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A survey on maritime fleet size and mix problems

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ABSTRACT

This paper presents a literature survey on the fleet size and mix problem in maritime transportation. Fluctuations in the shipping market and frequent mismatches between fleet capacities and demands highlight the relevance of the problem and call for more accurate decision support. After analyzing the available scientific literature on the problem and its variants and extensions, we summarize the state of the art and highlight the main contributions of past research. Furthermore, by identifying important real life aspects of the problem which past research has failed to capture, we uncover the main areas where more research will be needed.

1. Introduction

As the first decade of the third millennium ended with a worldwide financial and economic crisis, several countries experienced a decrease in their gross domestic product. In 2009 the world trade fell by 22.9% compared with the year before, the deepest fall in 70 years, and this strong downturn also affected seaborne volumes, which decreased by 4.5% (UNCTAD, 2010). Looking beyond the recent downturn, maritime economics has always been characterized by a cyclic repetition of peaks and troughs in demand and freight rates. While the demand of maritime transportation reacts quickly to changes in freight rates, the supply adapts slowly to changes in demand, mostly because of the long lead time associated with the acquisition of new ships. Imbalances between supply and demand are therefore common. This can be illustrated by the fact that in 2009 the world fleet grew by 7% over the year before, a growth that continued also in the beginning of 2010, despite the reduction in trade volumes. The tonnage oversupply was the result of orders for new ships submitted before the downturn. One often sees that in a trough, the tonnage is renewed, while in a peak one tends to postpone the demolition of older ships. Illustrating this pattern, a 300% increase in demolitions of old tonnage was observed during 2009 (UNCTAD, 2010).

These dynamics are one of the main triggers of the wave-motions in freight rates which are typically referred to as shipping market cycles. They can be described as the overlapping of three different cycles (Stopford, 2009):

1. long-term cycles, typically driven by major changes in the industries of seaborne commodities,
2. short-term cycles, which mainly follow the evolution of the world economy, and
3. seasonal cycles, characteristic of many seaborne commodity trades (e.g. agricultural ones).

Shipping companies operate in such an uncertain and changeable environment, and a crucial strategic decision is that of designing an optimal fleet of ships. In its basic version the *maritime fleet size and mix problem* (MFSMP) consists of deciding how many ships of each type to use in order to meet the demand. The objective is typically to minimize the total cost of setting up and operating a fleet of ships and usually the problem includes ship routing or deployment decisions to support the tonnage estimation.

An example of an objective function for a basic version of the MFSMP is given in (1), and consists of a fixed term associated with the acquisition of ships and a variable term associated with their operations.

$$\min \sum_{v\in V} C^F_v y_v + \sum_{v\in V}\sum_{r\in R_v} C^V_{vr} x_{vr} \tag{1}$$

Here, V is the set of available ship types and R_v represents the set of routes r that a ship of type v can sail. In the first term of (1) C^F_v represents the cost of including a ship of type v in the fleet, while variable y_v represents the number of ships of type v to include. In the second term, C^V_{vr} represents the cost of sailing route r with ships of type v and decision variable x_{vr} represents the number of times route r is sailed by ships of type v.

To ensure feasibility of the fleet operations, constraints need to keep track of the consumption of resources associated with the ships. Constraints (2) provide an example, where Z_{vr} is the time consumed every time a ship of type v sails route r, and Z represents the total amount of time available for each ship within the planning horizon. In some applications, other resources than time, such

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as the number of available ships of a type, may be modeled in a similar way.

$$\sum_{r\in R_v} Z_{vr}x_{vr} - Zy_v \leqslant 0, \quad v \in V \tag{2}$$

Additionally, constraints are needed to ensure that ship operations are performed to meet the demand. Constraints (3) represent an example of such constraints ensuring that each port (or region) $i \in N$ is called at least D_i times during the planning horizon. The parameter A_{ir} is equal to 1 if route r calls port i, and is equal to 0 otherwise. Ships have to sail each route a number of times sufficient to meet the frequency requirement for each port. Alternatively, or in addition to constraints (3), one may want to control the amount of cargo shipped to each port. In this case, let D_i be the demand of port i and Q_v the capacity of a ship of type v. Constraints (3) could then be modified by multiplying the argument of the summation in the left-hand side by parameter Q_v. The left-hand side would then represent the total amount of cargo shipped to port i. However, the type of ship operations is very much dependent on the specific problem and may vary substantially from one problem to another. Therefore, different or additional restrictions might be wanted.

$$\sum_{v\in V}\sum_{r\in R_v} A_{ir}x_{vr} \geqslant D_i, \quad i \in N \tag{3}$$

Finally, a typical mathematical model includes restrictions on the variables domain, where variables of type y_v are usually restricted to take integer values while the restrictions put on variables of type x_{vr} depend on the specific problem.

In this paper we present a literature survey on the MFSMP and its variants and extensions. Based on the survey, we discuss the state of the art and point out possible directions for future research within the subject. The remainder of this paper is organized as follows. In Section 2 we give a more thorough motivation for the survey. The relevant literature is examined in Section 3. In Section 4 the state of the art is discussed and future research perspectives are pointed out. Concluding remarks are given in Section 5.

2. Background and motivation for the survey

A survey on the general fleet size and mix problem was presented by Hoff et al. (2010), who discussed the industrial aspects of the fleet composition and routing. The main focus was on the fleet size and mix vehicle routing problem and its variants. However, methods proposed for the fleet size and mix vehicle routing problem are not necessarily applicable to maritime problems which in most cases have operational characteristics that differ from those implied by a vehicle routing problem structure (see the discussions by Ronen (1983) and Christiansen et al. (2007)). Hoff et al. (2010) also surveyed a number of applications of both land-based and maritime problems. However, additional studies describing maritime applications are available in the literature, besides the ones they listed.

A specific investigation of the maritime applications literature is in place because several aspects of the MFSMP, other than the operational differences, make it different from the fleet size and mix problem for other transportation contexts. Distinguishing elements are, for example: (1) higher level of uncertainty, (2) higher amount of capital involved, and (3) the ships' value function. Below we elaborate upon each of these characteristics for maritime applications.

Uncertainty in maritime transportation, as discussed in the introduction, affects all planning levels. To the best of our knowledge, no other transportation context is affected by such high level of uncertainty in demand, ship costs and freight rates. As an example, in 2009 the average daily charter rate for 1600–1999 TEUs container ships fell by 67.6% from 2008, and in 2010 it was less than half than in 2008 (UNCTAD, 2011). Furthermore, uncertainty is emphasized by the long lifetime of ships which is usually around 30 years. This is much longer than for road-based vehicles, but can be comparable to the lifetime of aircraft and trains. Therefore, investments in ships require taking a long-term view of the shipping company's prospects. To this extent, Stopford (2009) suggests that the direction of change for the geopolitical environment should be the starting-point for any future analysis, rather than economics.

The amount of capital needed to acquire new (or second-hand) ships also distinguishes MFSMPs from their land-based counterparts, and is comparable with the amounts needed to acquire new airplanes. New ships may cost up to hundreds of million USD and this increases the relevance of the financing of the investment. Generally, several financing alternatives are available and the chosen one will influence the capital cost of a ship (i.e. the sum of debt repayment and interest or dividend). These costs can amount to more than 40% of the total running costs even for a ten-year-old ship (Stopford, 2009).

Finally, the evolution of the value (and price) of ships differ from that of most other vehicles which usually decreases as time goes by. As an example, Couillard and Martel (1990) modeled the value of road vehicles as a decreasing function of age and mileage. The value of a ship is a more complex parameter to model. Adland and Koekebakker (2007) conclude that the second-hand value of a given type of ship can be described as a non-linear function of three parameters: size, age, and the state of the freight market. Several other studies exist on modeling the variation of ship value over time. Examples are Tsolakis et al. (2003) and Ådland and Koekebakker (2004).

In this paper we focus on MFSMPs for shipping companies that are primarily interested in ships for transportation purposes. That is, we will not include literature where the MFSMP has been studied under the perspective of asset play (see, e.g., Alizadeh and Nomikos, 2007; Marcus et al., 1991; Bendall and Stent, 2005 and Sødal et al., 2009).

3. Literature review

In the following literature review on the MFSMP we distinguish between single-period MFSMPs which will be referred to simply as MFSMPs, and multi-period MFSMPs which will be referred to as *maritime fleet renewal problems* (MFRP). The former category of problems focus on the design of a fleet of ships for transportation systems whose characteristics are meant to remain unchanged over time and therefore do not to take into account the the evolution from a point in time to another. They may also represent short-term operations. The latter is an extension of the MFSMP in which a dynamic adjustment of the fleet in response to the evolution of the service requirements is sought. In this case the problem implies an existing fleet to be renewed from time to time and a planning horizon which is to be considered a succession of time periods. A variant of the MFSMP is the *maritime fleet size problem* (MFSP) which consists of determining the number of ships in a homogenous fleet, i.e. where all the ships have identical characteristics.

For each of the papers reviewed, Tables 2–5 report the following information: the way ships are acquired or disposed of, the mode of operations, the industry the study deals with, the methodology applied, and the type of operating decision the tonnage estimation is based on. As far as the operations mode is regarded, we refer to the classification given by Lawrence (1972), which distinguishes between tramp, liner and industrial. Tramp shipping operators