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Ship routing and scheduling for the assembly of a LNG plant in the arctic: a decision support system

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Abstract

The construction of a Liquid Natural Gas plant in Yamal, Russia, required the assembly of modules transported from yards in Asia. In early stages of such projects, the feasibility of on-time shipping plans is a critical area of risk assessment, in particular in the arctic where accessibility is limited by ice and vessel supply. By describing the modelling and implementation of a Decision Support System designed to create optimal shipping plans, this paper contributes to show the relevance of the Northern Sea Route for industrial projects in the arctic and to illustrate the role of risk mitigation tools.

Keywords: ship routing and scheduling, arctic shipping, supply chain planning

Introduction

The construction of a Liquid Natural Gas (LNG) plant in the Yamal peninsula, Russia, is a one-of-a-kind logistic case. LNG plants liquefy natural gas, originally in gaseous state, to allow for worldwide distribution in LNG vessels. The Yamal plant modules were assembled under extreme weather conditions, after being transported by sea to the port of Sabetta, from five manufacturing yards located in China, Indonesia and the Philippines. Operations in this plant started in December 2017 after the completion of the first LNG train. It was the first time that the Northern Sea Route (NSR) was used with such intensity on an industrial project, with more than 20 passages thought the Bering Strait. The Yamal region, and more broadly the Russian Arctic, has been identified as an important part of Russia's effort to replace maturing west Siberian oil and gas fields and support Russia's ongoing pivot towards Asian energy markets (Stephenson and Agnew, 2016). As a result, the region recently has seen significant Russian and foreign investment in new pipelines and maritime transport infrastructure such as ice-class LNG tankers and coastal search-and-rescue stations (Stephenson, 2017; Buxiadé Farré et al., 2014).

In early stages of such complex construction projects, the feasibility of on-time shipping plans, under a number of resources limitations and technical constraints is a critical area of risk assessment, in particular in the arctic where accessibility is limited by ice and scarce vessel supply. According to Carvalho et al. (2015), the academic literature presents a research–practice gap with a lack of studies on the application of decision support tools to address capacity planning problems in real-world Engineering-To-Order settings. This paper investigates the following research questions: what is the relevance of the NSR in industrial projects, in terms of costs and on-time delivery? And what role can have a Decisions Support System (DSS) for supply chain planning in Engineering, Production and Commissioning (EPC) projects delivered by sea? To do so, we describe the modelling and implementation of a ship routing and scheduling DSS developed for the Yamal case.

Description of the problem

The project was carried out by Yamal LNG, a joint-venture between Novatek (51%), Total (20%), CNPC (20%) and the Silk Road Fund (9.9%). Yamal LNG selected in May 2013 the consortium Yamgaz, which was in charge of the LNG plant Engineering, Production and Commissioning (EPC). The project was officially launched in December 2013 and the first plan module was ready for sailing away in August 2015. Some 144 modules in total were expected to be shipped, approximately 70% of these from three yards in China, and the remaining 30% from two yards in Indonesia and the Philippines. A fleet of 20 vessels was available, in majority in time charter contracts, however only two of those were of class Arc7, allowing for navigation in the arctic in winter. Furthermore, these two project-specific vessels, ordered in 2014 would be delivered in January and April 2016, after the beginning of the shipping operations. The limited availability of Arc7-class vessels for this project was perceived as a potential bottleneck of the project. Furthermore, some of the vessels could not access some of the shipyards due to draft constraints.

Soon after the project launch, the project teams raised concerns about the project risk assessment in relation to the shipping capabilities, and envisaged the use of the NSR as an alternative for risk mitigation and cost minimisation. The DSS described in the this paper aims to answer to these questions.

As illustrated in figure 1, the modules were shipped from Asia (here represented as node 1) and could reach Sabetta (node 3) directly via Suez or navigating through the NSR, or alternatively be transhipped in the Modular Intermediate Storage Yard at the Port of Zeebrugge, in Belgium (node 2). Each module had an expected production date and an expected date of arrival on the assembly site. About 30% of the modules had other modules as predecessors, requiring a strict synchronisation of deliveries between those. Routes between nodes are oriented and will be represented as indicated in figure 1, where each arc be either a Loaded or Ballast route.

The ports located in Indonesia and the Philippines (representing 30% of modules produced) were treated as if they were located in node 1 with an extra loading time when a voyage required a call in one of these ports. This modelling choice may penalise some optimal solutions (typically, a shipment with modules from Indonesia and Philippines only will have a voyage duration a few days shorter than the one used in the model). However, since only 30% of the modules were produces there, it seemed an acceptable assumption for the purpose of the model. In the model parameters, it is possible to allow or disallow these modules to use the NSR (the latter being the default choice).

Up to the tool development the shipping plans were built manually, which would not allow for a systematic control of the shipping constraints, neither for scenarios testing in a situation of recurring hypothesis changes. Typically, the vessel fleet and the modules' attributes (quantity, size, predecessors, production yards and requirement dates) could change from one planning version to another, requiring recurrent redesigns of shipping plans.

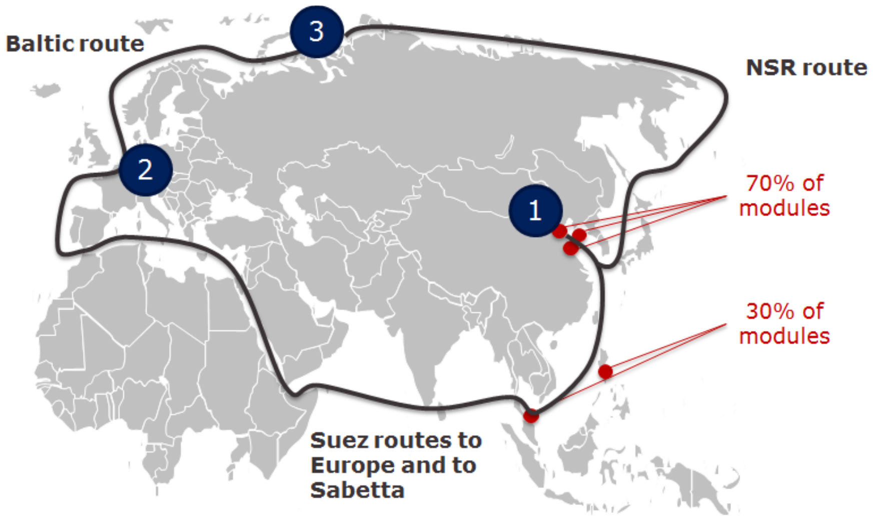

Figure 1 – Shipping routes and main ports

Literature review

Shipping optimisation problems

Shipping Optimisation Problems are well known in the academic field. Recent reviews and shipping optimisation problems classifications can be found in Christiansen et al. (2004, 2007 and 2013) and Christiansen and Fagerholt (2014). Christiansen et al. (2013) define four classes of shipping optimisation problems: 1) Liner shipping problems concern strategic planning issues such as Liner network design, or more strategic/tactical planning problems such as fleet deployment. 2) Industrial and Tramp shipping problems may concern strategic planning issues (fleet size and composition) or tactical planning issues (cargo routing and scheduling or inventory routing in supply chains). Remaining problem classes are more problem-specific 3) sailing speed, bunkering and emission problems and 4) offshore logistics, lightering and stowage problems.

Given the requirements to identify optimal shipping plans, our model is therefore a cargo routing and scheduling problem for project shipping. 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). Our case fits within 'project shipping' problems, a less explored sub-class of Industrial and Tramp shipping problems. Christiansen et al. (2013) identify one reference in this category (Fagerholt et al., 2013), and four references concerning a DSS implementation. Furthermore, one reference considers precedence constraints, one soft-time windows (Fargerholt, 2000, 2001) and one considers split deliveries (Lee and Kim, 2015), but there is no identified paper covering all these constraints altogether. Halvorsen-Weare (2013) address LNG distribution, but not the plant construction. Strategic ship routing and scheduling problems in shipping are solved in a number of ways, including Mixed-Integer Programing, Linear Programing, Set Partitioning, Heuristics, Simulation and expert opinion. Tactical routing and scheduling problems in industrial and tramp shipping are solved using approaches such as set partitioning, mixed-integer and integer programming and heuristics (Christiansen et al., 2004). Fagerholt et al. (2013) solve their project shipping problem using a tabu search heuristic.

Arctic Shipping

The field of NSR shipping has been recently analysed in terms of feasibility and economic relevance for bulk shipping by Cariou and Faury (2016), for Oil shipping by Faury and Cariou (2017) and for containers by: Zhao et al (2016), Zhang et al (2016a, 2016b), Lin and Chang (2018) and Lasserre (2014). Authors did not find however work covering the area of heavy goods: this paper will cover this sector.

The navigation along the NSR is impacted by three main typologies of factors: climatic, geographic and legal, which are strongly related to each other. The climatic factor is the changing thickness and extent of ice during the year and is hardly predictable on a daily basis. This level of unpredictability renders the navigation in this area highly complex and implies the use of specific vessels. The geographic factor refers to the low depth of the Russian shore (for example, Sannikov Strait with a depth of 13m) and the poor density of infrastructures such as repair yards, ports or icebreakers. Insurance companies consider these elements as potential risk catalyser (Fédi et al, 2018). Finally, the Polar Code (IMO, 2017) and the NSR administration (NSRA, 2017) provide a legal framework and impose the use of vessels with an ice class.

According to Doyon et al. (2016), the NSR may not be a competitor to the Suez Canal Route. Most of the cargo using the NSR are made of flows coming from or designated to a Russian port (Doyon et al, 2016) and deal with oil and gas. The NSR needs to manage at least 40 million tons to be profitable (Arctic Council, 2009; Kiiski et al, 2016). This quantity of cargo is needed to maintain infrastructures such as ports and icebreakers.

Grigoriev (2015) stressed that most of the oil and gas field under exploitation are situated on the western shore of the Russian arctic between the Kola peninsula and the Yamal peninsula. Stephenson and Agnew (2016), shed a light on the coming necessity to exploit the eastern fields in the future. The lack of infrastructures and among them ports updated are one of the main reason why shippers do not use the NSR and insurance companies are reluctant to insure vessels sailing in these areas. Aware of this challenge, the Russian government decided to update some ports such as Murmansk and created others such as Sabetta. The objective of the Russian Federation is to export between 133 and 153 million Tons by 2030 (Russia Strategy, 2030).

The port of Sabetta, which will export firstly the production of the Yamal LNG plant with a production capacity of 16.5 million tons per year and secondly the 18 million tons coming from "Arctic LNG-2" project1, is one of the pillars of the Arctic development in Russia. The concretization of such a project necessitated an investment of USD 27 billion and to invest in 17 ARC 7 LNG vessels dedicated with a unit cost of USD 350 Million (Clarksons, 2018).

Hence, the NSR and more broadly the arctic region is highly sensitive to ice conditions from a technical point of view and, since first of January, by the Polar Code. However, as it is a region with untapped resources, the Russian government is making massive investments to develop infrastructure such as ports and plants and these should be the corner stone of its development in the future.

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[1] http://tass.com/economy/990028

Model Description

As illustrated in figure 2, the designed solution is a strategic and tactical routing and scheduling model, with a heterogeneous vessel fleet (attributes: length, width, draft, ice class, costs, and charter contract). Hard time windows are applied for production dates at loading ports (no shipment before production), shipping routes and time-charter vessels availability. Flexible time windows are applied at delivery ports. The model considers multiple loads on vessels, split loads (loads can be transhipped), and synchronization of deliveries among cargoes (precedence constraints at delivery point). Stowage constraints are dealt in their majority in a pre-processing phase. The problem is solved with an Integer Programming model minimizing real shipping costs and inconvenience costs for delays. Time is considered using discrete modelling. This was made possible by considering only three ports (nodes) in the problem. A user-interface allows sequential runs of the model for different time windows, taking into consideration on-going, and already planned shipments. Results are presented in tables and Gantt charts. Exchange of information with the main stakeholders were carried out through meetings and workshops. This paper will focus on describing the modelling approach and illustrating results rather than establishing its mathematical formulation, which can be done in 23 equations.

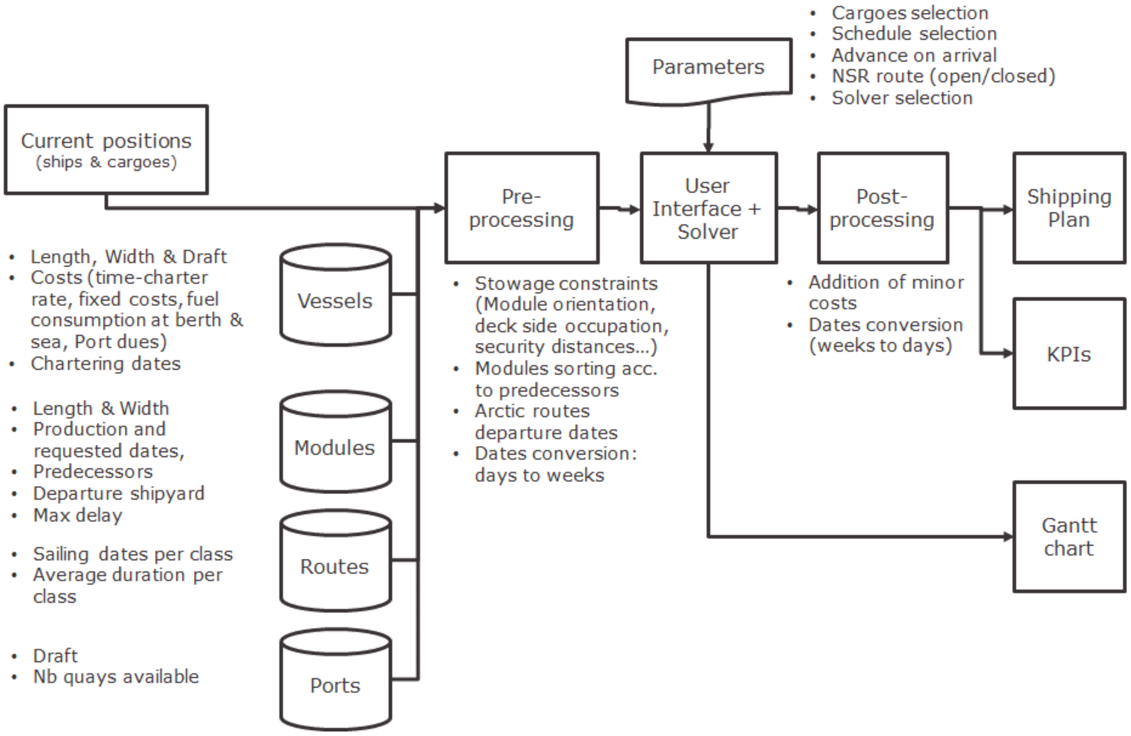


Figure 2 – Modelling approach

Model Constraints

The model constraints ensured that all modules must leave ports and arrive at destination, that modules leave after their production date, that modules arrive within a predefined maximum allowed advance or delay. We also ensured that transhipped modules would only leave Europe after their arrival, plus a transhipment duration. Synchronicity of modules at arrival was ensured by allocating to each module up to five predecessors and forcing the module's arrival date to be higher than the predecessors' ones. We also checked that the sum of the length of modules on-board of the vessel fit in the vessels' deck length. Moreover, 'short' modules (which length is smaller than the minimum vessel's width) are rotated by 90 degrees: in such cases, the 'on-board' length is actually the module's width. All modules with 'on-board width' larger than 50% of the smallest vessel's deck width occupy both sides a the deck, otherwise they would be considered 'thin' modules and allocated to the vessel's left or right side during pre-processing stage, as indicated in figure 3.

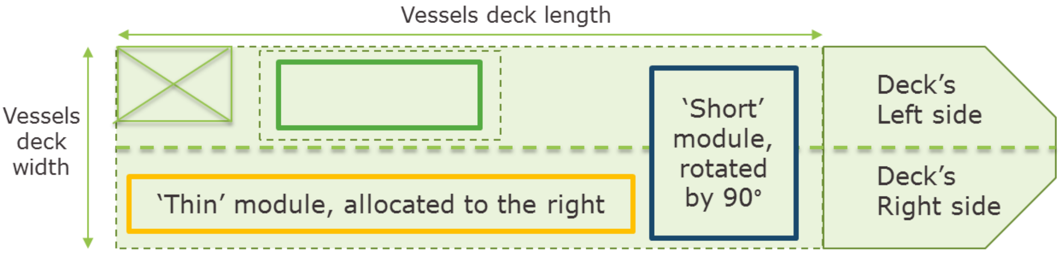


Figure 3 – Modules' on-deck allocation rules

Ice constraints ensured that the vessel would not leave the departure port towards Sabetta if it will not be able to return before the end of the allowed navigability period. These periods are calculated in the pre-processing stage. Navigability conditions are defined according to the Polar Operational Limit Assessment Risk Indexing System (POLARIS) as mentioned in the Polar Code (IMO. 2016). Arctic sea ice concentration and thickness of the 25 last years were downloaded from the European COPERNICUS marine repository ARCTIC_REANALYSIS_PHYS_002_003 dataset (von Schuckmann et al., 2017). The POLARIS risk index values are computed for different ship ice classes and aggregated for each day of the year. Figure 4 depicts the POLARIS risk index maps for a IA vessel navigating the NSR (purple line). Red and orange area indicates that the ship should not navigate in this area. In green zones, ship can navigate freely. In yellow areas, the ship would require an icebreaker escort. The left map illustrates one selected day in winter showing that, in the median case scenario, a IA ship cannot navigate whereas on the right map, in summer, a IA ship can travel the NSR without an icebreaker escort.

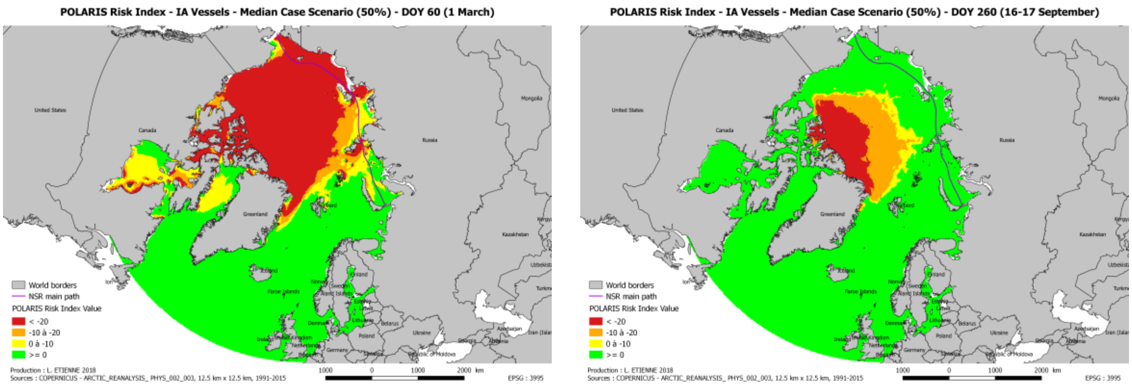


Figure 4 – POLARIS Navigability risk assessment in winter march 1st (left) and summer September 16th (right) for a IA Vessel transiting on the NSR

A flow conservation constraint applied in all three nodes (Asia, Europe and Sabetta) ensures that at all times a vessel must have left the node before returning, and that only after returning it would be allowed to leave it again. We also added constraint that ensure that charter vessels are used during their availability period, and port constraints ensuring that, in Europe and Sabetta, vessels arrive when ports quays are unoccupied and that vessels' drafts allow them to call in ports. A final constraint forbids the 30% of modules that not in China to use the NSR route, as they are too far from node 3.

Results

Relevance of NSR

The execution of the model showed the relevance of the NSR to achieve better delivery times for the plant assembly. Figure 5 and tables 1 and 2 illustrate and compare the model results for three scenarios. In all three the same data and parameters are used, excepted that in the first scenario the NSR is open for modules produced in China, and in the second the NSR is closed for all forthcoming shipments. In the second scenario the model minimises total costs by significantly postponing one module. Consequently, in the third scenario, we impose a limited maximum delay on that specific module and the tool proposes a module reallocation ensuring an earlier end of the project, as shown in table 1. This reallocation comes to an added total cost as shown in table 2.

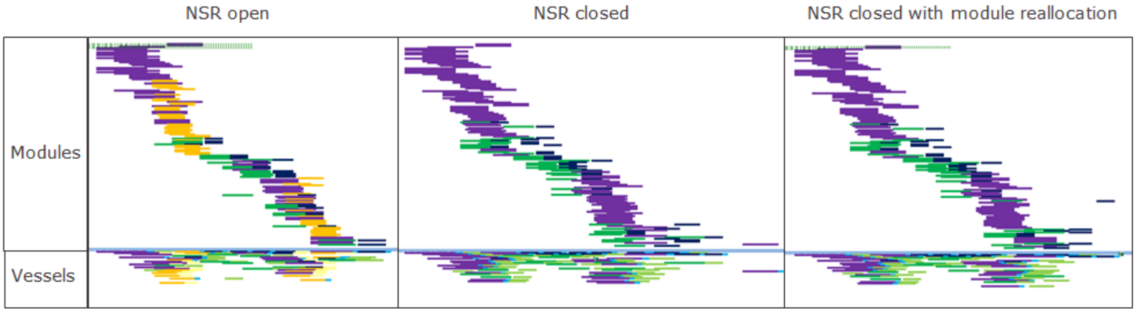
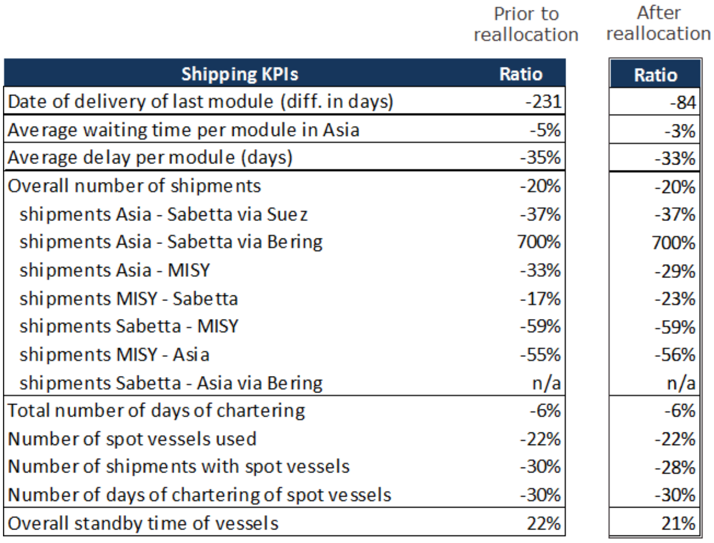


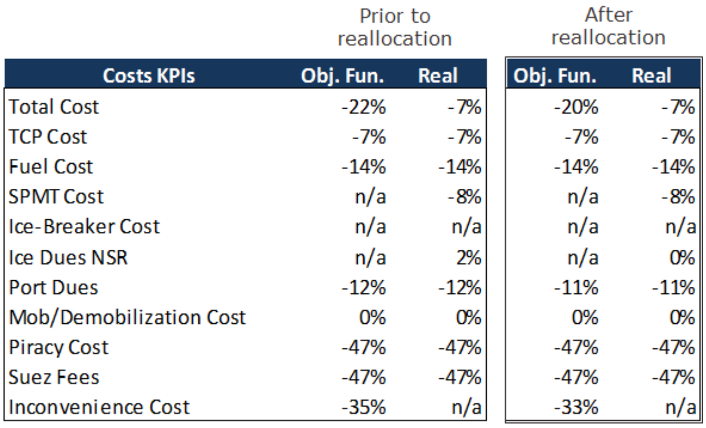
Figure 5 – Illustration: Gantt charts for three scenarios.
Routes: yellow=direct via NSR, purple= direct via Suez, green=Asia-Europe, Blue=Baltic

Table 1 – Shipping KPIs: performance ratios of plans with NSR open and closed



	Prior to reallocation	After reallocation
Shipping KPIs	**Ratio**	**Ratio**
Date of delivery of last module (diff. in days)	-231	-84
Average waiting time per module in Asia	-5%	-3%
Average delay per module (days)	-35%	-33%
Overall number of shipments	-20%	-20%
shipments Asia - Sabetta via Suez	-37%	-37%
shipments Asia - Sabetta via Bering	700%	700%
shipments Asia - MISY	-33%	-29%
shipments MISY - Sabetta	-17%	-23%
shipments Sabetta - MISY	-59%	-59%
shipments MISY - Asia	-55%	-56%
shipments Sabetta - Asia via Bering	n/a	n/a
Total number of days of chartering	-6%	-6%
Number of spot vessels used	-22%	-22%
Number of shipments with spot vessels	-30%	-28%
Number of days of chartering of spot vessels	-30%	-30%
Overall standby time of vessels	22%	21%

Table 2 – Shipping KPIs: cost ratios of plans with NSR open and closed



	Prior to reallocation		After reallocation	
Costs KPIs	**Obj. Fun.**	**Real**	**Obj. Fun.**	**Real**
Total Cost	-22%	-7%	-20%	-7%
TCP Cost	-7%	-7%	-7%	-7%
Fuel Cost	-14%	-14%	-14%	-14%
SPMT Cost	n/a	-8%	n/a	-8%
Ice-Breaker Cost	n/a	n/a	n/a	n/a
Ice Dues NSR	n/a	2%	n/a	0%
Port Dues	-12%	-12%	-11%	-11%
Mob/Demobilization Cost	0%	0%	0%	0%
Piracy Cost	-47%	-47%	-47%	-47%
Suez Fees	-47%	-47%	-47%	-47%
Inconvenience Cost	-35%	n/a	-33%	n/a

Strategic and tactical planning for risk assessment and mitigation

Consistently with Fagerholt (2004), the DSS implementation showed that from a practitioner's perspective diverse, realistic solutions were as relevant as optimal ones. Satisfying solutions would not be defined solely by optimality on costs and average delay, but also by a trade-off on which modules to delay, requiring coordination with engineering teams. The planning level remaining strategic and tactical, focused in feasibility checks and overall delay risk mitigation. The weekly approach used did not allow for a use at the operational level. Due to high number of data, variables and constraints, the analysis and interpretation of the tool's results required a good level of expertise about both the project and the model.

The study also illustrates the interest of the modelling process as promoting early customer-supplier coordination: the tool served as a coordination facilitator, allowing an improved communication and the constitution and sharing of the project database for shipping activity.

Conclusion

This paper describes and proposes a solution to a routing and scheduling problem not addressed yet in the literature. It discusses practical considerations related to the use of a DSS by practitioners in complex projects, another topic less considered in the literature.

The model proved the shipping project's feasibility with the resources available and illustrated, from a logistics perspective, the relevance of the NSR for industrial projects in the arctic region, reducing in our case the number of shipments by 20%, the average delay per module of 33% and anticipating the delivery of the last module by 84 days. This is the first known project to use the NSR in such a large scale.

Given the recent developments of infrastructure in the Russian arctic, we expect that this work may contribute to the understanding of the relevance of the NSR and the importance of strategic and tactical planning in complex EPC projects in the Russian arctic region.

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