from chapter 3. We will study the sensitivity of parameters based on 5 cases defined as (1) unimodal– with medium ice-class containership and IB support, (2) unimodal– with high ice-class containership, (3) intermodal– feeders in combination with medium ice-class containership and IB support, (4) intermodal– feeders in combination with high ice-class containership, and (5) regular containership along the traditional route via the Suez Canal. In the following application, the main focus is on the differences in generalized cost elements between alternatives. This simplification means that we do not account for parameters having the same values in all alternative transport solutions and a summarizing of the figures do not represent the total generalized costs.

Assumptions

Let us first define the basic scenario of the NEP with some approximated values for the initial parameters. Building on the case presentation in Sect. "Context: Container shipping over the NEP", we further elaborate on the route, the importance of seasonal variations and the types of vessels.

Origin and destination, and intermediate port calls

To compare different transport alternatives, Rotterdam and Shanghai are selected as points of origin and destination, respectively. Evidently, the transport between NE Asia and NW Europe goes both ways and includes multiple ports, however, for the purpose of this calculation example, we focus on one specific route. This limitation is necessary for the demonstration. To consider uncertainty and enable the transferability of results, we address other parameter values in the sensitivity analysis.

For intermodal alternatives (3) and (4), we consider two additional ports in the analysis as transhipment terminals. According to Gunnarsson (2013), three candidates could be considered for the role of transhipment terminals in the eastern part of the NEP: the Russian port of Petropavlovsk-Kamchatsky and the two U.S. ports of Adak and Dutch. In the following analyses, we have selected the port of Petropavlovsk-Kamchatsky since it provides the shortest transport distance for the cargo flow in the Eastern part of the route. Currently, this port has specialized transhipment areas, cranes and cargo areas for 20- to 40-foot containers.

Murmansk and Kirkenes are existing ice-free ports that are suitable for transhipment operations in the western part of the NEP. Murmansk is considered in the analysis since it is ice-free on a year-round basis and has good port facilities for loading and managing vessels bigger than the Panamax class. Moreover, Murmansk is connected with the rest of the Russian logistic network (Faury et al. 2019). However, the port of Kirkenes has the potential for transhipment in the future, for example, if the railway network to Finland is developed (Kovalenko et al. 2018) and benefits from more stable geopolitical relationships with countries that are potential users of the NEP.

For regular containerships along the traditional route via the Suez Canal (alternative (5)), it assumes a total of seven intermediate ports for transhipment operations. This is an average value, and both higher and lower numbers of transhipments can occur when using this route. For example, the Maersk Eastbound service (AE11, AE7 etc.) serves between 1 and 13 ports in a voyage (Maersk 2022).

Season

To compare different options for year-round transit via the NEP, it is important to consider the restrictions imposed primarily at the NSR part of the route by the ice conditions during the winter season. According to the 'Rules on navigation in the water area of the NSR' (2020), medium ice-class vessels can only sail if they have IB assistance in medium ice conditions which is often the case in winter. High ice-class vessels can navigate in all areas without IB assistance in medium ice conditions but could need IB assistance in some zones under more adverse conditions. During light ice conditions, medium ice-class vessels can navigate independently in all areas all year round. For the calculation example, the medium ice conditions during the winter season are considered for all Arctic transport alternatives.

Types of vessels

To compare different options for navigation along the NEP we assume Arc 4 as medium ice- class vessels (which will require IB in all zones during winter) and Arc 7 as high ice-class vessels. Given the vessel's draft restrictions mentioned in Sect. "Context: Container shipping over the NEP", ice-class container ships no larger than 5,000 TEU can currently be used for navigation along the NSR (Zhao et al. 2022), but this limit will probably be challenged in the future. Hence, vessels with a capacity of 5,000 TEU are considered to be used for unimodal alternatives (1) and (2) and for the long haul part of intermodal alternatives (3) and (4). For operating in ice-free water areas, feeders up to 2,500 TEU without ice-class are considered in the analysis. For the traditional route in alternative (5), containership around 18,500 TEU without ice-class is considered for the Suez Canal. The detailed characteristics of vessels are presented in Appendix 1.

Parameters of the model

Pecuniary costs

Since there are few transport operations currently running in this area, we must offer assumptions on underlying cost drivers that allow us to provide estimates for transport activity over this route. Some studies (e.g., Lasserre 2014) assumed extra costs for the new building of ice-class containerships. However, more recently, Pruyn and van Hassel (2022) analysed the effects of ice-class on the cost of new ship construction and found that until Arc 4, there are no significant extra costs related to ice-class. The prices for transport using Arc 4 ships are about the same as for regular containerships. Since there are currently no container ships higher than Arc 4 on the market, the price of Arc 7 will be approximated. Although there might be some special training and risk add-on for crew operating in high ice conditions, extra wages would not make a great part of the cost and are assumed to be equal across all types of vessels. The main cost driver for Arc 7 will be capital expenditure. The higher ice-class increases the engine size and amount of building materials required (Dvorak 2009). Without specific information on additional costs, we assume in this example that these elements in total increase the cost of Arc 7 to a degree that the time charter rate (TCR) becomes 10% higher than for Arc 4.

Based on the Clarkson (2021) database, we can roughly assume that the average TCRs per day in 2021 for containerships of 2,500 TEU, 5,000 TEU and 20,000 TEU were $44,500, $75,000 and $200,000, respectively. Hence, for a hypothetical Arc 7 vessel with a capacity of 5,000 TEU, this value could be approximated to $82,500 per day. The rates are dynamic and have increased considerably since the pre-pandemic period and are, in 2022, subject to the worldwide high inflation trend. An additional feature of TCR is that it includes the insurance cost of the vessel and thereby provides a proxy of expected damage costs to cargo during the trip.

With the lack of more detailed information on each parameter, the TCR is a useful variable in representing the cost per day for renting the vessel. In a perfectly competitive market, the profit will be reduced to a minimum so that this rate gives an indication of actual costs. In any case, the profit margin could be assumed as equal for all types of vessels so that the error in estimates is about the same for all classes. In contrast to fuel costs depending directly on the distance of the voyage, the TCR depends primarily on time usage, which also includes the time spent in ports for transhipment during the voyage.

Handling fees run when visiting intermediate ports and for loading/unloading operations. In the calculations for all alternatives, we included the first loading and the last unloading. According to the rules of the port of Rotterdam, the visiting port fee depends on the size of the ship, while the loading/unloading operations fee depends on the volume/amount of transhipped cargo.

The canal fee and IB support are considered elements of fixed cost. In practice, the total cost for IB support for a voyage is determined by gross tonnage, ice-class, navigation period and quantity of zones (Northern Sea Route Administration 2020). This fee is included in calculations for all transport alternatives with Arc 4 containership since IB support will be needed in all zones of the NSR in the considered season and conditions. Calculation of the canal fee for the Suez Canal is based on vessel draft, gross tonnage, net tonnage, ship status and navigation direction. The fuel cost assumptions are based on the average price of very-low sulphur fuel oil (VLSFO) in USD per ton for the year 2021. For the purpose of this analysis, it is assumed that all vessels utilize this type of fuel.

Time costs

Sailing time is, in its simplest form, a product of speed and distance. There is a difference in speed depending on weather conditions (e.g., ice level) and the type of vessel. The speed of each vessel is presented in Appendix 1. The time cost is also running during transshipment including TEU loading in origin port and unloading it in destination port. Transhipment is a complex procedure of loading/unloading operations. Loading and unloading time directly depends on many factors of port infrastructure (e.g., quay port policy, types and number of cranes, storage space). There are different types of transhipment, but the most popular for vessel-to-vessel is the 'ship-to-shore' system. The detailed calculation of transhipment time is a separate field within logistics, and arriving at precise estimates requires an additional study of the ports in question. Rather, we aim for average values and present only approximations of this element for alternatives (3)–(5). According to Bartošek and Marek (2013), quay cranes are currently able to achieve about 30–50 moves per hour in practice. We assume that each analysed transhipment hub in the Arctic has two quay cranes which can perform loading and unloading operations in parallel. For alternative (5), consider ship size and assume six quay cranes. The transhipment time in intermediate ports for alternative (5) is assumed to be two days per port according to the on-time rate of main routes of major ports in the world taken from the Shanghai Shipping Exchange (Jiang et al. 2021). Transit time is a total time for transporting one TEU from origin to destination which includes both sailing and all types of transhipment time.

For the basic scenario, we consider the time costs for the transportation of high-value cargo. Our calculation example is based on the "machinery" group since it has one of the highest values per unit of time. According to Pruyn and van Hassel (2022) high-value cargo can be attractive for the NEP since it is characterised by high time costs and would benefit from the shorter transport distance. Moreover, this type of goods can be light but requires much space and has the potential to fill a whole 5,000 TEU containership. A larger ship with lighter containers might still be able to fit within the draft and width limitations for the NEP via the NSR (Pruyn and van Hassel 2022). In addition, for the sensitivity analysis in Sect. "Sensitivity analysis" we include a medium-value group represented by products such as "other general cargo" which can be transported by containerships and a low value cargo group with products such as "timber and other forest products". Halse et al. (2019) provided the recommended time values per tonne for these product groups. The values were converted to TEU capacity and adjusted to the 2021 price level using the price index of Statistics Norway.

Damage costs

The shipper usually takes cargo insurance. The insurance fee considers the expected damage cost as a product of the average probability of damage and the average cost if damages occur. Evidence indicates that in maritime transport on average, less than 1% of the cargo value will be damaged.

According to two examples of cargo insurance calculations on the Hapag-Lloyd website, we can assume that the average insurance of cargo is about 0.21%. Given the adverse weather conditions in the Artic, we would expect both higher risk and larger consequences in case of damage for transports over the NEP. We do not have any reliable estimates of risk adjustment but assume that NEP insurance costs will double from 0.21% to 0.42%. This value represents the situation during transport, and additional risk must be added for transhipments. In the following, we assume that any additional transhipments add 0.21% of the value as insurance cost (damage cost). In addition, we assume that loading and unloading in intermediate ports will add 0.01% of the value as insurance cost.

Table 1 Details on sources

Cost parameter	Description	Source
Pecuniary cost group		
Fixed costs		
Canal fee	Transit via Suez Canal (only for alt. (5))	Suez Toll Calculator (2022)
IB support fee	For Arc4 shipping via the NSR (only for alt. (1) and (3))	Northern Sea Route Administration (2021)
Handling fee	Port dues related to the cargo + port dues related to the transhipped quantity	Port of Rotterdam (2022)
Distance varying costs		
Fuel costs	Average cost of VLSFO in USD per ton in 2021	Ship & Bunker (2022)
Time charter	Average rate for 2021 in USD for each type of container vessel (including insurance for vessels)	Shipping Intelligence Network (2021)
Distances	Between all considered ports in nm (more detailed in Appendix 2)	Ports.com and MapInfo Gis
Time cost group		
Transhipment time	Assumptions 1 quay crane 40 moves per hour	Bartošek and Marek (2013)
Sailing time	Speed times distance of voyage (calculations in Appendix 3)	Clarkson (2021)
Time costs	Time costs per unit of time for the goods themselves that are transported	Halse et al. (2019)
Damage cost group		
Insurance costs Probability of damage	For goods only. Indicated by insurance premium; extra premium for each transhipment and extra premium for loading and unloading operations in intermediate ports for alt. (5)	Hapag-Lloyd website

IB- Icebreaking vessel; NSR-Northern Sea Route; VLSFO- Very low sulphur fuel oil; USD- United States dollar

Summary

To complement the description above, Table 1 provides details on the parameter description and sources used to set approximate values of the parameters included in the generalized cost model.

Results from the calculation example

The assumptions on parameter values given in Sects. "Assumptions" and "Parameters of the model" allow us to calculate generalized transport costs for transporting a TEU over a future route using the NEP. The results are in Fig. 4 indexed and presented as percentages relative to the scenario of the Suez route (5). Moreover, Fig. 4 visualizes generalized costs separated into the three main costs categories of the model presented in Sect. "Theoretical framework" for the transport alternatives.

In Fig. 5 pecuniary costs from Fig. 4 are further specified in categories of distance dependent costs (such as fuel costs and time charter costs) and fixed costs. Values are indexed also in Fig. 5, where alternative (3) with the highest pecuniary costs as basis.

When comparing the generalized transport costs of the five transport solutions in the basic scenario, it is demonstrated in Fig. 4 that the most expensive alternative for 1 TEU of high-value cargo is the Suez route (alternative 5). The high generalized cost for this route relies mainly on high time costs due to long transit time and multiple ports of call.

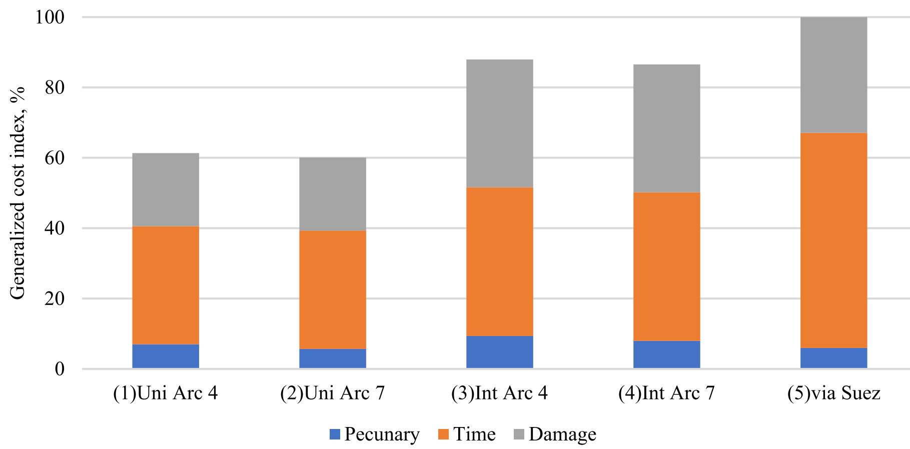

Fig. 4 Estimated generalized freight costs per TEU for the scenarios

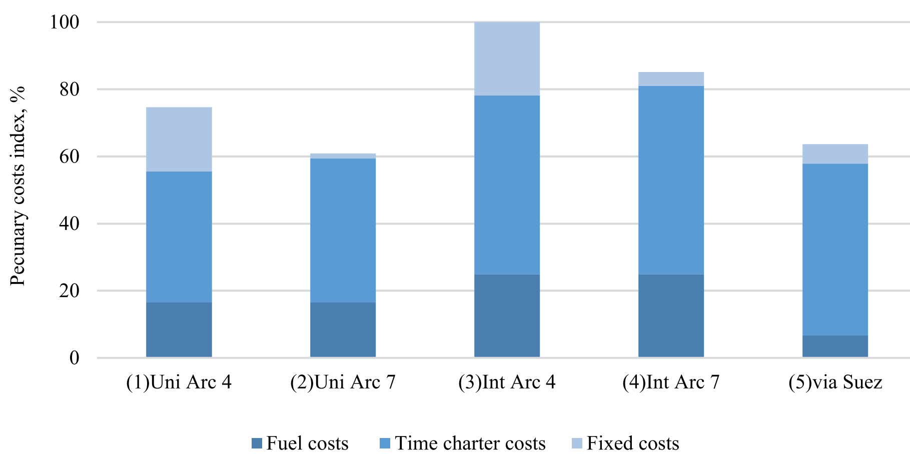

Fig. 5 Specification of pecuniary costs per TEU for the scenarios

However, the pecuniary cost (or monetary expenses) of this alternative is considerably lower than the Arctic alternatives (1), (3) and (4). It is evident from Fig. 5 that the higher pecuniary costs of these alternatives are caused by the deployment of smaller vessels on the NEP having higher fuel costs per TEU since they are unable to match the economies of scale for the Suez route. Although the unimodal alternative (2) with Arc 7 has the lowest total pecuniary costs among the alternatives (about 39% lower than the intermodal alternative (3) and 3% lower than Suez (5)), the small vessel size makes fuel cost per TEU higher compared to the Suez route.

It is evident from Fig. 4 that the most attractive transport solution for high-value cargo is the unimodal alternative (2) with Arc 7 containership which has about 57% lower generalized transport costs than the Suez route. This is explained by significantly lower transit time, no transhipment operations during the voyage and the absence of the IB support fee and canal fee. In the case of intermodal shipping, alternative (4) with Arc 7 is the most attractive one. The generalized costs of (4) are about 29% lower than the Suez route and they must be reduced by about 28% to compete with (2). Both intermodal alternatives are cheaper than the Suez route in terms of time costs but more expensive in terms of damage costs and pecuniary costs such as distance-dependent costs (fuel costs, time charter costs) than all unimodal alternatives.

Sensitivity analysis

We have made simulations and identified the most important factors influencing the competitiveness in terms of generalized costs for considered transport alternatives.

Time is the most critical factor since it is included in calculations of pecuniary and time costs. The changes in this parameter can significantly alter the ranking of alternatives according to total generalized costs. For example, a 26% reduction in voyage time via the Suez Canal leads to about a 33% decrease in generalized transport costs. This could be the case if the number of intermediate ports is reduced from 7 to 1 via the Suez route. Although such a significant decrease in total time would make the Suez Canal alternative preferred in terms of pecuniary costs per TEU, it is still more expensive in terms of generalized costs relative to the unimodal arctic alternatives (1) and (2) (by 6.8% and 8.3%).[6] If we look at the intermodal transport alternatives, they require an 82% reduction in transhipment time for the time cost to become lower than the unimodal transport alternatives. Such a considerable reduction of transhipment time seems unrealistic in the short-run and would require a significant investment to increase the efficiency of cranes in ports. Still, considerable reduction is required for alternative (4) to obtain the lowest generalized costs.

A substantial element for uncertainty in sailing time for the Arctic transport alternatives is ice conditions and season. The summer season and light ice conditions will increase time advantages for unimodal and intermodal alternatives with Arc 4 since this type of vessel can sail without ice-breaker support and speed can be increased in the NSR area. Moreover, sailing without IB support significantly decreases pecuniary costs for alternatives with Arc 4 and this amounts to 19% and 24% for the intermodal and unimodal alternatives, respectively. Hence, under such conditions the unimodal alternative (1) with Arc 4 will become the most attractive in terms of generalized costs per TEU and the intermodal with Arc 4 will become more competitive than the intermodal alternatives with Arc 7. In addition, favourable ice conditions could allow for sailing via the international zone which is farther from the coastline than the NSR and may decrease the distance by 10% (BednBlue 2022). Even though this is currently related to high risk, it indicates a potential of decreasing the voyage time in case of ice reduction. Other benefits of using sailing in open water are that the draft limitations could be abandoned, and the size of the vessel may increase so that economy of scale can be exploited also in Arctic shipping. However, in this case, we can only consider the high-class vessels since there is uncertainty for the IB support in this area.

The next critical factor for ranking transport alternatives is cargo value. It influences significantly on time costs and damage costs. As demonstrated in Fig. 4, for high-value cargo (e.g. machinery; electrical equipment, household articles) time costs are the most important while pecuniary costs make up a minor part of generalized transport costs. However, for low-value cargo (e.g. timber and other forest products) the situation is the

[6] These calculations assume the normal operation of the Suez route. However, there have been incidents blocking the Suez Canal and safety challenges following political uncertainty in the Middle East, implying that this route requires vessels to pass south of the African continent for a considerably longer journey time (UNCTAD 2024). All else equal, this increases the relative attractiveness of the NEP route.

opposite; pecuniary costs are the most important and the time costs are the least important. For medium-value cargo (e.g. other general cargo) the distribution between pecuniary, time and damage costs are more even. Some example calculations for medium and low-value types of cargo are presented in Appendixes 4 and 5. These calculations show that, since pecuniary costs make up only a small part of the generalized costs for high-value cargo, any changes in this cost group will be of minor importance for the ranking among the transport options. However, the picture is different for other types of cargo. In the case of low-value cargo, the filling rate of the vessel is a critical element since pecuniary costs per TEU rely heavily on economies of scale. For example, if the filling rate of 5,000 TEU ice-class vessel decreases by 50%, the pecuniary costs of alternative (4) will be 16% lower than the alternative (1) and also makes (4) the preferred transport solution in terms of generalized costs. Among the other elements of the pecuniary costs, the time charter rate is the most critical factor. As a basis for our estimates, we have used 2021 rates. However, variation has been unnatural after the COVID outbreak in 2020 and still has not normalised. For instance, the average value of the time charter rate for a 5,000 TEU containership was 77% lower in 2019 compared to 2021 (Clarkson 2021). Since these types of costs make up the biggest part in the pecuniary costs group, the changes show high sensitivity for the outcome ranking in the case of transportation of medium and low-value cargo. For the remaining part of pecuniary costs, such as fuel costs, the impact on generalized costs is low for all types of cargo.

Conclusion and implications

In this study, we have expanded upon a theoretical framework for assessing the generalized transport costs of intermodal transport solutions in the maritime sector. The existing literature is mainly empirical, and, to our knowledge, this model is one of the first to provide a conceptual framework based on generalized costs for such an intermodal maritime context. This framework is suitable for discussing the conditions under which an intermodal transport solution is preferred to a unimodal transport solution when considering a broad set of cost elements, including operating costs and pecuniary assessments of time usage and risk of damage. In the context of maritime transportation over the Northeast Passage, we define intermodality as the use of different types of vessels on the route.

In principle, the intermodal solution with feeders and high ice-class vessels without ice-breaking support, in the context of container shipping, was regarded as the most attractive alternative according to the theoretical model since it exploits the advantages of different vessels at different stages of the voyage. However, it should be noted that this option is currently not feasible mainly due to two reasons. First, the fleet of high ice-class (Arc 7) container vessels is on the drawing board but does not currently exist. Second, there is a lack of necessary infrastructure such as container ship port terminals, service and maintenance facilities, and poor SAR capabilities in the Eastern part of the route. These are important preconditions for decision-makers to develop at the NEP to prepare for a viable intermodal transport corridor for container shipping.

The theoretical model suggests that an intermodal solution using feeders for the post- and pre-haulage and ice-class vessels for the long-haul could be the most attractive alternative. This is, however, a proof of concept and not a validation of the conclusion. In order to further analyse whether this is could actually be the case in practice, we have collected underlying data enabling us to estimate parameter values for a calculation example in the context of transporting containers from NE Asia to NW Europe over the Northeast Passage. The empirical evidence suggests that under the current regulations and the technical level of development, the unimodal solution with high ice-class vessels without IB support is highly attractive relative to the traditional Suez route. The successful application of the concept which includes many cost elements to rank the attractiveness of alternatives could be of interest for logistical planners when making the choice of both route and mode for a transport solution also in other context.

Numerous assumptions form the basis for this conclusion. Aspects such as the chosen route, characteristics of goods, and properties of the vessels all influence the result. The attractiveness of the Suez alternative, for example, is considerably improved if the route involves a reduced number of intermediate ports. The sensitivity analysis demonstrates that among the most important advantages of the NEP, the time savings are most prominent. Hence, for policymakers it is relevant to know that investments to provide efficient port infrastructure that reduces time in transshipment are vital. Port fees and fuel are of less importance for the high value cargo that would find the NEP alternative attractive. This could be exploited by stakeholders for example by increasing rates for less price sensitive users to increase funding for infrastructure investments. It also means that any pecuniary costs or fines imposed by regulators to make the operators behave in a more environmentally friendly way must be of considerable size. This is relevant for example for the ongoing work with regulation of transport in international waters by International Maritime Organization.

Factors that are exogenous to the transport companies, such as shipbuilding technologies, global warming, and world uncertainty, have a decisive impact. If global warming continues, it will gradually shorten the winter season and reduce the disadvantages related to the high ice-classing of vessels. Moreover, the NSR part of the NEP is difficult to use under the current geopolitical situation, but we have demonstrated that it might be an attractive route when the situation allows for international trade in this region.

Evidently, such a study has some weaknesses and limitations. A more detailed model specification could better inform policymakers on the studied issues. The model simplifies by assuming mainly linear relationships and constant parameter values over the transport distance. Future studies need to consider the reasonability of these assumptions and expand upon those necessary to represent the NEP. The research community must cooperate with stakeholders to obtain the empirical evidence required to study the reasonability of the assumptions and assign values to the parameters in the model. A major challenge is that most of these data are difficult to collect since they are sensitive or properties of the state (for example, data related to the ice-breakers).

The model could be refined and extended to consider environmental aspects by including external costs and thereby better represent the socially generalized transport costs. Currently, we are taking the transport purchasers' point of view and are only considering private costs, not the external costs that are necessary for making considerations for society. External costs are relevant to include if we are to discuss environmental aspects such as sustainability in the fragile Arctic region, but it is challenging to find available data on measures for calculating the impact on the environment at the moment. Finally, we would like to emphasize that the suggested framework is not limited to our context but can be applied to other transport routes such as the Northwest Passage, other land-based alternatives using railway, and for cargo types other than container liners which are addressed in this study.

Appendix

Appendix 1

See Table 2.

Table 2 Characteristics of the selected vessels

	Feeder	Containership Arc4 (medium ice-class vessel)	Containership Arc 7 (high ice-class vessel)	Containership for Suez route
TEU	2500	5000	5000	18,500
GT	27,051	55,335	55,335	195,915
Deadweight (ton)	34,567	65,700	65,700	196,470
Estimated cargo (ton)	27,500	55,000	55,000	185,000
Average load per ton	11	11	11	10
Draught (m)	9,2	13,5	13,5	16
Ice-class	–	Arc4	Arc7	–
Ice-breaker support	–	all NSR zones in winter in medium conditions	–	–
Paying the fee for the canal	–	–	–	Yes
Speed NSR (kn)	–	12	12	–
Speed outside (kn)	95% Design	95% Design	95% Design	95% Design
Fuels to be used	VLSFO	VLSFO	VLSFO	VLSFO

Source: Authors based on Clarkson (2021) and Pruyn and van Hassel (2022)

Appendix 2

See Table 3.

Table 3 Distances

		Unimodal cases	Intermodal cases	via Suez
(D) Distance nm	Pre		1619	-
	Long			
	Free water	6027	2221	
	Ice water	2500	2500	–
	Post		2187	–
	Total	8527	8527	10,548

Appendix 3

See Table 4.

Table 4 Transhipment and sailing time in days

Time use	Intermodal 1 Arc4	Intermodal 2 Arc7	Unimodal 1 Arc4	Unimodal2 Arc7	Suez Canal
Loading in origin	1,3	1,3	2,6	2,6	3,2
Pre-haul (feeder) free water	3,4	3,4			
1st transhiment	3,9	3,9			
Long-haul:					
-Free water	4,0	4,0	10,7	10,7	24,4
-Ice water	8,7	8,7	8,7	8,7	
2nd transhipment 2	3,9	3,9			
Post-haul (feeder) free water	4,6	4,6			
Loading in destination	1,3	1,3	2,6	2,6	3,2
Total travel time (in days)	31,0	31,0	24,6	24,6	44,8

Appendix 4

See Fig. 6.

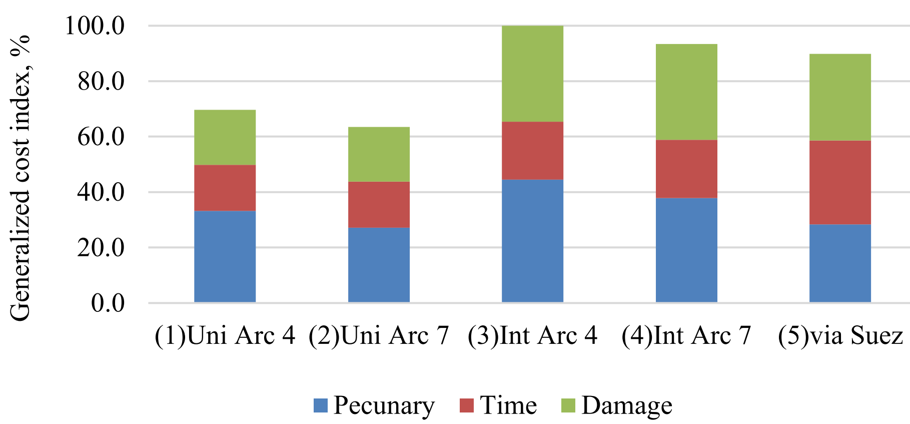

Fig. 6 Cost results for medium value cargo for the scenarios

Appendix 5

See Fig. 7.

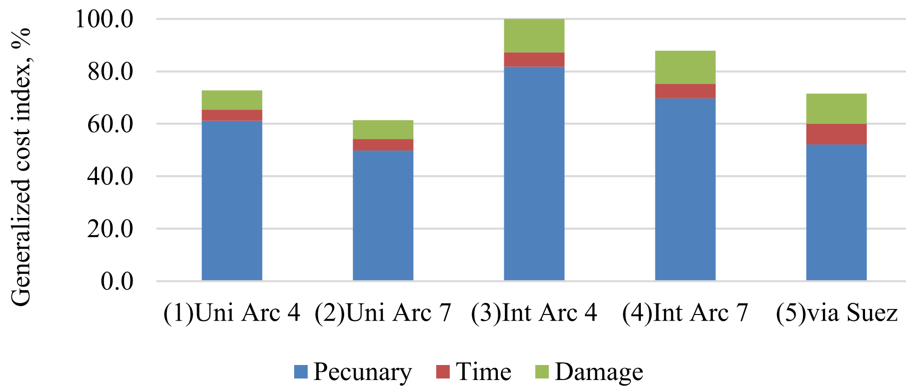

Fig. 7 Cost results for low value cargo for the scenarios

Abbreviations

NEP	Northeast Passage
NSR	Northern Sea Route
NE	Northeast
NW	Northwest
TEU	Twenty-foot equivalent unit
IB	Ice-breaker
SAR	Search and rescue
TCR	Time charter rate
VLSFO	Very low sulphur fuel oil
USD	United States dollar

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Author contributions
AK was a major contributor to writing and editing the manuscript. She also performed conceptualization, data collection and curation, and formal and empirical analyses. TAM supervised AK during the development of the study, engaged in conceptualization and validation, and participated in writing, reviewing and editing the manuscript. JP edited and reviewed the manuscript, collected data and participated in empirical analysis. All authors contributed to finalizing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
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Declarations

Competing interests
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