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A mixed-integer linear programming-based scheduling model for refined-oil shipping

Yixin Ye[a,b], Shengming Liang[a], Yushan Zhu[a,*]

[a] Department of Chemical Engineering, Tsinghua University, Beijing 100084, PR China
[b] Present address: Department of Chemical Engineering, Carnegie-Mellon University, Pittsburgh, PA, USA

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ABSTRACT

The refined oil transportation problem investigated in this paper lies on the intersection of the scheduling and routing of tramp shipping and the petroleum supply chain, with unprecedented large-scale and complex rules. Two mixed-integer linear programming formulations are developed for the assignment between tasks, vessels, and timing issues. The first model uses a time-slot concept under a continuous-time representation, where the constraints that deal with vessel assignment, capacity, timing, demand, and slack stock control are considered. The second model uses a discrete-time representation with time assignment, portal counting, and strict stock control constraints. By virtue of the data collected from an oil company, this modeling approach is validated and used to generate feasible scheduling solutions with lower costs than are currently achieved in the real situation. Finally, the impact of the model parameters is analyzed under different optimization scenarios.

1. Introduction

The supply chain in the petroleum industry comprises exploration at the wellhead, crude oil transportation, manufacturing at refineries, and the distribution and delivery of refined oil products (Shah et al., 2011; Pinto et al., 2000). Although the trend in the petroleum industry is towards enterprise-wide optimization to ensure competitiveness in the global market (Grossmann, 2005; Grossmann and Furman, 2009; Ross, 2000), the optimization of each component of the petroleum supply chain remains challenging because of the huge scale and complex operational characteristics. China is a geographically large country, and the distribution of its crude oil resources is imbalanced. About half of the refined oil is produced in the north of China, whereas this region accounts for only 20% of the total energy consumption of the country. This leads to large-scale oil transportation between the major oil producing areas and the more developed and higher energy-consuming southeast coastal regions. Shipping from northeast to southeast through the East China Sea is the favored route, as shown in Fig. 1. This study attempts to optimize the vessel scheduling of the shipping process based on a real case from a major oil enterprise in China. As larger vessels usually cost less per unit volume and distance, different scheduling plans may produce significant cost savings. Current transportation costs can be millions of RMB per month, which indicates the great potential for savings. At present, the scheduling process is operated manually, with hundreds of people frequently updating information and making decisions regarding traveling and loading/unloading, a system which suffers frequent conflicts. Therefore, mathematical programming-based scheduling (Méndez et al., 2006; Maravelias, 2012; Maravelias and Grossmann, 2003; Ierapetritou and Floudas, 1998), albeit with simplifications with respect to the real problem, offers the potential to enhance the usage of both human and shipping resources.

The maritime transportation of large quantities of bulk cargoes (in our case, refined oil) is often referred to as tramp shipping. Because of the crucial role tramp shipping plays in regional and international trade (Christiansen et al., 2013), there has been considerable research involving scheduling and routing in this domain. Christiansen et al. (2013) conducted a comprehensive review on ship routing and scheduling, including liner, industrial, and tramp shipping. Hoff et al. (2010) described the industrial aspects of combined fleet composition and routing in maritime and road-based transportation. Various methods have been employed to tackle tramp shipping problems, such as constructive heuristics, simulation, and mathematical modeling. Set partitioning and Integer

* Corresponding author.
E-mail address: yszhu@tsinghua.edu.cn (Y. Zhu).

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Nomenclature

Sets

I	Shipping tasks
I_j	Shipping tasks that potentially can be assigned to vessel j
$I(X)$	Shipping tasks that deliver gasoline
$I(Y)$	Shipping tasks that deliver diesel
I_{jk}	Shipping tasks that are required to be assigned to slot k in vessel j (calculated by continuous model, for discrete-time model only)
J	Vessels (ships)
J^{L3}	Vessels in group L3 (same with others)
JK_i	Time slot k in vessel j that is assigned to task i (calculated by continuous model, for the discrete-time model only)
K	Time slots
K_j	Potential time slot set for vessel j
KK_j	Time slots that are required to work in vessel j (calculated by continuous model, for the discrete-time model only)
X	Gasoline
Y	Diesel

Indices

i,i'	Shipping tasks
j	Vessels (ships)
k	Time slots
n	Destination portals
u	Oil subtypes
t,θ	Time intervals (8 h)
day	Days

Parameters

Bx_j^{MIN}	Lower bound of loading capacity of vessel j
Bx_j^{MAX}	Upper bound of loading capacity of vessel j
Bl^{MIN}	Lower bound of one-species loading capacity for L3 vessels
α_X	Volume-mass coefficient of gasoline
α_Y	Volume-mass coefficient of diesel
$dist_{n(i)}$	Distance of destination portal n from the starting portal (km), which belongs to task i
D_i	Demand of task$i$
pp_{jk}	Time length of slot k in vessel j (calculated by continuous model, for the discrete-time model only)
ppp_{ijk}	Time length of slot k in vessel j before arriving at task i's destination portal (calculated from continuous model, for the discrete-time model only)
N^D	Number of days in scheduling horizon
N^T	Number of time intervals in scheduling horizon
Rx	Average daily restocking of gasoline
Ry	Average daily restocking of diesel
$SSX0$	Initial inventory of gasoline
$SSY0$	Initial inventory of diesel
$SSXm$	Highest inventory of gasoline
$SSYm$	Highest inventory of diesel
vl_j	Loading/unloading speed of vessel j (ton per day)
v_j	Traveling speed of vessel j (ton per day)

Variables

B_{ijk}	Loading amount of slot k in vessel j which is assigned with task i
B_{jk}	Loading amount of slot k in vessel j
ccx_{nj}	Cost coefficient of vessel j carrying gasoline to destination portal n
ccy_{nj}	Cost coefficient of vessel j carrying diesel to destination portal n
Cx_{jk}	Cost of slot k in vessel j carrying gasoline
Cy_{jk}	Cost of slot k in vessel j carrying diesel
Ma_{jk}	Time length of the longest travel of slot k in vessel j (for vessels belonging to L3 group)
$nums_{jk}$	Number of time intervels needed for uploading at starting port of vessel j operating in slot k
$numd_{ijk}$	Number of time intervels needed for unloading at destination port of vessel j operating in slot k
p_{jk}	Time length of slot k in vessel j
T_{jk}	Starting time of slot k in vessel j
Bx_{day}	Loading amount of gasoline this day
By_{day}	Loading amount of diesel this day
Sx_{day}	Inventory level of gasoline this day
Sy_{day}	Inventory level of gasoline this day
W_{ijk}	Define whether task i is assigned to slot k of vessel j
Y_{jkt}, $Y_{jk\theta}$	Define whether slot k in vessel j starts on the t^{th}/θ^{th} time intervel
Z_{ijkt}, $Z_{ijk\theta}$	Define whether slot k in vessel j which is assigned with task i arrives at a destination portal on the t^{th}/θ^{th} time intervel

Programming/Mixed-Integer Linear Programming (IP/MILP) models are often used, with MILP models the most dominant (Hoff et al., 2010). By considering the shipping problem as a stage in the petroleum supply chain and surveying the other stages, MILP still represents an important mathematical modeling tool. Iyer et al. (1998) developed a multi-period MILP for the planning and scheduling of offshore oil field infrastructure investments and operations. Más and Pinto (2003) developed a MILP formulation addressing short-term crude oil scheduling problems in a distribution complex that contains ports, refineries, and the pipeline infrastructure between them.

Recent research on MILP modeling includes the work of Sherali et al. (1999), who constructed a discrete-time MILP model for a ship routing and scheduling problem from Kuwait Petroleum Corporation involving five vessel types and ten destinations over the horizon of a year. Jetlund and Karimi (2004) proposed a MILP formulation using variable-length slots to decompose the fleet schedule into single-ship problems. In 2015, Cóccola and Méndez introduced a continuous time precedence-based MILP mathematical formulation embedded within a heuristic-based algorithm to obtain sub-optimal solutions for routing and scheduling a fleet of multi-parcel chemical tankers involving three ports. Compared with existing models, the problem considered in this paper has a much larger event space regarding the number of different vessels and portals. The hybrid pattern of single and multiple destinations also increases the modeling complexity. As a result, heuristic decomposition is introduced, resulting in the fleet composition and time assignment problems being solved iteratively. The first model is constructed based on the time-slot concept (Pinto and Grossmann, 1995), whereas the second is a discrete-time model. Sub-optimal results can be achieved within a reasonable time, reducing the total cost by approximately 6%. In the following sections, the problem statement for refined oil shipping scheduling is described, and then the mathematical programming models are formulated. Finally, the results of an industrial case study are presented and discussed.