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The role of polarseaworthiness in shipping planning for infrastructure projects in the Arctic: The case of Yamal LNG plant

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ABSTRACT

The numerous Artic port industrial complex projects are currently marked by a lack of both railroad and road infrastructures and require a heavy cargo shipping service. Yet, navigation in the Arctic implies facing harsh sailing conditions. To prevent risk arising from this singular region, the IMO Polar Code imposes mandatory tools as the Polar Ship Certificate and suggests others such as POLARIS. At the crossroads of container and tramp market, scholars have paid little attention to the transportation of heavy cargo.

The objective of this research is to assess the impact of the Polar Code policy framework and its tools on the management of a highly strategic project. To do so, we shall rely on the case of the transport and assembly of the Yamal LNG plant modules. Yamal LNG started its production in late 2019 and has already produced 19 million tons per year. The paper contemplates a ship routing and scheduling optimization model that considers different fleet types and ice conditions and applies the POLARIS Risk Index Outcome (RIO) in Arctic waters.

Even though the modules are required on site in summer, due to the extreme weather conditions and limited accessibility in winter, our results highlight that the use of Polar Class vessels allowing year-round navigation in Arctic waters is critical to ensure the success of such projects. Indeed, Polar Class 3 vessels, as ships with the greatest possible "polarseaworthiness", are capable of significantly reducing delays in project's completion. It also emphasizes the paramount role of the Polar Code and related tools in the shipping risk management of Arctic infrastructure projects.

1. Introduction

The development of the Arctic shore is of utmost importance for Russia for both economic and geopolitical reasons. Economically, the Russian Arctic constitutes a tank of hydrocarbons and rare earth minerals (Faury et al., 2021) that benefits from promising shipping lanes, especially the Northern Sea Route (NSR) via the Bering Strait, that allows a 40% potential shortcut between Asia and Europe (e.

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g. Lasserre, 2014). Crude oil and gas represent the great majority of Arctic cargo flows coming from Russian ports as Sabetta or Novy (Gunnarsson, 2021). Whatever the challenges faced, being able to export oil and gas is paramount for the Russian economy, whose budget is highly dependent on such resources (Aalto, 2016). Geopolitically, if these ports are designed to export raw materials westward and eastward from remote oil and gas fields (Gunnarsson and Moe, 2021), their operations are also necessary to maintain a Russian presence in a highly coveted ocean. In order to counter-balance the dependence towards the European market for energy materials (IES, 2010), the Russian objective to enhance the share of Asia as final customer has met the Chinese strategy to increase the use of LNG in the coming years (S&P Global Platts, 2018). As a major partner in the Yamal project, China also considers the exploitation and exploration of resources in the Arctic as a strategic development goal (China's Arctic Policy, 2018). Hence, the building or the maintenance of plants, ports and other infrastructures dedicated to the socio-economic development of the NSR as a shipping lane, is considered highly strategic for Russia (Faury et al., 2021; Rosmoport Report, 2013).

As predicted by some authors with regard to the Eastern Arctic fields (Stephenson & Agnew, 2016), the Russian government has made massive investments to enhance facilities such as ports and plants which should be the keystones of its development in the future. To reach the objective of 80 million tons by 2024 (Staalesen, 2018), some port facilities have been modernized namely Murmansk, and others have been built as Sabetta that currently represents 29.5% of the total volume shipped along the NSR (Sea News, 2020). Besides, while Sabetta is the first large project in this area personifying the strategic importance of the Arctic for Russia, it should not be the last since 15 other oil, gas, iron ore and coal projects are planned (Faury et al., 2021). Nevertheless, extreme climatic conditions and the long period of darkness complexify the management of such projects and increase their cost. Moreover, Arctic navigation implies dealing with numerous risks and related constraints (Haavik, 2017; Fu et al., 2016), in particular the presence of ice. The unpredictability of ice conditions on a monthly basis renders the transportation of cargo that have schedule constraints highly complex (Lasserre, 2014; Lasserre and Pelletier, 2011).

This paper investigates a real-life case study concerning the transportation of heavy modules dedicated to the construction of the Yamal LNG plant. The transportation problem is solved using a ship routing and scheduling optimization model that considers different vessel types and ice conditions. The "Polar Operational Limit Assessment Risk Indexing System" (POLARIS) framework is applied to draw lessons regarding the planning of these operations and evaluate risk mitigation options. Adopted by the International Maritime Organization (IMO) in the aftermath of the "Polar Code" (IMO, 2014), POLARIS (IMO, 2016) has provided a method to compute the level of risk within an area based on ice thickness, concentration and classification of the vessel. Some authors (Fedi et al., 2018a, 2018b) have already underlined the contributions of the "couple" PC and POLARIS to a safer navigation and a formal Arctic "polarseaworthiness".

The related objectives of this paper are twofold. In accordance with the new IMO policy tools, it firstly investigates the best fleet type and route choices for large construction projects in the Arctic zone, while considering the scheduling-related aspects. Secondly, it proposes a model for a real-life shipping scheduling problem for large size modules assessing both ice conditions and their effect on the navigability periods and sailing speed depending on the POLARIS risk index, which, to the best of the authors' knowledge, has not been analyzed in previous studies. The shipping optimization model was largely built ex-ante with industry partner specifications, as a strategic decision-support tool designed to assess the cost and feasibility of the shipping plan. The risk analysis with the different fleet types and ice conditions, using the POLARIS risk index was carried out ex-post and was used as new input data in the model.

As contributions, the research provides a better understanding of Arctic navigation for heavy goods and emphasizes the determining role of Polar Class 3 (PC3) vessels showing the greatest possible "polarseaworthiness" in the shipping risk management of Arctic infrastructure projects. It also underlines that the NSR via the Bering Strait can act as a real time saver compared to the Suez Canal Route (SCR) and thus, can play a pivotal role for the implementation of future industrial projects in the Arctic. Finally, this research contributes to clarifying how complex Arctic operations management such as scheduling for Arctic projects with time constraints can be better handled in a risky environment.

The remainder of the paper is structured as follows: Section 2 overviews the relevant literature while Section 3 details the methodology including the problem description, the model and the navigation assumptions. Section 4 contemplates the scenarios applied to the case and the results. Section 5 provides a discussion and managerial implications while conclusions are drawn in Section 6.

2. Review of relevant literature

As explained by Lasserre (2014), Meng et al. (2017), Theocharis et al. (2018) and Lavissiere et al. (2020) Arctic shipping has been the subject of numerous studies over the last decades. If these four literature reviews stressed that most of the articles dealing with Arctic shipping focus on container, bulk and general cargo, they also demonstrate the different results obtained when comparing the attractiveness of the NSR to the SCR. The NSR has been analyzed in terms of feasibility and economic relevance for bulk shipping (Cariou and Faury, 2015), for oil shipping (Faury and Cariou, 2016; Theocharis et al., 2019) and for container shipping by Sun and Zheng (2016), Zhao et al. (2016), Zhang et al. (2016a, 2016b), Xu et al. (2018), Lin and Chang (2018), Zeng et al. (2020) and Lasserre (2014). As explained by the latter and Theocharis et al. (2018), most of the analysis deals with the container transportation whereas the main flows concern bulk carriage (Li et al., 2020; Faury et al., 2021).

Lavissiere et al. (2020) have recently underlined five research areas on Arctic shipping that invite scholars' investigation. Among them, they identified the "management constraints" imposed by the Arctic specific conditions, "risk management" through the lens of "legal context and the constraints on business", "decision models or best practices" of industrial projects and "vessel management". Our paper will try to shed a light on these gaps in analyzing the Yamal LNG plant case on heavy cargo transportation that, contrary to the professional press, has not much received attention in the academic management literature.

2.1. Risk management and polarseaworthiness in Arctic waters

Navigation along the NSR is impacted by three main types of factors which are strongly interrelated: climatic, geographic and finally legal. The climatic factor influences the thickness, concentration and extent of ice during the year and is difficult to predict on a daily basis. This level of unpredictability renders navigation in this area highly complex (ABS, 2014; Fu et al., 2016), risky (Marchenko, 2012; Johannsdottir and Cook, 2014; Montewka et al., 2015; Haavik, 2017; ALLIANZ, 2018) and implies the use of ice class vessels as encouraged by the NSR Administration (NSRA, 2017). Marchenko (2014) and Zhang et al. (2020) stressed the importance of suitable speed in Arctic waters and Löptien and Axell (2014) underlined its relationship with ice conditions and the vessel's ice class. Zhang et al. (2020) highlighted the importance of interactions between ice concentration, ship speed and ice thickness to avoid both risks of being stuck and ice collision.

Considered as the backbone of the NSR (Faury et al., 2020), icebreakers are often necessary since they allow to sail in safer conditions, even if the cost may have a strong impact on NSR economic attractiveness (Gritsenko and Kiiski, 2016; Liu and Kronbak, 2010). They enhance the sailing period and benefit from a 40% shortcut (Lasserre, 2014). Nevertheless, being escorted by an icebreaker does not necessarily mean an absolutely safe passage and may lead to a collision (Fedi et al., 2020). Cariou et al. (2019), Cheaitou et al. (2020) and Xu et al. (2018) as Lasserre and Pelletier (2011) also stressed the container liner companies' difficulty to provide a reliable transit time because of the unpredictability of ice conditions.

The geographic factor refers to the low depth of the Russian shore (for example, Sannikov Strait with a depth of 13 m) and the poor density of infrastructures such as repair yards, ports or icebreakers. The lack of infrastructures is still perceived as a major drawback to the development of navigation along the NSR (FoU-RAPPORT., 2016; Frolov, 2015; AMSA, 2009) and insurance companies consider it as a potential risk catalyzer (Fedi et al., 2018a).

With regard to the legal factor, despite the decreasing ice thickness (Comiso, 2012; Boé et al., 2009), the risk for vessels is still present (Fedi et al., 2018a). As demonstrated by Stephenson et al. (2013), Arctic ice is highly unpredictable and variable. Meng et al. (2017) highlighted the sensitivity of Arctic navigation as regards ice features. They stressed the difficulty to forecast ice conditions that the ships may encounter and that this unpredictability acts as a break to NSR development. To provide safer navigation, the IMO adopted the PC that entered into force in January 2017 (IMO, 2014). As a universal legal binding instrument (Chircop, 2013; Henriksen, 2014; Bai, 2015; Fedi and Faury, 2016), the PC sets out different risk management tools that aim to prevent risk occurrence with detrimental consequences for crews, ships (Dalaklis et al., 2018) and the fragile environment. Through the "Polar Ship Certificate" (PSC), the "Polar Water Operational Manual" (PWOM) or the "Voyage Planning" in particular, the PC frames the proceduralization of polar risk (Fedi et al., 2018a; Fedi, 2020) depending on how a vessel is designed and how it is operated in circumpolar areas (DNV-GL, 2017).

Furthermore, these PC formal procedures are completed by POLARIS that provides a comparison of different typologies of ice to ship's class in order to determine a safe routing and the most appropriate class (IMO, 2016). Part of its DNA, POLARIS focuses on the speed that vessels shall adopt to avoid accidents and if they shall be assisted by an icebreaker. POLARIS is considered by Kujala et al. (2016) as a "modern methodology" and 'the best present practice for the risk-based design" while Stoddard et al. (2018) analyze it as a decision-making tool for the planning of a safe journey within polar waters. Fedi et al. (2018b) gained more insight into POLARIS in showing that it was a strategic "multipurpose tool" working "upstream and downstream of the shipowner's decision process". More recently, the latter demonstrated the benefits of the couple PC and POLARIS in risk prevention for ice-covered waters in particular along the NSR (Fedi et al., 2020).

Accordingly, the authors assume that the PC and POLARIS set out a systemic framework of polarseaworthiness. Introduced by Cullen (2015) this concept has been further developed by Fedi et al. (2018b, 2020). This concept must be tied up to the "seaworthiness" ones. Pursuant to a famous jurisprudence: "[…] its meaning is dependent upon the vessel involved and the service in which it is to be employed. In general, a ship must be sufficiently strong and staunch and equipped with the appropriate appurtenances to allow it to safely engage in the trade for which it was intended" (US District Court of Louisiana, 1975). Thereby, when we raise the concept of polarseaworthiness, we suppose that vessel hull, machinery and equipment as a whole are technically able to meet the hazards of polar waters (ice, low air temperature, etc.). It implies not merely the ship herself, but also the polar skills of crew members. Thus, shipping companies that plan to operate in Arctic regions have to exercise a due diligence audit to make their vessels "polar seaworthy" in accordance with the mandatory PC provisions and the recommended POLARIS ones.

2.2. LNG production and Yamal LNG plant

As a result of the Russian energy policy, LNG represents the lion's share of the cargo transported along the NSR in 2020 and shall remain as one of the main priorities for the Russian government (Henderson, 2019). At the core of this policy, the Yamal LNG plant, that has been subject of abundant professional press articles, is considered both as a highly strategic project for Russia (Dai et al. 2021; Henderson and Yermakov, 2019) and a pilot project (Hannon, 2019). The implementation of the Yamal LNG project has had numerous impacts on the NSR (Gunnarsson, 2021) in particular in terms of raising the number of cargos shipped and producing up to16.5 million tons of LNG (Li et al., 2020; Mignacca et al., 2020).

The construction of the Yamal LNG plant also had to manage climate, economic and logistic constraints (e.g. Yulong et al., 2016; Katysheva, 2019; Hannon, 2019; Mignacca et al., 2020; Merkulov, 2020; Razmonova and Steblyanskaya, 2020). Concerning climate constraints, most of the studies dealing with the Yamal LNG plant agree on the fact that ice conditions represent a main challenge for the navigation and consequently stakeholders invested in specific vessels capable of navigating throughout the year (Van Lievenoogen et al., 2018). On a purely economic level, the cost of the project is estimated to be around USD 27.6 billion (Mignacca et al., 2020) which is highly significant. Considered as one of the largest industrial projects in recent years, it used half of the world's heavy load vessel fleet and required the building of new dedicated vessels (Hannon 2019; Van Lievenoogen et al., 2018). In addition, the use of modules already built allowed to reduce costs (Mignacca et al., 2020). In order to respect the project schedule previously decided, Mignacca et al. (2020) highlighted the positive impact of modules but also their complexities. Concerning logistics, Hannon (2019) provided a global picture of the project and the different routes used by vessels via the Bering Strait and the Suez Canal.

Yet, if the aforementioned studies made a focus on the Yamal LNG plant, and agreed on the complexity to ship the concerned modules, as far as we know, none of them have analyzed the maritime logistics and related optimization that were required to respect the project schedule.

2.3. Shipping optimization problems

Maritime shipping problems have been investigated in the literature since the 1950′s with an initial focus on tankers (Dantzig and Fulkerson, 1954) and therefore many models exist and address different related aspects. Comprehensive reviews of shipping optimization problems can be found in Ronen (1993), Christiansen et al. (2004, 2007, 2013), and Christiansen and Fagerholt (2014). Regarding bulk transportation, Li et al. (2019) proposed an integer programming formulation considering dynamic cargo price, transportation cost and timely demand of steel plants over multiple periods.

More specifically, Christiansen et al. (2013) categorize maritime shipping problems into three categories: first, liner shipping problems where vessels follow a predefined route and operate depending on fixed schedules. Second, industrial shipping problems, in which the same company owns the cargo and the vessels and therefore tries to minimize its transportation costs. Third, tramp shipping, in which the vessels operate in a way similar to the operations of 'taxis' and sail to the locations where the cargo is available. All of these problems show different decision levels: strategic planning issues (e.g. fleet size and composition and liner network design), and tactical planning issues (e.g. fleet deployment, cargo routing and scheduling or inventory routing in supply chains). Other studies analyze these types of maritime transportation from different perspectives such as sailing speed optimization, bunkering and emission problems or offshore logistics, lightering and stowage matters.

For instance, Meng and Wang (2011) develop a mixed-integer nonlinear programming model for liner shipping that aims to determine the optimal service frequency, containership fleet deployment, and sailing speed. Others consider the vessel's speed optimization from an environmental perspective such as Cariou and Cheaitou (2012) in assessing CO_2 emissions. Routing and scheduling optimization in tramp shipping has recently been addressed under stochastic environment by Wu et al. (2018) and considering the bunkering problem by Meng et al. (2015).

According to Christiansen et al. (2007), routing is the assignment of a sequence of ports to a vessel and scheduling the assigning of times (or time windows) to the various events on a ship's route (usually short term – days or weeks). Christiansen et al. (2013) also show that cargo routing and scheduling problems are solved in many different ways, in particular when solving 'real-life' problems which include aspects that are not included in standard model formulations. Project cargo shipping problems is a less explored subclass of industrial and tramp shipping problems. Christiansen et al. (2013) identify only two references in this category (Fagerholt et al., 2013; Andersson et al., 2011). For Andersson et al. (2011), the routing and scheduling of vessels is constrained by cargo precedence (or synchronization constraint). Precedence constraints are addressed by Fagerholt and Christiansen (2000), Fagerholt (2001), time-windows by Fagerholt et al. (2013), and Lee and Kim (2015) consider split deliveries, but not in a project cargo shipping context. An exact solution for large-scale industrial routing and scheduling problems with pick-up, deliveries and time windows is presented by Homsi et al. (2020), without addressing some aspects from our problem such as split loads, multiple time-windows for each cargo in the delivery port and synchronization of deliveries among cargoes at the destination port. Halvorsen-Weare et al. (2013) and Cho et al. (2018) contemplate LNG distribution, but not plant construction. Other authors also model the oil shipping problem but not oil plant modules transportation (Hennig et al., 2012; Hennig et al., 2015). Thus, the authors could not find in the literature works that cover these constraints altogether for project cargo shipping problems.

3. Methodology

3.1. Description of the case study

The construction of Yamal LNG project was carried out by a joint venture between Novatek (51%), Total (20%), CNPC (20%) and the Silk Road Fund (9%). The project was launched in December 2013, and the first equipment module was shipped from Asia in August 2015. Some 149 modules in total were expected to be shipped to Sabetta; approximately 70% of these from three yards in China, and the remaining 30% from two yards in Indonesia and the Philippines. A fleet of up to 20 vessels was envisaged to transport the modules whereas only two of those were of Polar Class 3 (PC3) enabling year-round navigation in the Arctic. Furthermore, these two project-specific vessels were ordered in 2014 to be delivered in January and April 2016, after the beginning of the shipping operations. The limited availability of PC3 vessels was perceived as a potential bottleneck of the project. Moreover, some of the vessels could not access certain shipyards due to draft constraints. Five vessels had long-term time-chart contracts (two PC3, two 1A and one Open Waters), and the remaining ones could be hired from the spot market based on a short-term chartering contract.

Soon after the launching, the project teams raised concerns over risk assessment related to the shipping capabilities and envisaged the use of the NSR via the Bering Strait as an alternative to the SCR for risk mitigation and cost minimization. The ship routing and scheduling model, for the most part developed ex-ante, provided proof of the shipping plan feasibility within three years using the Bering Strait Route, and contributed to optimize the use of the available resources. Vessel fleet, sailing speeds and navigability periods

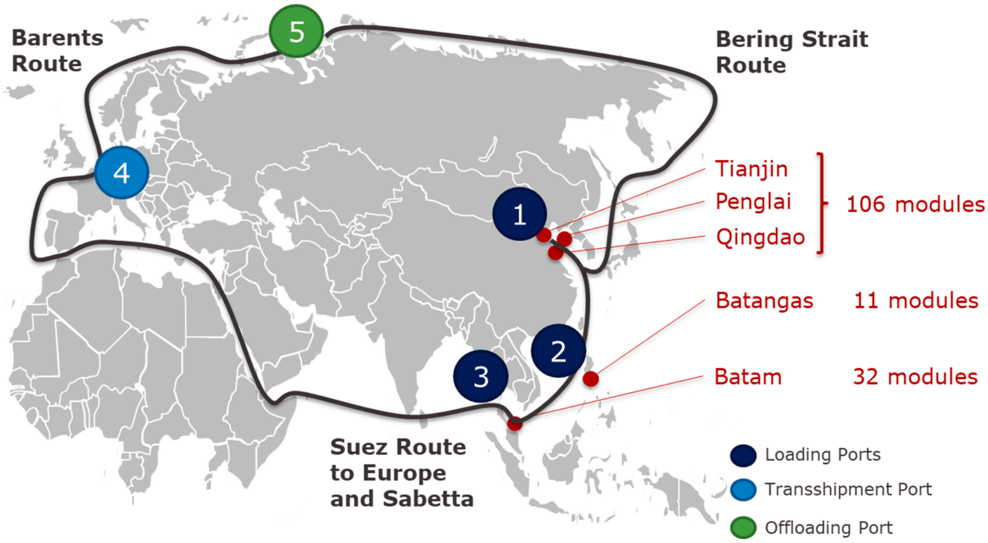

Fig. 1. Shipping routes and main ports. Source: Authors.

used at the time were provided by the industry partner, as the POLARIS risk index was not available then.

In this paper, we present the problem formulation and use the POLARIS risk index to generate new input data into the model, to investigate the impacts that changing ice conditions and alternative fleets may have on the project costs and schedule.

In the formulation presented hereafter, we merge the three yards in China, as one, due to their geographical proximity, located in Tianjin. Vessels could reach Sabetta either via the Suez Canal and the Barents Sea or navigating along the NSR via the Bering Strait. Alternatively, they could be transshipped in the Modular Intermediate Storage Yard (MISY) at the Port of Zeebrugge, (Belgium). As shown in Fig. 1, Chinese ports are represented as node 1, the Philippine port (Batangas) as node 2, the Indonesian port (Batam) as node 3, European transshipment port as node 4 and the destination port, Sabetta, as node 5. Each module had an expected production date and an expected date of arrival at the assembly site. Around 30% of the modules had other modules as predecessors, requiring a strict synchronization of deliveries between them.

Previous shipping schedules were built manually, which would not allow for a systematic control of the shipping constraints, or for scenario testing with recurring hypothesis changes. Typically, the vessel fleet and the modules' attributes (quantity, size, predecessors, production yards and delivery dates) could change from one schedule version to another, requiring recurrent redesigns of shipping schedules. Data collection was carried out through meetings and focus groups, mostly in the first half of 2015.

3.2. Decision support system description

The problem can be described as a strategic, tactical routing and scheduling one, with a heterogeneous vessel fleet (attributes: length, width, draft, ice class, costs, and charter contract), strict time windows for production dates at loading ports (no shipment before production), shipping route and time-charter vessel availability and changing navigability conditions.

The model minimizes an objective function that considers vessel mobilization costs (fixed, and applied to long-term time charter vessels only), chartering costs, fuel costs, port dues, piracy costs, Suez Canal fees, NSR fees and the costs of delay, also called inconvenience cost. The cost of the delay is arbitrary, however it is set high enough to ensure that the cost of a 1-week delay will prevail over the shipping costs difference between the Suez and Bering routes, as schedule adherence was defined as a priority in this project. The Self-Propelled Modular Transporters (SMPT) costs which have no influence on the route allocation decision in this model, are not included in the objective function and are calculated in the post-processing stage.

Navigability conditions in polar waters are defined according to POLARIS (IMO, 2016; Fedi et al., 2018b). These conditions define whether the vessel is allowed to navigate along the NSR and at which speed. As POLARIS gives a clear approach of the risk level along the route (Stoddard et al., 2018), the model ensured that the vessel would not leave the departure port towards Sabetta if it would not be able to return before the end of the allowed navigability period. These periods are calculated in the pre-processing stage.

The model uses a discrete approach for time with 200 periods of one week each. This modelling approach offered the flexibility to include many time-based real-life constraints such as route changing costs and forbidden periods due to ice. The week was used as the time unit because the existence of many project uncertainties over its duration of three years, did not justify a daily approach.

It is worth mentioning that the formulation presented hereafter is a general one that can be used for more than three production sites located in different locations. However, if the number of ports in the network is large, then a heuristic solution approach would be required.

3.3. Mathematical formulation

3.3.1. Problem description

Presume a modular plant is to be built/assembled in the Russian Arctic using a set M of modules. The modules are manufactured in a set of production sites in Asia and have to be shipped to be assembled on site. The production sites cannot produce all the modules at the same time and these modules must be delivered on the assembly site following a certain order (synchronicity) that depends on the assembly plan of the plant. Any delay in a module delivery or any delivery in advance of the schedule may lead to delay costs. Moreover, a module cannot be delivered before the previous delivery of all its predecessor modules into the assembly site.

Moreover, the modules that have to be transported can be loaded, based on their design, either on the left-hand side of the vessel decks, on the right-hand side, or they occupy both sides due to their width.

The project has a given total duration (T) that may be divided into periods (weeks) in order to carry out the delivery scheduling of the modules. The modules can be shipped from their production sites to the assembly site using a fleet of available long-term chartered vessels V_c and if necessary another set of vessels that can be hired from the spot market based on a short-term chartering contract V_s. The available vessels are of different ice types and based on the sailing conditions, especially in the NSR part of the routes, their sailing speed varies. Moreover, a transshipment site (Belgium) can be used where the modules may be transshipped between open water vessels transporting them from Asia into ice class vessels that will carry them to their assembly sites. However, the modules may be transported directly from their production sites in Asia to their delivery sites in the Russian Arctic, using appropriate vessels following the navigation period, either passing along the Bering Strait Route or the SCR. A vessel may start its route in one of the Asian ports, call at other Asian ports to collect more modules and then sails either to the transshipment hub to transship the modules or to the Russian Arctic directly (SCR or Bering Strait Route) and then back either to Europe or to one of the Asian ports.

The vessel type (long-term VS short-term chartered vessels), ice class (open-water, 1A or PC3) and engine size, as well as the ice conditions in the NSR sailing zones determine the vessel sailing speeds and therefore sailing time. This also determines the fuel consumption and chartering cost, the need for ice-breaker assistance and its related cost, the Suez Canal and other fees, and the fixed cost of every vessel for every trip.

The problem is then to find the best delivery schedule of the modules from their points of origin in Asia to their point of assembly in the Russian Arctic so that the total shipping costs (including fuel cost, vessel chartering costs (long-term and short-term), fixed operating costs, and Suez Canal fees and ice-breaker assistance costs) and the project delay costs (including all the module delay or advance costs) are minimized.

This problem is complex since it requires selecting the fleet to be used from a combination of different vessel types (long-term VS short-term charter) and vessel ice classes (open-water, 1A or PC3), then choosing the route and the departure date for every ship eastbound (Russia or Europe to Asia) and westbound (Asia to Russia or to Europe) or between Europe and Russia. It also determines which modules will be loaded on which ships and at which period while considering some managerial and technical constraints including vessel capacity, module synchronicity, delivery schedule and the depth of the ports of call.

The problem is very difficult to be solved, above all when the number of vessels and modules and their delivery time windows are large. Large-scale routing and scheduling problems are seen as a considerable challenge and tend to be solved using heuristics and in particular column generation approaches, where routes (sequences of port calls) are generated a priori for each ship (Homsi et al., 2020). This approach relies on effective ways to generate routes, while preserving the exhaustiveness of the search. However, the number of routes increases with the introduction of transshipments in the problem (or split loads), and this type of problems has only been solved in the literature for small and medium instances (Andersson et al., 2011; Lee and Kim, 2015). Furthermore, given the configuration of the network of ports considered in this study, it is possible to have routes with many short shipping voyages with backhauls between nodes 4 and 5 during the duration of the project (3 years), creating thus a combination of port calls that increases the number routes to a point where this approach seemed impractical.

In many problems, routes with transshipments and backhauls are easily dominated by other routes, however, in our case, with the closure of routes in winter for some vessels and given the limited availability of PC3 vessels that have the ability to make the final delivery in Sabetta (node 5) in winter, we considered that combinations of direct shipments with transshipments in MISY should be investigated thoroughly. Furthermore, formulations where time is modelled as a continuous variable consider a single time window on arrival per cargo, whereas the cargoes in this paper could have multiple ones, given that the project spanned over many winter seasons (three more precisely). Allowing long delays on a limited number of unconstrained cargoes was considered an option worth investigation. Finally, we had to consider the capacity constraint in Sabetta port, where only up to four vessels could call simultaneously. Therefore, to deal with these specificities we propose to model this problem using integer linear programming with discretized time and we use the POLARIS system to define the vessel speed and accessibility in the NSR zones.

3.3.2. Model sets

We define the following sets:

- I: set of nodes indexed i, j and k. It consists of the subsets I_P, I_A and I_T representing the subsets of production sites/ports, arctic destination port(s), and transshipment hub(s) respectively.

For the purpose of the case study detailed earlier in Sections 3.1 and 3.2, and as shown in Fig. 1, the indices of set I take the following values: 1 for Tianjin (China), 2 for Batangas (Philippines), 3 for Batam (Indonesia), 4 for Zeebrugge (Belgium) and 5 for Sabetta (Russia). The index I_A takes the value of 5 and the index of I_T the value of 4. However, the model is general enough to consider more ports in the subset I_P in case more production sites are to be considered.

- V: set of vessels with index v, that consists of the subsets V_c and V_s of the long-term and short-term chartered vessels respectively.
- R: set, indexed with r, of all possible routes that a vessel may use between the Asian ports on one hand and the transshipment hub or the Russian port on the other hand, or between the transshipment hub and the Russian port and vice-versa. $R = R^{R2} \cup R^{B2} \cup R^{C2} \cup R^{P2} \cup R^{I2}$ with:
  - o R^{R2},R^{B2},R^{C2},R^{P2},R^{I2}: sets of routes having the Russian port (Sabetta), the transshipment port (Belgium), and the three production sites respectively (China, Philippines, and Indonesia) as last port of call (destination). It is worth noting that R can consist of any other subsets that may correspond to another combination of production sites for example.

If more production sites are to be considered, then R will include more subsets of routes originating from or having destination in these sites.

The elements in R (routes) are of three categories:

- o Eastbound (sets R^{C2},R^{P2},R^{I2}): the elements in these sets are $x_l^{i,SCR}$, with $i \in I_P$ and $l \in \{I_A \cup I_T\}$ and $x_l^{i,NSR}$ with $i \in I_P$ and $l \in I_A$ and they represent the direct route between l and i along the SCR or the Bering Strait Route respectively. For example, $x_4^{1,SCR}$ is the direct route between Zeebrugge (4) and Tianjin (1) and that sails via the SCR.
- o Transshipment (R^{B2}): the elements in this set are $y_i^{l,SCR}, z_{i,j}^{l,SCR}, e_{i,j,k}^{l,SCR}$ with $i,j,k \in I_P$ and $i \neq j \neq k$ and $l \in I_T$ and $y_i^{l,NSR}$ with $i \in I_A$ and $l \in I_T$. For example, $z_{i,j}^{4,SCR}$ is the route that leaves port i calls at port j and has as destination port 4 and that passes along the SCR. All the routes of R^{B2} pass via the SCR, except $y_5^{4,NSR}$.
- o Delivery (R^{R2}): the elements of this set are $q_i^{l,P}, r_{i,j}^{l,P}, s_{i,j,k}^{l,P}$ with $i,j,k \in I_P$, $i \neq j \neq k$, $l \in I_A$, and $P \in \{SCR, NSR\}$ and $q_i^{l,NSR}$ $i \in I_T$ and $l \in I_A$. For example, $q_1^{5,SCR}$ is the direct route along the SCR between Tianjin (1) and Sabetta (5) that does not call at any other port.

It is worth noting that these same routes are also elements of the following sets as well:

- o R^{R1}, R^{B1}, R^{C1}, R^{P1}, R^{I1}: sets of routes having the Port of Sabetta (Russia), Zeebrugge (Belgium), Tianjin (China), Batangas (Philippines), and Batam (Indonesia) as first port of call (departure) respectively.

More generally, route $q_i^{l,P}$ is the direct route between i and l along P, while route $r_{i,j}^{l,P}$ is the route that leaves i, calls at j and has l as port of destination along P, with $i,j \in I_P$, $l \in \{I_A \cup I_T\}$ and $P \in \{SCR, NSR\}$. Finally, $s_{i,j,k}^{l,P}$ is similar to $r_{i,j}^{l,P}$ but with an additional call at port j between i and k.

- M^{CLS}, M^{PLS}, M^{ILS}: set of modules that are classified in the pre-processing stage to be loaded on the left side of the vessel deck and that have Tianjin (China), Batangas (Philippines), and Batam (Indonesia) as port of origin, respectively.
- M^{CRS}, M^{PRS}, M^{IRS}: set of modules that are classified in the pre-processing stage to be loaded on the right side of the vessel deck and that have Tianjin (China), Batangas (Philippines), and Batam (Indonesia) as port of origin, respectively.
- M^{CBS}, M^{PBS}, M^{IRS}: set of modules that are classified in the pre-processing stage to be loaded on both sides of the vessel deck, i.e. with a width exceeding 50% of the vessel width, and that have Tianjin (China), Batangas (Philippines), and Batam (Indonesia) as port of origin, respectively.
- M: set of all modules with all origins and loading side.
- M^{LS},M^{RS},M^{BS}: sets of modules from any origin port and that can be loaded on the left side, right side, or both sides respectively.
- M_p^m: set of predecessor modules of module $m \in M$, indexed with m_p, containing up to 5 pre-defined modules.
- H: set of time periods (weeks) in the planning horizon indexed with $t = 1, \cdots, T$.

3.3.3. Model decision variables

Three types of decision variables are used:

$$\chi_{vrt} = \begin{cases} 1, \text{if vessel } v \text{ takes route } r \text{ at time } t \\ 0, \text{otherwise} \end{cases} ; v \in V; r \in R; t \in H.$$

$$\omega_v = \begin{cases} 1, \text{if chartered vessel } v \text{ is used at least once during the planning horizon} \\ 0, \text{otherwise} \end{cases} ; v \in V_C.$$

$$\psi_{mrt}^{v} = \begin{cases} 1, \text{if module } m \text{ takes route } r \text{ onboard vessel } v \text{ at time } t \\ 0, \text{otherwise} \end{cases} ; v \in V; r \in R; m \in M; t \in H.$$

3.3.4. Model parameters

- f_v^c: fixed chartering cost for the whole planning horizon T of the long-term chartered vessel $v \in V_C$ (mobilisation and demobilisation costs, time charter rate, standby fuel consumption) [USD].
- c_{vrt} [USD/trip]: average variable costs of vessel v navigating along route r with a departure in period $t \in H$. For the long-term chartered vessels, this cost includes different route fees, f_{vrt}^{Fees}, in addition to the fuel cost, f_{vrt}^{Fuel}.

For the short-term chartered vessels, i.e. vessels hired from the spot market, c_{vrt} consists in the daily spot cost multiplied by the number of days of navigation along route r, which results in f_{vrt}^{S}, in addition to different route fees, f_{vrt}^{Fees}. It is expressed as:

$$c_{vrt} = \begin{cases} f_{vrt}^{Fuel} + f_{vrt}^{Fees}; v \in V_C \\ f_{vrt}^{S} + f_{vrt}^{Fees}; v \in V_S \end{cases}; r \in R.$$

It is worth noting that route fees include port dues, Suez Canal fees and piracy protection. In addition, f_{vrt}^{Fuel} is calculated based on the vessel type and therefore the engine size, the day of departure of the trip, the selected route and the ice conditions which imply the sailing speed. Finally, the cost of the short-term chartered vessel for the selected route (f_{vrt}^{S}) has a fixed rate per day based on the spot market rate, that is paid to the shipping company, and depends on the number of sailing days of the trip.

- a_v^l, a_v^u: lower and upper bounds of the availability period of the chartered vessel $v \in V_C$, with $a_v^l, a_v^u \in H$, and $a_v^l \le a_v^u$.
- w_v^{draft}: draft of vessel $v \in V$ [meters].
- L_v^{deck}: deck length of vessel $v \in V$ [meters].
- d_{vrt}^{time}: a parameter that is equal to 1 if the departure of vessel $v \in V$ is allowed in period $t \in H$ on route $r \in R^5$, and 0 otherwise due to ice constraints. It is determined in the pre-processing stage.
- d_{vrt}: total duration of route $r \in R$ including the sailing time by vessel $v \in V$ and the port times between the first port in the route and the destination port with a departure in period $t \in H$ [weeks].
- $d_{ij,t}^{v,r}$: total duration of the direct sailing between port $i \in I$ and port $j \in I$ by vessel $v \in V$ including half the port times of both ports with a departure in period $t \in H$ and using route $r \in R$ [weeks].
- $d_{r,t}^{i,v}$: total duration of the part of route $r \in R$ that is between port $i \in I_P$ and the destination port (one of the ports in $\{I_A \cup I_T\}$) by vessel $v \in V$ including the port times with a departure in period $t \in H$ [weeks].
- p_i^t: port time in port $i \in I$ [weeks].
- h_i: depth of port $i \in I$ [meters].
- K_i^t: available capacity of port $i \in I$ in period $t \in H$ [number of quays].
- o_m: origin port of module $m \in M$ with $o_m \in I_P$.
- g_m: length of module $m \in M$ [meters].
- d_m^{Trans}: total required time for the transshipment of module $m \in M$ in the transshipment hub [weeks].
- p_m^{ROS}: requested on site delivery date of module $m \in M$ [weeks].
- p_m^{RSA}: ready for sailing away of date of module $m \in M$ [weeks].
- d_m^{Max}, a_m^{Max}: maximum acceptable delay and advance respectively in the delivery date of module $m \in M$ [weeks].
- f_d^m: costs of delay per time unit of module $m \in M$ [USD/week].

3.3.5. Integer linear programming model

As previously explained in Section 3.2, the aim of the model is to find the optimal solution for the scheduling and shipping from Asia of heavy modules for an energy construction project located in Sabetta, while considering the sailing risks related to ice conditions. The optimal solution minimizes shipping costs and delay costs, and includes the fleet to be used, the selected route for every vessel, the schedule of delivery (loading and unloading) for every module and on which vessel every module will be shipped.

Hence, the problem is formulated as follows:

The objective function (1) minimizes the total fixed and variable costs of the vessels and the delay costs of the modules.

$$Min z = \sum_{v \in V} \sum_{r \in R} \sum_{t \in H} c_{vrt} \chi_{vrt} + \sum_{v \in V_C} f_v^c \omega_v + \sum_{v \in V} \sum_{m \in M} f_d^m \sum_{r \in R^{R2}} \sum_{t \in H} \psi_{mrt}^v \left(t + d_{r,t}^{o_m,v} - p_m^{ROS} \right) \tag{1}$$

The first term in Equation (1) represents the total variable costs for all the used vessels including the fuel cost for the long-term chartered vessels, the daily charter cost multiplied by the trip duration for the short-term chartered vessels (spot market vessels), icebreaker assistance and Suez Canal fees. The second term represents the total fixed cost for all the long-term chartered vessels. The third term represents the total advance or delay costs of all the shipped modules compared to their schedule. It is worth noting that the advance will be privileged (negative value in the objective function) within the maximum acceptable limit fixed by a_m^{Max} and by constraint (6) explained later. If the advance delivery is not acceptable for module m, then a_m^{Max} can simply be set at zero.

s.t.

Constraints (2) makes sure that all modules arrive at the destination port.

$$\sum_{v\in V}\sum_{r\in R^{R2}}\sum_{t\in H}\psi^{v}_{mrt}=1,\quad m\in M \tag{2}$$

Constraints (3) ensure that any module that is transshipped in the transshipment hub, i.e. node 4 (Belgium), leaves that port for the destination port.

$$\sum_{v\in V}\sum_{r\in R^{B2}}\sum_{t\in H}\psi^{v}_{mrt}=\sum_{v\in V}\sum_{t\in H}\psi^{v}_{m\left(q_i^{l,NSR}\right)t},\quad m\in M,i\in I_T,l\in I_A \tag{3}$$

Constraints (4) guarantee that the modules leave after their Ready For Sailing Away (RFSA) date.

$$\sum_{r\in R}\sum_{t\in H}y^{v}_{mrt}t\geq p_m^{RSA},\quad m\in M,v\in V \tag{4}$$

Constraints (5)-(6) ensure that the modules arrive within a predefined maximum allowed advance or delay from their Required-On Site (ROS) date

$$\sum_{r\in R^{R2}}\sum_{t\in H}\psi^{v}_{mrt}\left(t+d_{r,t}^{o_m,v}\right)\leq p_m^{ROS}+d_m^{Max},\quad m\in M,v\in V \tag{5}$$

$$\sum_{r\in R^{R2}}\sum_{t\in H}\psi^{v}_{mrt}\times\left(t+d_{r,t}^{o_m,v}\right)\geq p_m^{ROS}-a_m^{Max},\quad \forall m\in M,\forall v\in V \tag{6}$$

Constraints (7) prevent the transshipped modules from leaving Europe before a transshipment period after their arrival.

$$\sum_{t\in H}\psi^{v}_{m\left(q_i^{l,NSR}\right)t}t\geq\sum_{r\in R^{B2}\setminus\left\{y_l^{i,NSR}\right\}}\sum_{t\in H}\psi^{v}_{mr\left(t-d_{r,t}^{o_m,v}\right)}\left(t-d_{r,t}^{o_m,v}-d_m^{Trans}\right),\quad m\in M,v\in V,i\in I_T,l\in I_A \tag{7}$$

Constraints (8) ensure the synchronicity of modules on arrival at the destination port (Sabetta). Indeed, due to the nature of the project, some modules cannot be delivered before other modules have already been delivered to the assembly site in Sabetta. Therefore, synchronicity between the modules is related to the existence of this precedence constraint between some modules that defines the order of delivery to the assembly site in Sabetta.

$$\sum_{r\in R^{R2}}\sum_{t\in H}\psi^{v}_{mrt}\left(t+d_{r,t}^{o_m,v}\right)\geq\sum_{r\in R^{R2}}\sum_{t\in H}\psi^{v'}_{m_prt}\left(t+d_{r,t}^{o_{mp},v'}\right),\quad m\in M,m_p\in M_p^m,v,v'\in V \tag{8}$$

In this context, constraints (8) ensure that module m is delivered after all its predecessors $m_p\in M_p^m$ have been delivered to Sabetta.

Constraints (9) assure that the ship does not leave the departure port towards the Arctic destination (i.e Sabetta) if she will not be able to return before the end of the allowed navigability period where the ice is not too thick. The values of d_{vrt}^{time} are calculated in the pre-processing stage.

$$\chi_{vrt}\leq d_{vrt}^{time},\quad v\in V,r\in R^{R2},t\in H \tag{9}$$

Constraints (10) maintain every ship in at most one route in every period.

$$\sum_{r\in R}\sum_{t\in H}\chi_{vrt}\leq 1,\quad v\in V \tag{10}$$

Constraints (11)-(12) ensure the flow conservation for the vessels in the first node of the network, i.e. Tianjin (1), which means that a vessel cannot leave node 1 in a period if it did not reach it earlier. More specifically, the departure time from the port should be later than the departure time of the preceding trip towards this same port plus the duration of the trip and the port time.

$$\sum_{r\in R^{C1}}\chi_{vrt}\leq\sum_{r\in R^{C2}}\sum_{l=d_{vrt}+p_1^{time}+1}^{t}\chi_{vr\left(l-d_{vrt}-p_1^{time}\right)},\quad v\in V,t\in H \tag{11}$$

$$\sum_{r\in R^{C1}}\chi_{vrt}t\geq\sum_{r\in R^{C2}}\chi_{vrl}\left(l+d_{vrt}+p_1^{time}\right),\quad v\in V,t\in H,l\in H,l<t \tag{12}$$

Constraints (11)–(12) must be added for all the other ports, i.e. in this case study to all the four ports, by replacing p_1^{time} with the corresponding port time and R^{C1} and R^{C2} by the corresponding sets.

Constraints (13)-(14) assert that charter vessels are used during their availability period.

$$\chi_{vrt}(t+d_{vrt})\leq a_v^u,\quad v\in V_C,t\in H,r\in R \tag{13}$$

$$\chi_{vrt}(t+d_{vrt})\geq a_v^l,\quad v\in V_C,t\in H,r\in R \tag{14}$$

Constraints (15) state that a ship can call at the first node in the network, i.e. Tianjin (node 1) in this case study, if her draft is less than the port depth.

$$\psi_{vrt} w_v^{draft} \leq h_1, \quad v \in V, t \in H, r \in R^{C1} \tag{15}$$

Constraint (15) must also be included for all the other ports in the network by replacing h_1 by the corresponding value and R^{C1} by the corresponding set.

Constraints (16) ensure that the total length of the loaded modules (that were classified as left-sided or both-sided modules in the pre-processing stage) onboard a vessel that has node 1 (i.e. Tianjin) as first port of call, does not exceed the vessel's deck length.

$$\sum_{m\in\{M^{LS},M^{BS}\}} g_m \psi^v_{mrt} + \sum_{m\in\{M^{LS},M^{BS}\}} g_m \psi^v_{mr\left(t+d^{v,r}_{1j,t}+p^{time}_j\right)} + \sum_{m\in\{M^{LS},M^{BS}\}} g_m \psi^v_{mr\left(t+d^{v,r}_{1j,t}+p^{time}_j+d^{v,r}_{jk,t}+p^{time}_k\right)} \leq \chi_{vrt} L^{deck}_v, \quad t \in H, v \in V, r \in R^{C1}, j \in I_P \setminus \{1\}, k \in I_P \setminus \{1\} with k \neq j \tag{16}$$

Constraint (16) must also be added for the other two Asian ports by replacing $d^v_{1j,t}$ by $d^v_{2j,t}$ and $d^v_{3j,t}$ respectively and changing R^{C1} with the corresponding sets, and the domain of the definition of j and k accordingly.

Constraints (17) play the same role for the right-sided and both-sided modules.

$$\sum_{m\in\{M^{RS},M^{BS}\}} g_m \psi^v_{mrt} + \sum_{m\in\{M^{RS},M^{BS}\}} g_m \psi^v_{mr\left(t+d^{v,r}_{1j,t}+p^{time}_j\right)} + \sum_{m\in\{M^{RS},M^{BS}\}} g_m \psi^v_{mr\left(t+d^{v,r}_{1j,t}+p^{time}_j+d^{v,r}_{jk,t}+p^{time}_k\right)} \leq \chi_{vrt} L^{deck}_v, \quad t \in H, v \in V, r \in R^{C1}, j \in I_P \setminus \{1\}, k \in I_P \setminus \{1\} with k \neq j \tag{17}$$

Constraint (17) must also be repeated for the routes that originate from the other Asian ports.

Constraints (18)-(19) play the same role for the vessels sailing between the transshipment hub (i.e. node 4) and the Arctic destination (i.e. node 5).

$$\sum_{m\in M^{LS}} g_m \psi^v_{mq_i^{l,NSR}t} + \sum_{m\in M^{BS}} g_m \psi^v_{mq_i^{l,NSR}t} \leq \chi_{vrt} L^{deck}_v, \quad v \in V, t \in H, i \in I_T, l \in I_A \tag{18}$$

$$\sum_{m\in M^{RS}} g_m \psi^v_{mq_i^{l,NSR}t} + \sum_{m\in M^{BS}} g_m \psi^v_{mq_i^{l,NSR}t} \leq \chi_{vrt} L^{deck}_v, \quad v \in V, t \in H, i \in I_T, l \in I_A \tag{19}$$

Constraints (20) secure that the number of ships calling at the first port in the network (i.e. Port of Tianjin) in any period is less than or equal to the number of available quays in that port.

$$\sum_{P\in\{SCR,NSR\}} \left(\sum_{l\in\{I_T\cup I_A\}} \sum_{v\in V} \sum_{r\in\left\{z^{l,P}_{j,i}, r^{l,P}_{j,i}, e^{l,P}_{j,i,k}, s^{l,P}_{j,i,k}\right\}} \chi_{vr\left(t-d^v_{ji,t}\right)} + \sum_{l\in\{I_T\cup I_A\}} \sum_{v\in V} \sum_{r\in\left\{z^{l,P}_{k,i}, r^{l,P}_{k,i}, e^{l,P}_{k,i,j}, s^{l,P}_{k,i,j}\right\}} \chi_{vr\left(t-d^v_{ki,t}\right)} + \sum_{l\in I_T} \sum_{v\in V} \chi_{ve^{l,P}_{k,j,i}\left(t-d^v_{kj,t}-d^v_{ji,t}\right)} + \sum_{l\in I_T} \sum_{v\in V} \chi_{ve^{l,P}_{j,k,i}\left(t-d^v_{jk,t}-d^v_{ki,t}\right)} + \sum_{l\in I_T} \sum_{v\in V} \chi_{vy^{i,P}_l\left(t-d^v_{li,t}\right)} + \sum_{l\in I_A} \sum_{v\in V} \chi_{vs^{l,P}_{k,j,i}\left(t-d^v_{kj,t}-d^v_{ji,t}\right)} + \sum_{l\in I_A} \sum_{v\in V} \chi_{vs^{l,P}_{j,k,i}\left(t-d^v_{jk,t}-d^v_{ki,t}\right)} + \sum_{l\in I_A} \sum_{v\in V} \chi_{vq^{i,P}_l\left(t-d^v_{li,t}\right)} \right) \leq K^t_i, \quad i=1, j,k\in I_P\setminus\{1\}, j\neq k, t\in H \tag{20}$$

Constraints (20) must also be included for the other Asian ports by replacing i and j and k accordingly.

Constraints (21)-(22) play the same role for the transshipment hub (i.e. Zeebrugge) and the Arctic destination port (i.e. Sabetta) respectively.

$$\sum_{v\in V} \sum_{r\in R^{B2}} \chi_{vr(t-d_{vrt})} \leq K^t_i, \quad t \in H, i \in I_T \tag{21}$$

$$\sum_{v\in V} \sum_{r\in R^{R2}} \chi_{vr(t-d_{vrt})} \leq K^t_i, \quad t \in H, i \in I_A \tag{22}$$

Constraints (23)-(25) ensure that in every period of the planning horizon, only one vessel can depart from any loading port located in Asia.

Table 1
Risk Index Values.

Categories	Ice Class	Ice Free	New Ice	Grey Ice	Grey White Ice	Thin First Year Ice, 1st	Thin First Year ice, 2nd	Medium First Year Ice	Medium First Year Ice 2nd	Thick First Year Ice	Second Year Ice	Light Multi Year Ice	Heavy Multi-Year Ice
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
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
Cat. C	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
	Not IS	3	1	0	−1	−2	−3	−4	−5	−6	−7	−8	−8
		Normal operation		Low speed		Ice Breaker escort		Ice Breaker escort at low speed		Operation not permitted			

Source: Authors based on IMO (2016) and DNV GL[1]
[1]https://www.dnvgl.com/maritime/polar/services.html.

Table 2
Risk Index Outcome Criteria.

RIOSHIP	Ice Class PC1-PC7	Vessels with a class below PC7 and ships not assigned an ice class
RIO≧0	Normal operations	Normal operation
−10≦RIO < 0	Elevated operational risk	Operation subject to special consideration
RIO≦-10	Operation subject to special consideration	Operation subject to special consideration

Source: Authors Based on IMO (2016).

$$\sum_{v\in V}\sum_{r\in R^{C1}}\chi_{vrt}\leq 1, \quad t\in H, \tag{23}$$

$$\sum_{v\in V}\sum_{r\in R^{P1}}\chi_{vrt}\leq 1, \quad t\in H, \tag{24}$$

$$\sum_{v\in V}\sum_{r\in R^{I1}}\chi_{vrt}\leq 1, \quad t\in H, \tag{25}$$

Constraints (26) guarantee that the decision variable ω_v is equal to one if the vessel v is used in at least one route in any period.

$$\omega_v \geq \chi_{vrt}, \quad v\in V, t\in H, r\in R \tag{26}$$

Constraints (27) enforce the integrality of the decision variables.

$$\chi_{vrt}, \omega_v, \psi^{v}_{mrt} \in \{0,1\}, \quad v\in V, t\in H, r\in R, m\in M \tag{27}$$

It is worth noting that in constraints (16)-(22), an approximation is used for the calculation of the duration of the trip for a given route or between two ports, based on a departure date not necessarily corresponding to the real departure date. Moreover, this approximation may have an effect only on the vessels that take the Bering Strait Route, but not the other routes.

3.4. Navigation assumptions

3.4.1. Sailing speed in ice and navigability period

In Arctic regions, the vessel speed depends on exogenous and endogenous parameters. In our case, the exogenous elements considered are the ice thickness and concentration faced by the vessel during its journey, while the endogenous factors are the vessel nominal speed and its ice class or Polar Class. The PC ranks vessels in three categories: A, B and C (DNV-GL, 2017; Fedi et al., 2018b). Vessels in categories A and B are Polar Class (PC) vessels. Those in category A (PC1 to PC5) have a year-round operation capability, and those in category B (PC6-PC7) have summer and autumn operating capability. Vessels in category C have smaller operation capabilities: they can be either ice class vessels, able to navigate in thin ice only (such as 1A or 1B vessels) or vessels that are not ice-strengthened, and therefore can only sail in open water conditions.

The Arctic Ocean can be composed of numerous types of ice (WMO, 1970; JCOMM, 2014) with different densities, which have an

Table 3
Speed level depending on Risk Index Outcome (RIO).

Vessel name	Class[1]	Design speed in knots (RIO = 30)[1]	Minimum speed for an independent navigation in knots (RIO = 0)[2]	Speed at its technical limit in knots[3]
Audax	PC3	13	8	5
Big Roll1	1A	13.5	8	3
Xiang Yun Kou	Not Ice class	13	8	3

Source: based on [1] Clarksons database (2018), [2] Faury et al. (2020), [3] IMO (2016).

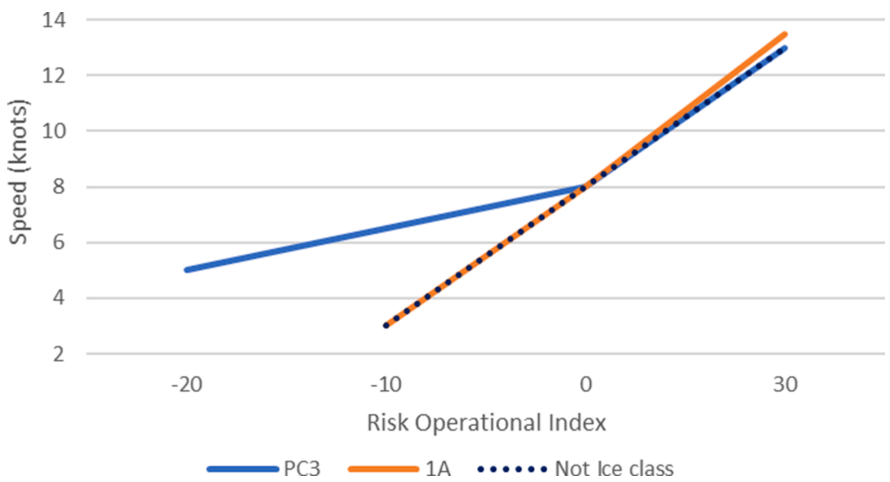

Fig. 2. Vessels' speed depending on their class and RIO when sailing independently or assisted by an icebreaker. Source: Authors.

impact on the vessel speed and its ability to sail within a defined zone. To determine the ship speed, we used the POLARIS System and the Risk Index Value (RIV), which depends on the type of ice and the vessel class as shown in Table 1 (IMO, 2016).

From the RIV, the Risk Index Outcome (RIO) is then calculated as follows: $RIO = (RIV_1.C_1) + (RIV_2.C_2)\cdots\cdots\cdots. + (RIV_n.C_n)$, where RIV_n is an index representing the capacity of the hull to be manoeuvrable within a defined type of ice. C_n is the concentration in tenth of this typology of ice within the area analyzed. The resulting RIO will range from 30 (best conditions) and −80 (worst conditions).

The IMO provides a recommended speed (which in this paper is the minimum speed) depending on ice conditions and vessel Polar Class, and hence the level of RIO encountered during navigation (IMO, 2016).

The maximum vessel speed, i.e. its design speed, is considered as the optimal one. The ship is assumed to sail at her design speed when her RIO is at its maximum (30). When the RIO reaches 0, icebreaker assistance may be required depending on the capacity of the hull to resist ice. For this situation, we relied on Faury et al. (2020) who showed that the nominal speed of an ice class 1A or 1AS vessel is 8 knots.

In accordance with the "Guidance on methodologies for assessing operational capabilities and limitations in ice" (IMO, 2016), we consider that ice class vessels (1A in this paper) in Table 2 are limited to a minimum RIO of −10 and are not allowed to sail below this value. Furthermore, section 1.4 of IMO (2016) explains that when Polar Class vessels (PC3 in this paper) sail with an RIO between 0 and −10, they should decrease the speed. At the intermediate RIO value of −10, the speed shall be 5 knots. When the ship is assisted by an icebreaker with an RIO equal to 10, we assume that the icebreaker has an RIO of +10, and that it is able to sail until the PC3 RIO reaches −20. However, at this level, PC3 vessels sail at the minimum speed required to be able to maintain maneuverability (Kitigawa et al., 2001).

Based on available data, a fleet composed of PC3, 1A and vessels that are not ice-strengthened was contemplated. Table 3 summarizes the different considered values and the vessel names used to assess the sailing speed.

In line with Marchenko (2014) and Zhang et al. (2020) who showed that an unsuitable speed could lead to an accident, we assumed that the vessel speed shall be correlated to the RIO in accordance with POLARIS. Based on three speed levels (Table 3), and on the fact that with a greater risk, in other words a decrease RIO value, the vessel may have to decrease its speed, we considered that a linear regression would provide us with a reliable way to define the speed depending on the different possible RIO values during the journey. This assumption resulted in the speed-RIO correlation presented in Fig. 2.

Ice classes 1A and non-ice class vessels have in common the fact that they have to be assisted by an ice breaker when their RIO value is below 0 (IMO, 2016). Yet, a PC3 vessel is able to choose whether to be assisted by an icebreaker or to sail on its own. When it is assisted by an Artika class icebreaker it can sail in harsher conditions with an RIO of −20, but due to these more complex sailing conditions, its speed becomes 5 knots, which is considered as the minimum speed that permits its maneuverability.

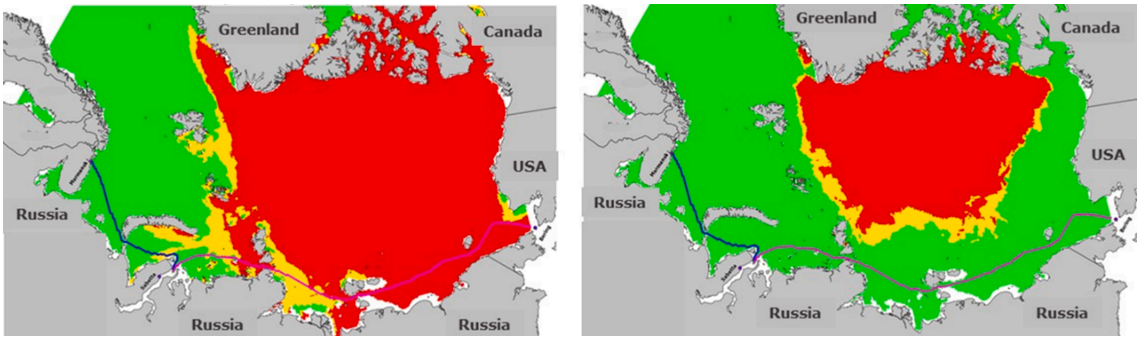

Fig. 3. Navigability risk assessment on March 1st (left) and September 16th (right) for an 1A Vessel transiting the NSR. Key: Red = No go; Orange = Ice-breaker escort; Green = Go. Production: Authors. Dataset: Copernicus - Arctic_Reanalysis_Phys_002_003. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

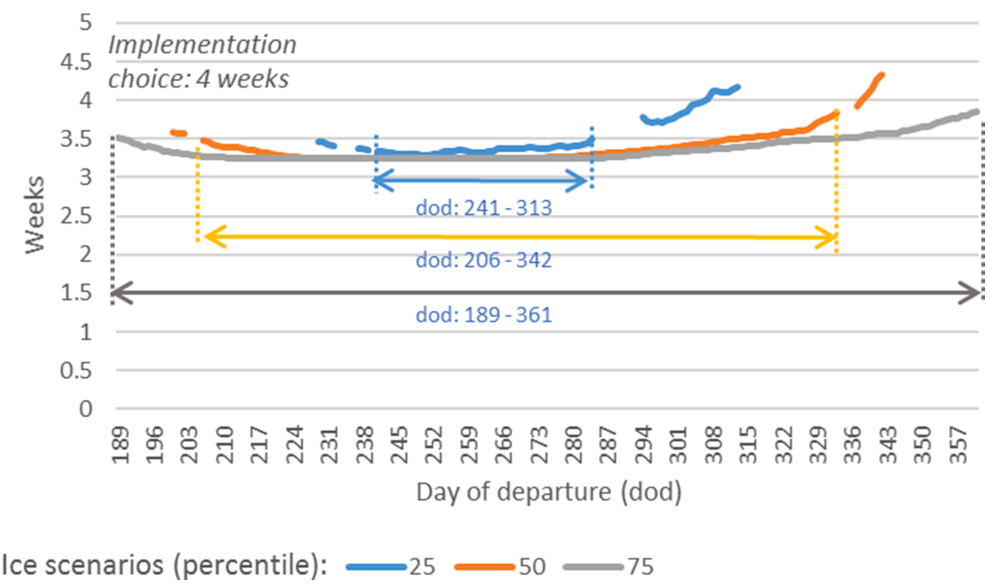

Fig. 4. Sailing duration and allowed navigability periods for a 1A vessel on the Tianjin – Sabetta route depending on the Day of Departure, for the 25th, 50th, and 75th percentiles of ice conditions of the past 25 years. Nominal speed assumed. Source: Authors.

The European Copernicus Marine Repository provides different historical datasets describing the Arctic Sea environment. The TOPAZ4 Arctic Ocean Physics Reanalysis provides 3D physical ocean and sea ice variables. The TOPAZ Reanalysis System assimilates available satellite and in situ observations available over the period 1991–2015. The ARCTIC_REANALYSIS_PHYS_002_003 dataset (Von Schuckmann et al., 2017) was downloaded from Copernicus. This dataset describes daily sea ice concentration and thickness of the full Arctic Ocean using a 12.5 × 12.5 km raster grid for 25 years (1991–2015).

The POLARIS Risk Index Values (RIV) are computed as described above, for every date (25 years × 365 days), grid cells (140 835) and different ship ice classes (12). For each grid cell of the Arctic Ocean, the POLARIS risk values are aggregated by ship ice class to compute boxplot statistics (Stoddard et al., 2018). The computed POLARIS spatiotemporal boxplots can depict both the seasonality and variability of the sea ice navigation risk in the Arctic.

Different legs crossing the NSR route were created (Bering-Sabetta and Sabetta-Murmansk). Based on the RIO values obtained along the grid cells of these routes (with a 12.5 km spatial resolution), the speeds of each ship ice class were calculated for three scenarios:

- the 75th best percentile in terms of POLARIS RIO (good navigation conditions);
- the median scenario;
- the 25th lowest percentile in terms of POLARIS RIO (poor navigation conditions).

Fig. 3 depicts the POLARIS risk index maps for an ice class 1A vessel navigating in the Arctic, under median ice conditions. The red color indicates forbidden areas. In orange areas, the ship would require an icebreaker escort while in green zones she can navigate freely. The left map illustrates a chosen day in winter (March 1st) in which it is obvious that an ice class 1A ship cannot navigate

Table 4
Sailing duration per route in days.

From	To	Duration in days
Tianjin	MISY (Zeebrugge)	42
Tianjin	Sabetta via Bering	28
Tianjin	Sabetta via Suez	49
MISY	Tianjin	42
MISY	Sabetta	14
Sabetta	Tianjin	28
Sabetta	Tianjin	49
Sabetta	MISY	14

Source: Authors.

Table 5
Typology of vessels used.

Vessel type (Benchmark)	Class	Length	Width	Draft	*Fleet 1 (OW)*	*Fleet 2 (OW + 1A)*	*Fleet 3 (OW + 1A + PC3)*
Audnax and Pugnax	PC3	172	42	8	0 vessel	0 vessel	4 vessels
Big Roll 1 and 2	1A	120	42	5.5	0 vessel	4 vessels	4 vessels
Red Box RedZed 1 and 2	N/A	172	42	8	2 vessels	2 vessels	2 vessels
Yamato and Yamatai	N/A	125	36	6.3	2 vessels	2 vessels	2 vessels
Mega Caravan 1 and 2	N/A	135	40	6	2 vessels	2 vessels	2 vessels
COSCO KSK	N/A	172	42	9	1 vessel	1 vessel	1 vessel
Dockwise Forte	N/A	172	43	9	1 vessel	1 vessel	1 vessel
Hua Yang Long	N/A	160	43	9	1 vessel	1 vessel	1 vessel
Dockwise Finesse	N/A	172	43	9	1 vessel	1 vessel	1 vessel
Remaining OW vessels	N/A	172	42	9	20 vessels	16 vessels	12 vessels
Total fleet					*30 vessels*	*30 vessels*	*30 vessels*

Source: Authors.

between Sabetta and Bering. The right map shows a selected day in summer (September 16th) in which an ice class 1A can travel the NSR without any icebreaker escort.

Using this approach, we assessed the vessel sailing durations and navigability periods over the year, by calculating the feasible route and average speed of each vessel ice class per scenario, for every day of departure within a year. Fig. 4 shows the results for a 1A vessel along the route from Tianjin to Sabetta via the Bering Strait, where we observe an increased sailing duration (lower speed due to more severe ice conditions) during the melting and freezing ice seasons. The navigability period between the melting and freezing seasons can be longer or shorter depending on the percentile scenario.

This approach showed that the sailing duration variability remains smaller than our weekly basis approach and therefore we assumed a constant speed for the routes transiting the NSR throughout the year. It also enabled the definition of navigability periods for each percentile scenario shown in Appendix A.

Sailing navigation times for route sections in open waters were calculated using port-to-port distance databases such as www.marinetraffic.org or www.port-distances.org and assuming an operational speed of 11 knots. The result was rounded to the later week as shown in Table 4.

3.4.2. Asian ports

In order to reduce the number of variables and allow for a solving time not longer than one hour, we reduced the number of nodes by considering nodes 2 and 3 as located in node 1 (Tianjin). This choice was made for practicability reasons: since these ports are located along the SCR, a call at these ports would have little impact on the total navigation time from Tianjin. However, this choice penalizes some optimal solutions: typically, a shipment with modules from Indonesia and the Philippines will have a real voyage duration a few days shorter than the one used in the model. Consequently, the RFSA dates of modules in these two ports could be virtually anticipated by the user to include the travel duration from Tianjin. Also, given that these ports are farther from the Bering Strait than Tianjin, the shipments from these ports to Sabetta via the Bering Strait Route would not be feasible as they would be longer in practice than the modelled value. In the parameters, it was therefore possible to disallow these modules to use the Bering Strait Route, and this choice was applied here. The impact should be limited for shipments from Batam port (21% of modules) as Batam is nearly equidistant to Yamal via one or the other route, and the SCR is less expensive than the Bering Strait Route, which needs a longer icebreaker escort. Furthermore, all three modules were required in Sabetta at periods when it was accessible by Open Water (OW) vessels, easily available on the spot market. For Batangas shipments (7% of modules) the cost via Suez is also less costly, however the shorter Bering Strait Route may provide benefits that the model does not explore.

Table 6
Average delay per module compared to the schedule, in weeks.

Bering Strait Route	*Expected ice conditions (POLARIS RIO)*	*Fleet 1 (OW)*	*Fleet 2 (OW + 1A)*	*Fleet 3 (OW + 1A + PC3)*
Allowed	Good (75th percentile)	8.46	4.09	3.87
Allowed	Median	11.03	8.15	3.93
Allowed	Poor (25th percentile)	23.79	11.86	4.80
Disallowed	Poor (25th percentile)	23.79	15.88	5.34

Table 7
Delay on project completion in weeks (for a project expected to last 127 weeks).

Bering Strait Route	*Expected ice conditions (POLARIS RIO)*	*Fleet 1 (OW)*	*Fleet 2 (OW + 1A)*	*Fleet 3 (OW + 1A + PC3)*
Allowed	Good (75th percentile)	33	2	1
Allowed	Median	43	36	1
Allowed	Poor (25th percentile)	40	36	11
Disallowed	Poor (25th percentile)	40	38	6

Source: Authors

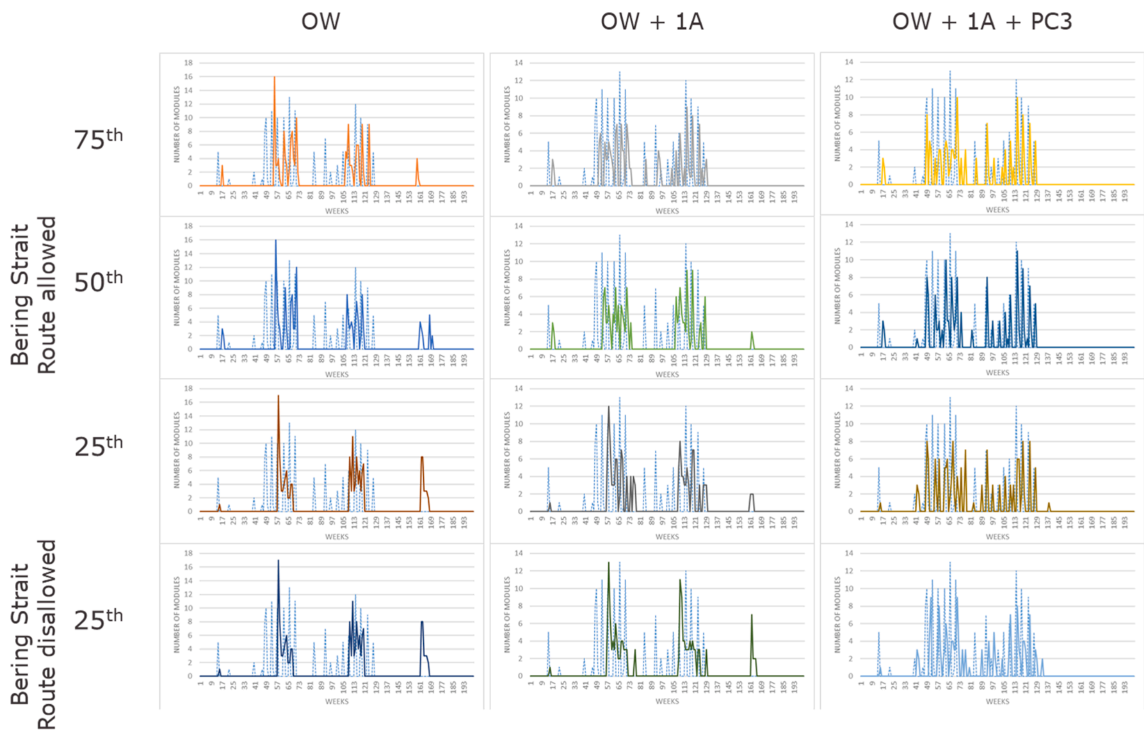

Fig. 5. Project completion charts depending on ice and fleet scenarios. Source: Authors.

4. Scenarios applied and results

4.1. Scenarios applied

The construction of the Yamal LNG plant was successfully completed in two and a half years with a fleet that included two PC3s and two 1As. As stated in the introduction, the following scenarios were created ex-post and aim to assess the role and relevance of fleet polarseaworthiness for infrastructure projects in the Arctic. To do so, we created fleets with 30 vessels available, enough to ensure that delays would not be due to the lack of vessels. We then created a fleet without any ice or polar class vessel (fleet 1), a fleet with OW vessels and 1A vessels only (fleet 2) and a fleet including 1A and PC3 vessels (fleet 3). Fleet 3 is deliberately over designed to account for the poor ice conditions scenario. Furthermore, to apply industry practices, the 1A and PC3 vessels had long-term time charter contracts, with approximately two-year terms starting at the winter season. Given the uncertainty of the project completion time in each scenario and considering our aim to assess the actual relevance of 1A and PC3 vessels, we allowed the model to use the long-term time charter vessels after the end of their 2-year charter contract, with supplementary costs calculated as short-term chartered vessels.

Table 8
Objective function, in million USD.

Bering Strait Route	*Expected ice conditions (POLARIS RIO)*	*Fleet 1 (OW)*	*Fleet 2 (OW + 1A)*	*Fleet 3 (OW + 1A + PC3)*
Allowed	Good (75th percentile)	1,429	1,011	1,066
Allowed	Median	1,684	1,499	1,085
Allowed	Poor (25th percentile)	3,044	1,963	1,239
Disallowed	Poor (25th percentile)	3,044	2,245	1,364

Source: Authors.

Table 9
Shipping cost, in million USD.

Bering Strait Route	*Expected ice conditions (POLARIS RIO)*	*Fleet 1 (OW)*	*Fleet 2 (OW + 1A)*	*Fleet 3 (OW + 1A + PC3)*	*Fleet 3 / Fleet 1 cost ratio*
Allowed	Good (75th percentile)	587	624	703	120%
Allowed	Median	574	687	714	125%
Allowed	Poor (25th percentile)	610	769	778	128%
Disallowed	Poor (25th percentile)	610	630	849	139%

Source: Authors.

This approach provides a more accurate information as to whether these vessels are required after the end of their contract. In all scenarios five OW vessels were available as long-term time charter. For the remaining vessels we assumed short-term time charter contracts. The three theoretical fleet compositions were defined as below and are illustrated in Table 5:

- Fleet 1: 30 OW, i.e. non-ice class vessels, based on a fleet of vessels used in this project.
- Fleet 2: 4 ice class vessels 1A (using the sister ships Big Roll 1 and 2 as references), plus 26 OW vessels.
- Fleet 3: 4 Polar Class vessels PC3 (using the sister ships Audnax and Pugnax as references), plus the previous 4 ice class 1A vessels, and 22 OW vessels.

To assess the robustness of each fleet composition regarding the seasonal ice variations for good and poor years, we defined opening and closing dates by route (with and without icebreakers) for the 25th, 50th and 75th percentiles of RIO, as explained in Section 3.4.1 and shown in Appendix A.

In total 12 scenarios, or problem instances, were created and solved: 9 scenarios allowing navigation in the Bering Strait Route, with the 3 RIO and the 3 abovementioned fleets, plus 3 scenarios where navigation via the Bering Strait Route is disallowed – where vessels can only navigate via the SCR – in poor ice conditions, a situation where the SCR route via the Barents Sea would make most sense.

4.2. Results

4.2.1. Respect of the schedule

Tables 6 and 7 show respectively the average delay per module and the delay on project completion. The delay on the project completion shown is the difference in weeks between the actual and expected week of delivery of the last module. We notice that the use of PC3 vessels (Fleet 3) is by far the best alternative, considering that ice conditions are usually unknown: the average delay per module remains limited to 3.87–5.34 weeks across all ice conditions (Table 6), while the delay on project completion is limited to 11 weeks (Table 7). Delays observed in the best scenario (Fleet 3 with good RIO) are inherent to the assembly schedule provided: some required dates in Sabetta were too close to the production dates to ensure on-time delivery.

Notably, except when ice conditions are favorable, the delay on project completion becomes significant without PC3 vessels, due to the closure of the Arctic routes in winter (Table 7). If all modules are not delivered over the summer weeks, the project must wait until the following route opening and the delay reaches levels above 30 weeks as shown in Table 7. This is illustrated in Fig. 5, which shows for each scenario the number of modules delivered per week (over a time horizon of 200 weeks). Required dates are the same for all scenarios and are shown in dotted lines, while the actual deliveries are shown in full lines. Overall, we observe that the use of Fleet 3 allows for module deliveries very close to the project requirements, while the use of Fleets 1 and 2 does not allow to fulfil these same requirements for all ice conditions.

When we compare the project performance using Fleet 1 and Fleet 2, we find that, thanks to the longer period of navigation of the 1A vessels compared to the OW vessels, Fleet 2 offers lower average delays than Fleet 1. Furthermore, since the model focuses on minimizing the average delay among modules rather than the delay of the last module (project completion time), solutions with similar average delays can have different project completion times, as similar average delays can be obtained by accumulating delays in a limited number of modules or spreading them evenly over many modules. We can however see that solutions with lower average delay per module tend to have better completion times as well.

Table 10
Percentage of shipments by route for each scenario.

Bering Strait Route	*Expected ice conditions (POLARIS RIO)*	*Routes used*	*Fleet 1 (OW)*	*Fleet 2 (OW + 1A)*	*Fleet 3 (OW + 1A + PC3*
Allowed	Good (75th percentile)	BSR	23%	31%	23%
		SCR	55%	56%	64%
		SCR + Hub	21%	13%	14%
Allowed	Median	BSR	27%	25%	46%
		SCR	52%	63%	46%
		SCR + Hub	21%	12%	9%
Allowed	Poor (25th percentile)	BSR	0%	10%	38%
		SCR	64%	60%	45%
		SCR + Hub	36%	29%	17%
Disallowed	Poor (25th percentile)	BSR	0%	0%	0%
		SCR	64%	82%	78%
		SCR + Hub	36%	18%	22%

Source: Authors.

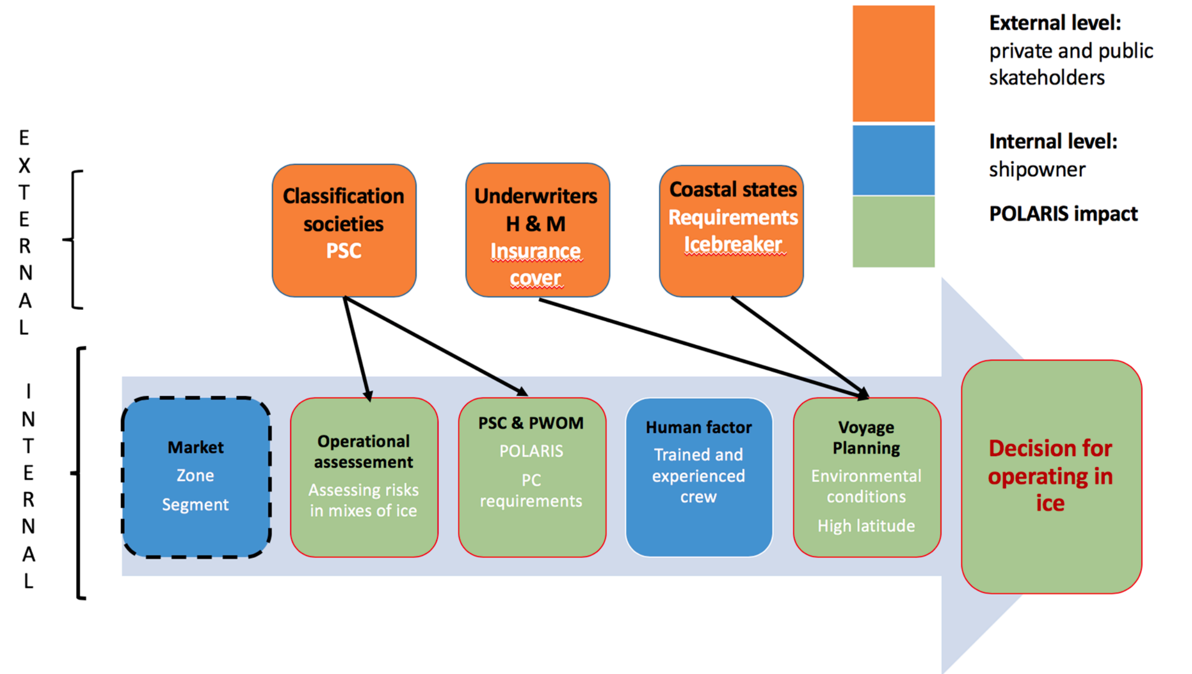

Fig. 6. POLARIS as a Decision Support Tool. Source: Fedi et al. (2018b).

4.2.2. *Cost of the delay*

Tables 8 and 9 show the economic impact of the relation of ice conditions, ice class vessel and fleet composition on the objective function (shipping and delay costs) and on the shipping costs taken separately.

Table 8 highlights that Fleet 3 provides the lowest objective function value in all scenarios, including when the expected level of risk due to the ice presence is low: this can be explained by the high delay costs (here arbitrarily set at 100,000 USD per module per day) which significantly penalizes scenarios with higher delays. Similarly, Fleet 2 provides better results than Fleet 1, as Fleet 2 provides lower average delay per module than Fleet 1.

When we look at shipping costs only (Table 9), we notice that Fleet 1 offers the lowest shipping costs, followed by Fleet 2 and Fleet 3. Fleet 3 increases shipping costs by roughly 28% across all scenarios, compared to Fleet 1. Nevertheless, it ensures the reliability of the project completion time. We also notice that the cost difference increases with unfavorable ice conditions – as PC3 vessels are used more intensely – and when the Bering Strait is disallowed, as this would minimize the benefits of PC3 vessels. Indeed, as shown in Appendix B, scenarios using fleet 3 require three PC3 vessels when expected ice conditions are good and median, and four PC3 vessels when conditions are poor.

However, if the cost of running a fleet with PC3 and/or 1A is higher than the cost of a fleet exclusively made of OW, the use of a fleet with high polarseaworthiness is a better solution.

Table A1
Navigation periods per route and vessel class: 25th percentile.

From	To	Ice Class	Start Date (with Icebreaker)	Start Date (without Icebreaker)	End Date (without Icebreaker)	End Date (with Icebreaker)
Tianjin (via Suez)	MISY	1A	01-Jan	01-Jan	31-Dec	31-Dec
Tianjin (via Suez)	MISY	PC3	01-Jan	01-Jan	31-Dec	31-Dec
Tianjin (via Suez)	MISY	N/A	01-Jan	01-Jan	31-Dec	31-Dec
Tianjin (via Bering)	Sabetta	1A	29-Aug	29-Aug	29-Aug	09-Nov
Tianjin (via Bering)	Sabetta	PC3	01-Jan	10-Jul	31-Dec	31-Dec
Tianjin (via Bering)	Sabetta	N/A	01-Aug	01-Aug	01-Aug	01-Aug
Tianjin (via Suez)	Sabetta	1A	02-Jul	06-Jul	25-Dec	31-Dec
Tianjin (via Suez)	Sabetta	PC3	01-Jan	01-Jan	01-Jan	31-Dec
Tianjin (via Suez)	Sabetta	N/A	09-Jul	10-Jul	19-Oct	26-Oct
MISY (via Suez)	Tianjin	1A	01-Jan	01-Jan	31-Dec	31-Dec
MISY (via Suez)	Tianjin	PC3	01-Jan	01-Jan	31-Dec	31-Dec
MISY (via Suez)	Tianjin	N/A	01-Jan	01-Jan	31-Dec	31-Dec
MISY (via Barents)	Sabetta	1A	02-Jul	06-Jul	25-Dec	31-Dec
MISY (via Barents)	Sabetta	Arc7	01-Jan	01-Jan	01-Jan	31-Dec
MISY (via Barents)	Sabetta	N/A	09-Jul	10-Jul	19-Oct	26-Oct
Sabetta (via Bering)	Tianjin	1A	26-Aug	26-Aug	26-Aug	16-Nov
Sabetta (via Bering)	Tianjin	PC3	01-Jan	09-Jul	31-Dec	31-Dec
Sabetta (via Bering)	Tianjin	N/A	01-Aug	01-Aug	01-Aug	01-Aug
Sabetta (via Suez)	Tianjin	1A	02-Jul	07-Jul	27-Dec	31-Dec
Sabetta (via Suez)	Tianjin	PC3	01-Jan	01-Jan	01-Jan	31-Dec
Sabetta (via Suez)	Tianjin	N/A	09-Jul	10-Jul	22-Oct	29-Oct
Sabetta (via Barents)	MISY	1A	02-Jul	07-Jul	27-Dec	31-Dec
Sabetta (via Barents)	MISY	PC3	01-Jan	01-Jan	01-Jan	31-Dec
Sabetta (via Barents)	MISY	N/A	09-Jul	10-Jul	22-Oct	29-Oct

4.2.3. *The relevancy of a Hub in Europe*

Finally, we can assess the relevance of the Bering Strait Route and the transshipment Hub in Zeebrugge by looking at the percentage of shipments leaving Asian ports taking each one of the possible routes: the Bering Strait Route (BSR) directly to Sabetta, the SCR via Barents directly to Sabetta (SCR) or the SCR with a transshipment in Zeebrugge (SCR + Hub). Table 10 shows that the Hub is most relevant in the worst scenario and Fleet 1 with poor ice conditions. The more the ice conditions improve, or the fleet used improves its resistance to the ice, the less relevant is the Hub. Nevertheless, it is noteworthy that even when using the fleet with PC3, it remains relevant to implement a Hub in anticipation of poor ice conditions, a case where the Hub is used in 17% of shipments. Regarding the NSR usage, we find that it is significantly used throughout all scenarios where it is allowed, particularly when PC3 vessels are available.

Hence, our analysis highlighted five major points dealing with schedule adherence, cost management and logistics organization.

- Schedule adherence
  - o The use of the PC3 vessels allows to provide a higher level of respect of the planned schedule.
  - o Even if the final result is in favor of a fleet with PC3, the use of ice class (1A) also enhances the schedule adherence when compared to OW only.
- Cost management
  - o Thanks to the high reliability and seaworthiness, the use of the PC3 does not increase the shipping cost by significant amounts.
- Logistics organization
  - o Because sailing conditions are hardly predictable, the use of a Hub helps to counteract their potential negative effect.
  - o The Bering Strait Route is not to be seen as a challenger to the SCR, since each route has its specific role, and both are required in all scenarios.

Detailed results for all scenarios are presented in Appendix B.

5. Discussion and managerial learning outcomes

As mentioned, few academic articles have so far focused on the NSR from a cargo project shipping management perspective including several parameters and stressing the potential benefits to exploit year-round ice navigation Polar Class vessels. Our analysis

Table A2
Navigation periods per route and vessel class: 50th percentile.

From	To	Ice Class	Start Date (with Icebreaker)	Start Date (without Icebreaker)	End Date (without Icebreaker)	End Date (with Icebreaker)
Tianjin (via Suez)	MISY	1A	01-Jan	01-Jan	31-Dec	31-Dec
Tianjin (via Suez)	MISY	PC3	01-Jan	01-Jan	31-Dec	31-Dec
Tianjin (via Suez)	MISY	N/A	01-Jan	01-Jan	31-Dec	31-Dec
Tianjin (via Bering)	Sabetta	1A	25-Jul	07-Aug	17-Nov	08-Dec
Tianjin (via Bering)	Sabetta	PC3	01-Jan	23-Jun	31-Dec	01-Jan
Tianjin (via Bering)	Sabetta	N/A	09-Aug	12-Aug	07-Oct	18-Oct
Tianjin (via Suez)	Sabetta	1A	15-Jun	21-Jun	31-Dec	31-Dec
Tianjin (via Suez)	Sabetta	PC3	01-Jan	01-Jan	31-Dec	31-Dec
Tianjin (via Suez)	Sabetta	N/A	28-Jun	29-Jun	27-Oct	21-Nov
MISY (via Suez)	Tianjin	1A	01-Jan	01-Jan	31-Dec	31-Dec
MISY (via Suez)	Tianjin	PC3	01-Jan	01-Jan	31-Dec	31-Dec
MISY (via Suez)	Tianjin	N/A	01-Jan	01-Jan	31-Dec	31-Dec
MISY (via Barents)	Sabetta	1A	15-Jun	21-Jun	31-Dec	31-Dec
MISY (via Barents)	Sabetta	PC3	01-Jan	01-Jan	31-Dec	31-Dec
MISY (via Barents)	Sabetta	N/A	28-Jun	29-Jun	27-Oct	21-Nov
Sabetta (via Bering)	Tianjin	1A	30-Jul	08-Aug	18-Nov	11-Dec
Sabetta (via Bering)	Tianjin	PC3	01-Jan	22-Jun	31-Dec	31-Dec
Sabetta (via Bering)	Tianjin	N/A	12-Aug	16-Aug	07-Oct	17-Oct
Sabetta (via Suez)	Tianjin	1A	15-Jun	22-Jun	31-Dec	31-Dec
Sabetta (via Suez)	Tianjin	PC3	01-Jan	01-Jan	31-Dec	31-Dec
Sabetta (via Suez)	Tianjin	N/A	29-Jun	30-Jun	30-Oct	21-Nov
Sabetta (via Barents)	MISY	1A	15-Jun	22-Jun	31-Dec	31-Dec
Sabetta (via Barents)	MISY	PC3	01-Jan	01-Jan	31-Dec	31-Dec
Sabetta (via Barents)	MISY	N/A	29-Jun	30-Jun	30-Oct	21-Nov

points out the strong relation between risk and project management in a complex area with a variable level of risk, a constrained policy framework, and different possible logistic organizations.

In terms of managerial learning outcomes, the use of POLARIS appears as a risk-oriented decision-making tool in the management of highly strategic projects such as Yamal. Indeed, as explained by Fedi et al. (2018b), if POLARIS plays a key role in the formal polar risk assessment such as the ship's certification and the PWOM required by the Polar Code (PC), this is also a decision tool at operational level via the definition of the route depending on the vessel's RIO. Thus, it can be surprising that POLARIS is not mandatory. Depending on the level of risk for the intended shipment of modules, the master can make appropriate decisions in order to prevent unwanted accidents and related consequences such as damages and delays. In addition, at a strategic level, considering the economic importance of the Yamal infrastructure project, POLARIS contributes to defining the type of investment required to fulfil the project. Besides, in line with Fedi et al. (2018b, 2020), POLARIS and the PC "work in pair" either for a single operation or for a project management involving several shipments such as Yamal. As illustrated in Fig. 6, these policy instruments are closely interrelated and complement each other. Above all, POLARIS does not integrate the human factor while the PC imposes a certain level of experience and related certification for navigating in polar areas. Accordingly, the PC and POLARIS create a systemic framework of formal risk assessment and polarseaworthiness. Nevertheless, zero risk does not exist and even though the final decision to operate in Arctic waters is in accordance with the PC requirements and POLARIS recommendations, this may lead to casualties (Fedi et al., 2020).

Additionally, our analysis stresses that opting for a fleet with PC3 has numerous benefits from a risk and project management perspective. First, from a risk management aspect, as explained by Marchenko (2014), an unsuitable speed is one of the main root causes of accidents. Second, as ice conditions and hence RIO is highly unpredictable (Fu et al., 2016), using a PC3 with the greatest possible polarseaworthiness, allows to counteract harsh sailing conditions and significantly reduce delays in project completion. This un-foreseeability of ice conditions, translated in our analysis as RIO and stressed by Fu et al. (2016), has been embodied by the three climate scenarios.

Furthermore, our analysis emphasizes that fleet management is a complex question in the context of Arctic navigation while dealing with vessels of different polarseaworthiness. This heterogeneity implies a complex management of different time lapses during which the NSR is navigable, a changing transit time with regard to the period of navigation depending on the type of vessel used (Stephenson et al., 2013). Hence to provide more schedules and to mitigate the risks represented by ice drifting, the use of icebreakers may be mandatory (Fedi et al., 2018a; Gritsenko and Kiiski, 2016). While being assisted by an icebreaker increases the costs of navigation, it has a positive effect on the length of passage by allowing safer navigation in harsher climate conditions (Appendix A).

Table A3
Navigation periods per route and vessel class: 75th percentile.

From	To	Ice Class	Start Date (with Icebreaker)	Start Date (without Icebreaker)	End Date (without Icebreaker)	End Date (with Icebreaker)
Tianjin (via Suez)	MISY	1A	01-Jan	01-Jan	31-Dec	31-Dec
Tianjin (via Suez)	MISY	PC3	01-Jan	01-Jan	31-Dec	31-Dec
Tianjin (via Suez)	MISY	N/A	01-Jan	01-Jan	31-Dec	31-Dec
Tianjin (via Bering)	Sabetta	1A	08-Jul	18-Jul	06-Dec	27-Dec
Tianjin (via Bering)	Sabetta	PC3	01-Jan	01-Jan	31-Dec	31-Dec
Tianjin (via Bering)	Sabetta	N/A	23-Jul	25-Jul	19-Oct	27-Oct
Tianjin (via Suez)	Sabetta	1A	01-Jan	23-May	31-Dec	31-Dec
Tianjin (via Suez)	Sabetta	PC3	01-Jan	01-Jan	31-Dec	31-Dec
Tianjin (via Suez)	Sabetta	N/A	16-Jun	19-Jun	11-Nov	24-Dec
MISY (via Suez)	Tianjin	1A	01-Jan	01-Jan	31-Dec	31-Dec
MISY (via Suez)	Tianjin	PC3	01-Jan	01-Jan	31-Dec	31-Dec
MISY (via Suez)	Tianjin	N/A	01-Jan	01-Jan	31-Dec	31-Dec
MISY (via Barents)	Sabetta	1A	01-Jan	23-May	31-Dec	31-Dec
MISY (via Barents)	Sabetta	PC3	01-Jan	01-Jan	31-Dec	31-Dec
MISY (via Barents)	Sabetta	N/A	16-Jun	19-Jun	11-Nov	24-Dec
Sabetta (via Bering)	Tianjin	1A	07-Jul	15-Jul	06-Dec	27-Dec
Sabetta (via Bering)	Tianjin	PC3	01-Jan	01-Jan	31-Dec	31-Dec
Sabetta (via Bering)	Tianjin	N/A	20-Jul	22-Jul	20-Oct	27-Oct
Sabetta (via Suez)	Tianjin	1A	01-Jan	24-May	31-Dec	31-Dec
Sabetta (via Suez)	Tianjin	PC3	01-Jan	01-Jan	31-Dec	31-Dec
Sabetta (via Suez)	Tianjin	N/A	17-Jun	20-Jun	14-Nov	27-Nov
Sabetta (via Barents)	MISY	1A	01-Jan	24-May	31-Dec	31-Dec
Sabetta (via Barents)	MISY	PC3	01-Jan	01-Jan	31-Dec	31-Dec
Sabetta (via Barents)	MISY	N/A	17-Jun	20-Jun	14-Nov	27-Nov

The other major issue raised in this paper focused on the way the use of two shipping lanes impacted the rotation of the fleet and hence the relevancy of hubs to enhance the productivity of the vessels and to respect the planned schedule. The respect of schedule, as demonstrated in our analysis, is paramount when dealing with such projects. As emphasized by Alix and Faury (2019), Vladimir Putin fixed a target of reaching 80 million tons of cargo in 2024, so here again the use of PC3 is vital knowing that the OW and/or 1A ship does not provide the required level of reliability for these types of projects. In fact, the project was managed with two PC3 and, partly thanks to this the production, started sooner than planned (Alix and Faury, 2019).

Thereby, this paper addresses some key research gaps in Arctic shipping underlined by Lavissiere et al. (2020) notably with regard to risk management, management constraints driven by the specific conditions of Arctic and its related legal context, decision models of industrial projects and vessel management.

Among the limitations of this study, it firstly lies in single case studies which are not prone to generalizations. Nevertheless, while there are not many current cases available in the region, some of the fundamentals such as vessel types and classes, navigability dates or a workload concentrated in summer are patterns that should be recur.

Another limitation is the nature of project performance, which can be evaluated from different perspectives such as cost, average delay per module or total time to completion. For instance, from a practitioner's perspective, satisfying solutions are not necessarily given by optimality on costs and delay, but by a trade-off on which modules to delay, requiring coordination with engineering teams. In line with Fagerholt (2004), the tool implementation shows that a diverse number of realistic solutions are as much or more relevant than one single optimal solution. Nonetheless it is noteworthy that our results remain consistent independently from the performance perspective taken. In addition, the weekly approach used makes this model strategic and tactical, rather than operational and does not consider sailing duration variability. However, our findings show that the duration variability remains limited within the navigability period. Moreover, due to the modelling choice to concentrate all Asian ports in one node, modules located in the southernmost ports are disallowed to use the Bering Strait Route. This limitation concerned 30% of modules which would benefit the least from the Bering Strait Route, being further south, and it is likely that if allowed, it would only further enhance the relevance of the Bering Strait Route and Polar Class vessels.

6. Conclusion

Based on a real case, our analysis provides some insights regarding the relation of risk and project management in Arctic. The analysis was grounded on a project conducted throughout the 2015–2017 period. We demonstrate that a constrained risk policy within project management is definitely not counterproductive, and rather, in fact, quite the opposite. With regard to heavy cargo transportation under time and loading compulsions, making the choice of the greatest polarseaworthiness for vessels despite their higher cost obviously allows to save money compared to options with lower polarseaworthiness. Our methodology, coupled with our results, show how to enhance the reliability of maritime transport and to secure time constraints in risky areas. It also points out the relevancy of the current legal framework in the Arctic and reinforces the idea that the current voluntary POLARIS, as a decision-making tool, should be made mandatory. Additionally, our article highlights the relevance of the Bering Strait Route for heavy cargo, intensively used in all scenarios where it is allowed, even when ice conditions are poor. The Bering Strait Route can be a real time saver compared to the SCR and consequently, can play a pivotal role for the implementation of future industrial projects in the Arctic. Finally, the model underlines the benefit of a Hub nearer the assembly site, particularly in anticipation of poor ice conditions or when the availability of PC3 vessels is limited.

Although the developed optimization model is focusing on a specific case study, it can be easily duplicated to other similar settings. For example, if more origin ports are considered, then the set of Asian ports can be changed to include more values than the current three ports. Moreover, if the transshipment ports are more than one, the same logic can be followed to generalize the model.

In the context of the recent development of infrastructures in the Russian Arctic, this research contributes to a better understanding of Arctic navigation for heavy goods and emphasizes the importance of strategic and tactical planning in complex projects for this dynamically growing region.

CRediT authorship contribution statement

Patrick Rigot-Müller: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Visualization, Writing – original draft, Writing – review & editing. **Ali Cheaitou:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Laurent Etienne:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Visualization, Writing – original draft, Writing – review & editing. **Olivier Faury:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing. **Laurent Fedi:** Conceptualization, Methodology, Resources, Writing – original draft, 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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Appendix A. Navigation periods per route and vessel class

See Tables A1-A3.

Appendix B. Detailed results per scenario

Fleet:	Fleet 1	Fleet 2	Fleet 3	Fleet 1	Fleet 2	Fleet 3	Fleet 1	Fleet 2	Fleet 3	Fleet 1	Fleet 2	Fleet 3	
Ice conditions:	Good	Good	Good	Median	Median	Median	Poor	Poor	Poor	Poor	Poor	Poor	
Bering Strait Route:	Allowed	Allowed	Allowed	Allowed	Allowed	Allowed	Allowed	Allowed	Allowed	Disallowed	Disallowed	Disallowed	
Optimization Outputs	Result	Result	Result	Result	Result	Result	Result	Result	Result	Result	Result	Result	Unit
Date of delivery of last module	18/07/18	13/12/17	06/12/17	26/09/18	08/08/18	06/12/17	05/09/18	08/08/18	14/02/18	05/09/18	22/08/18	10/01/18	(Date)
Average waiting time per module in Asia	67.79	39.23	35.42	88.51	66.95	43.50	144.32	80.34	45.52	144.32	104.67	37.77	(Days)
Average delay per module	59.24	28.61	27.06	77.19	57.03	27.48	166.50	83.01	33.59	166.50	111.15	37.35	(Days)
Overall number of shipments	113	136	106	124	125	108	138	146	122	138	134	143	(Shipments)
Number of shipments Asia - Sabetta via Suez	26	29	28	25	32	21	28	29	21	28	36	35	(Shipments)
Number of shipments Asia - Sabetta via Bering	11	16	10	13	13	21	0	5	18	0	0	0	(Shipments)

(continued on next page)

(*continued*)

Fleet:	Fleet 1	Fleet 2	Fleet 3	Fleet 1	Fleet 2	Fleet 3	Fleet 1	Fleet 2	Fleet 3	Fleet 1	Fleet 2	Fleet 3	
Number of shipments Asia - MISY	10	7	6	10	6	4	16	14	8	16	8	10	(Shipments)
Number of shipments MISY - Sabetta	6	9	7	7	4	4	12	9	7	12	6	10	(Shipments)
Number of shipments Sabetta - MISY	17	21	10	24	21	12	42	46	22	42	42	43	(Shipments)
Number of shipments MISY - Asia	15	25	13	23	21	14	40	43	23	40	42	45	(Shipments)
Number of shipments Sabetta - Asia via Bering	28	29	32	22	28	32	0	0	23	0	0	0	(Shipments)
Total number of days of chartering	7,392	7,574	7,014	7,308	8,617	7,210	7,420	9,562	7,224	7,420	7,231	7,987	(Days)
Number of shipments with spot* vessels	94	81	57	109	78	56	120	89	53	120	94	55	(Shipments)
Number of days of chartering of spot* vessels	4,648	3,892	2,905	5,222	3,787	2,625	5,502	4,263	2,576	5,502	4,347	2,618	(Days)
Overall standby time of vessels	1,743	1,106	1,729	1,330	2,492	2,023	924	2,758	1,477	924	945	1,351	(Days)
Number of spot* vessels used	22	17	14	22	18	14	21	19	13	21	19	11	(Vessels)
Number of PC3 used	0	0	3	0	0	3	0	0	4	0	0	4	(Vessels)
Number of 1A used	0	4	2	0	4	2	0	4	2	0	4	3	(Vessels)

* Short -Term Charter.

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