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Ship routing and freight assignment problem for liner shipping: Application to the Northern Sea Route planning problem

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ABSTRACT

In recent years, the Northern Sea Route (NSR) has attracted significant attention with respect to liner shipping. In this research, we propose a general time-space network-based mathematical formulation to analyze the ship routing and freight assignment problem in liner shipping and apply it to NSR planning problem. To solve the resulting program, we propose a Lagrangian relaxation-based decomposition algorithm that facilitates the network features. Empirical results show that navigation skill, bunker price, delay penalty and service commitment are the primary factors that affect the NSR's commercial practicability.

1. Introduction

Climate change and global warming have drawn the attention of the global shipping industry with respect to the Arctic sea routes (ASRs) (Pierre and Olivier, 2015). The ASRs are the maritime paths used by carriers to navigate through the Arctic and are regarded as the shortest sea routes between Europe, Asia and North America. Among all the ASRs, the most widely discussed routes are the Northwest Passage (NWP) and the Northeast Passage (NEP), which are depicted in Fig. 1 (Chang et al., 2015). The NWP is a sea route connecting the northern Atlantic and Pacific Oceans along the northern coast of North America via waterways through the Canadian Arctic island chain. The NEP is the Arctic Ocean shipping route connecting the Atlantic and Pacific Oceans, traversing the Arctic along Russia's and Norway's coasts. The Northern Sea Route (NSR) runs along the central NEP and has a longer ice-free season and hence a lower navigable cost, which has been widely discussed in recent studies (Furuichi and Otsuka, 2015; Gritsenko and Kiiski, 2016; Liu and Kronbak, 2010; Pierre and Olivier, 2015; Verny and Grigentin, 2009; Wang et al., 2016; Xu et al., 2011). Therefore, the NSR is predicted to improve marine access in the future with the investment of navigation technology and infrastructure for ice-free ports (Northern Sea Route Information Office, 2016). Because the NSR is the primary route discussed in the literature, we focus on only the NSR rather than other Arctic shipping routes in this paper.

In the Asia-Europe market, maritime trade from Shanghai to Rotterdam via the NSR can reduce the number of nautical miles traveled by approximately 40% in comparison with the conventional shipping route through the Suez Canal (SCR). In addition, shipping through the NSR avoids passing through the congested SCR and paying the corresponding toll fee. Therefore, navigating the NSR can not only reduce fuel costs but also contribute to more flexible and agile operation in the peak season of container shipping (Schoyen and Brathen, 2011). Unfortunately, due to the large challenge in navigation and uncertain ice conditions, the risks involved in navigating the NSR seem extremely high. According to a recent report, the cost of voyaging through the NSR (e.g., the icebreaker fee) is high, and due to the expensive capital costs of building an ice-class ship and the seasonality of navigation, the potential for liner shipping via the NSR is relatively uncertain (Verny and Grigentin, 2009).

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Nomenclature

Sets

S	Set of ships
N^s	Set of nodes in the ship subnetwork of ship s
$O^s \subset N^s$	The origin of ship s in the ship subnetwork
$D^s \subset N^s$	The destination of ship s in the ship subnetwork
B	Set of cargoes
O_b	The origin of cargo b in the cargo O/D subnetwork
D_b	The destination of cargo b in the cargo O/D subnetwork
N_b	Set of nodes in the cargo flow subnetwork
$LN \subset N_b$	Set of loading nodes in the cargo flow subnetwork
$UN \subset N_b$	Set of unloading nodes in the cargo flow subnetwork
SA^s	Set of arcs in the ship subnetwork of ship s
VA^s	Set of voyaging arcs in the ship subnetwork of ship s
BA	Set of arcs in the cargo flow subnetwork
LA	Set of loading arcs in the cargo subnetwork
UA	Set of unloading arcs in the cargo subnetwork

Parameters

Cs_{ij}^s	The arc cost in the ship subnetwork. The cost contains ship capital, bunker and relevant costs on voyage
Cl_{ij}^b	The loading cost of cargo b to arc (i,j). Note that Cl_{ij}^b contains port charge
Cu_{ij}^b	The unloading cost of cargo b to arc (i,j). Note that Cu_{ij}^b contains port cost
L_{ij}^b	The delay cost of cargo b to arc (i,j). Note that node i and j are the same port but at different time interval
f_{ij}^b	The price charged by a carrier to ship cargo b to arc (i,j).
P_{ij}^b	P_{ij}^b is calculated according to $P_{ij}^b = f_{ij}^b - Cu_{ij}^b - L_{ij}^b$
Ct_i^b	The transshipment cost of cargo b at port i
K^s	The capacity of ship s
V^b	The container volume of cargo b
M	A large positive number

Decision variables

X_{ij}^s	Binary decision variable. If $X_{i,j}^s = 1$, ship s voyages along arc (i,j) of the ship subnetwork. If $X_{i,j}^s = 0$, otherwise.
$Y_{ij}^{s,b}$	Binary decision variable. If $Y_{ij}^{s,b} = 1$, then cargo b is shipped via arc (i,j) on ship s. If $Y_{ij}^{s,b} = 0$, otherwise
$T_{i,b}^{s_1,s_2}$	Binary decision variable. $T_{i,b}^{s_1,s_2} = 1$ indicates that cargo b is transshipped from ship s_1 to s_2 at port i. If $T_{i,b}^{s_1,s_2} = 0$, otherwise.
$\alpha_{ij}^{s,b}$	Binary decision variable. If $\alpha_{ij}^{s,b} = 1$, cargo b is loaded from the origin i of the cargo O/D subnetwork onto the loading node j of ship s in the cargo flow subnetwork. If $\alpha_{ij}^{s,b} = 0$, otherwise
$\beta_{ij}^{s,b}$	Binary decision variable. If $\beta_{ij}^{s,b} = 1$, cargo b is unloaded from the unloading node i of ship s in the cargo flow subnetwork to the destination node j in the cargo O/D subnetwork. If $\beta_{ij}^{s,b} = 0$, otherwise

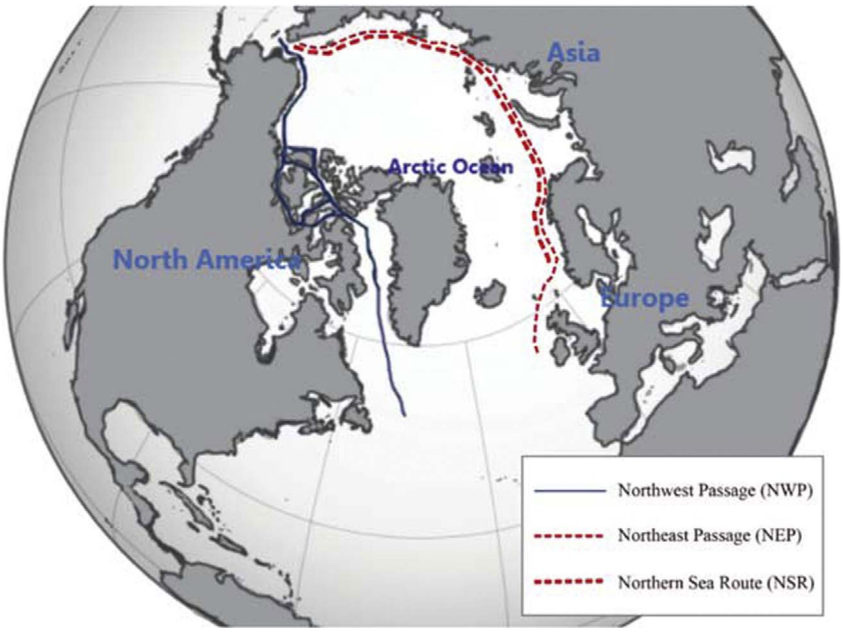

Fig. 1. Illustration of Arctic sea routes.