INTERACTIVE DECISION MAKING MODELS FOR MARITIME FREIGHT CARRIERS

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ABSTRACT

We model situations in which multiple cargo carriers interact under different scenarios to determine optimal carrier assignment to different routes and the optimal volume of cargo to be sent to different ports of the selected routs. We have first modeled the profit function for each carrier and next have introduced game theoretical models to be applied in different interactive scenarios. This study is an initial attempt to examine if the cooperative contracts among the cargo carriers can result in a higher profit. Further comparison between different carrier dynamics will show which contract will suit different situations best and resulting in maximum profit.

Keywords: Mixed linear programming, optimal cargo scheduling

LITERATURE REVIEW

Due to the opportunities and challenges new trends in global trade offer in research, numerous studies have focused on port operations and shipping. Despite this considerable amount of research, the economic aspects of oceanic shipping have not yet received substantial attention in literature. These topics are still in their initial stages, and need collaborative research with the sharing of experiences, from both academics and practitioners. In the followings, first, we briefly review the literature on port operations, then the literature on shipping.

Port Operations

Ports can be described as connecting nodes through which cargo flows. At one side of the port there is the sea or quay where the cargo is loaded on and unloaded off the ships, and at the other side there is the land of the port where the cargo is loaded on or unloaded off to trains, trucks or barges. Cargo is often stored for a period of time in the port waiting for further transportation on either by sea-going vessels or by a land based mode of transportation. Terminals serve as the main intermediator between seaside and landside operations.

Due to a rapid growth in world trade, sea ports play a vital role in global supply chains. As shippers take advantage of economies of scale by increasing vessel size to accommodate larger loads, ports must be capable of handling these massive vessels, in the shortest time possible, while offering competitive rates. To provide this cost effective and efficient service, terminal operators, shipping companies, and port authorities are investing in new technologies to improve handling infrastructure, operational efficiency, and security measures. Many major ports have increased their number of sea terminals, common train and barge terminals, storage, and inspection areas. Additionally, ports have deepened their navigable channels at the cost of millions of dollars. Further, to cope with congestion, terminal operators must make a choice between investing in automation or additional labor. Many operators must invest in larger cranes capable of reaching across these increasing large ships. Some companies now have “dry port” terminals which are inland terminals working in conjunction with sea terminals [1] [2]. These developments have led to major inter-terminal transport flows within the port area, with the aim of bundling cargo for transportation to hinterland destinations or distributing cargo from hinterland terminals for sea transport. Due to the opportunities and challenges that new trends in port operations offer, ports are receiving increased attention from the academic community. Analytical models have been used by port managers to make informed decisions on controlling expenses and deploying assets. Further, these models have improved the planning and execution of port and freight transportation services. For example, multiple papers have focused on the use of operations research models for handling (containerized) cargo [3] [4] [5] [6] [7] [8] [9] [10] [11] [12] [13].

Ships and Shipping

In view of the economic importance of oceanic freight transportation and the impact it has on the environment, planning the shipping operations significantly impacts its performance, and consequently the world economy. On general, the literature can be divided into two general categories [14], including (1) fleet design, (2) network design, routing and scheduling.
In the design of the fleet size and mix, the objective is to minimize the fixed and variable costs of the operating fleet subject to practical constraints such as satisfying the supply and demand. A homogeneous or heterogeneous fleet can be acquired to transport the cargo, where in the homogeneous fleet, all the vessels are of the same type, size, and cost. [15] is pioneering such models with formulating a problem with naval homogenous fuel oil tankers. Later, [16] extended the problem by considering a given number of tankers and a utility for each cargo. Other recent contributions can be found in [17] [18] [19] [20] [21] [22] [23]. The other area on which most authors have focused is the network design, routing, and scheduling ships transporting cargo (see, for example, [24] [25] [26] [27] [28] [29] [30] [31]. In the routing problem, the main decision is the sequence of ports that have to be visited by the ship, whereas in the scheduling problem, the temporal and spatial aspects are considered at the same time. Due to the constant increase of the international freight transportation, the importance of ship routing and scheduling problems has increased substantially. Introduction of OR models to routing and scheduling ships has improved several key performance indicators in different companies [32] [33]. Many applications can be also seen in the Navy [34] [35] [36].

THE MATHEMATICAL MODEL

Consider a port from where several ships are transporting cargoes to given set of destinations. Some of the destinations are connected in a way that they can be visited in one route and unloading cargoes. The problem is the determination of the most cost efficient assignment of the ships to the different routes and the optimal volume of cargos sent to the different ports of the selected routs. In developing the mathematical model we introduce the notation shown in Table 1.
Note x_{nk} is a binary variable while z_{np} is a continuous decision variable ($1 \leq n \leq N, 1 \leq k \leq K,$ and $1 \leq p \leq P$).
The constraints are given as follows:
Each ship cannot select more than one route:

$$\sum_{k=1}^{K} x_{nk} \leq 1 \qquad 1 \leq n \leq N \qquad (1)$$

N	number of ships	C_k	set of ports on route k
K	number of feasible routes	m_n	minimal cargo volume for ship n to be taken
P	number of destination ports	γ_{nk}	shipping cost on route k by ship n
R_{np}	unit revenue of taking cargo to port p by ship n	L_p	capacity limit for arriving cargo in port p
x_{nk}	$\begin{cases} 1 & \text{if ship n selects route k} \\ 0 & \text{else} \end{cases}$	z_{np}	amount of cargo taken by ship n to port p
M_n	cargo volume upper bound for ship n	μ_p	minimum requirement for arriving cargo in port p
I_p	maximum requirement for arriving cargo in port p		

TABLE 1. **Mathematical model notation**

The ships can deliver cargo to ports belonging only to the route of their choices, and total cargo volume cannot exceed the allowed upper bound M_n:

$$\sum_{p \in C_k} z_{np} \leq M_n x_{nk} \quad 1 \leq k \leq K, 1 \leq n \leq N \tag{2}$$

The total cargo volume must satisfy certain minimum requirements

$$m_n\, x_{nk} \leq \sum_{p \in C_k} z_{np} \quad 1 \leq k \leq K, 1 \leq n \leq N \tag{3}$$

For each port the total arriving cargo volume must satisfy minimum requirements and must not exceed total amount to be sent there and its accepting capacity limit

$$\mu_p \leq \sum_{n=1}^{N} z_{np} \leq \min\{L_p, I_p\} \quad 1 \leq p \leq P \tag{4}$$

The profit of the ship n is the difference of its revenue and cost:

$$\varphi_n = \sum_{p=1}^{P} R_{np}\; z_{np} - \sum_{k=1}^{K} x_{nk}\, \gamma_{nk} - \Delta_n \left(1 - \sum_{k=1}^{K} x_{nk}\right) \tag{5}$$

where in addition Δ_n is the unit cost by being idle not shipping anything.
Assume finally that the N ships belong to T different companies, and let F_t denote the set of ships owned by company t. Then the profit of company t is clearly

$$\phi_t = \sum_{n \in F_t} \varphi_n \tag{6}$$

The decision variables of the model are the route selection binary variables x_{nk} and the cargo volume continuous variables z_{np}. The objective function of each company as well as all constraints are linear, therefore the model is a mixed linear optimization problem with continuous and binary variables. The solution of the model provides the optimal routing and cargo size of each ship belonging to each company.

SOLUTION METHODOLOGY

A T-person game is defined, where the players are the ship companies. The strategy set of each player t is the set $\{ x_{nk} \in \{0,1\}, n \in F_t, 1 \leq k \leq K\} \cup \{z_{np} \geq 0, n \in F_t, 1 \leq p \leq P\}$ and its payoff function is ϕ_t. Notice that the strategy sets are not independent because of constraint (4).
There are several concepts of finding solution of this game. In applying non-cooperative game theory, the Nash-equilibrium is determined which gives maximum profit to each player, assuming that the other players keep their equilibrium decisions. In the case of cooperation, the firms first maximize their total profit:

$$\sum_{t=1}^{T} \phi_t \rightarrow \max \tag{7}$$

and then the maximum amount is divided up among the players based on certain fairness criteria. Depending on the condition what is considered fair by the players, different solutions can be obtained. In the case of partial cooperation each player takes the interest of the others into consideration in a certain portion. Then a non-cooperative game is solved with the modified payoffs:

$$\overline{\phi}_t = \phi_t + \sum_{\tau \neq t} \alpha_{t\tau} \phi_\tau \tag{8}$$

where $\alpha_{t\tau}$ gives the cooperation level of player t toward player τ. If the game is considered as a conflict among the players, then a conflict resolution method can be used. The most popular approach is the Nash bargaining solution, which maximizes the Nash-product:

$$\prod_{t=1}^{T} (\phi_t - \phi_{t*}) \rightarrow \max \tag{9}$$

where ϕ_{t*} is the disagreement value for player t, which can be taken as zero (if no business is realized) or the Nash-equilibrium payoff value.
In the special case when all ships belong to one company, then the problem is a simple optimization problem where the company profit is maximized:

$$\phi = \sum_{n=1}^{N} \varphi_n = \sum_{n=1}^{N} \{ \sum_{p=1}^{P} R_{np} \; z_{np} - \sum_{k=1}^{K} (\gamma_{nk} - \Delta_n) x_{nk} - \Delta_n \} \tag{10}$$

subject to the constraints $x_{nk} \in \{0,1\}, z_{nk} \geq 0, (1), (2), (3)$ and (4).
There are efficient methods and software packages for solving optimum problems with both binary and continuous variables. The overall objective function (7) as well as the individual objective (6) of each firm are linear, so for obtaining optimal solutions or the best responses of the firms the corresponding linear optimum problems have to be solved. The same holds in the case of partial cooperation of the firms, however in the case of the Nash bargaining solution (9) the objective function is nonlinear. However, by taking its logarithm, a concave function is obtained. Since all constraints are still linear, standard methods and software packages are available for finding the optimal solution.

CONCLUSIONS

In this paper we have introduced cooperative and non-cooperative game theoretical concepts to be used in the ship carrier contracting. Further study is needed to compare the different interactive models among the carriers and to determine the maximum profit. Mechanisms such as revenue sharing need to be designed for such cooperative contracts, as well.

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