

# 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.

*Keywords:* logistics, maritime transportation, fleet planning

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## 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

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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 ship 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 to their operations.

$$\min \sum_{v \in V} C_v^F y_v + \sum_{v \in V} \sum_{r \in R_v} C_{vr}^V x_{vr} \quad (1)$$

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)  $C_v^F$  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,  $C_{vr}^V$  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 as the number of available ships of a type, may be modeled in a similar way.

$$\sum_{r \in R_v} Z_{vr} x_{vr} - Zy_v \leq 0, v \in V \quad (2)$$

Finally, 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.

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

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 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

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9 and the chosen one will influence the capital cost of a ship (i.e. the sum of  
10 debt repayment and interest or dividend). These costs can amount to more  
11 than 40 % of the total running costs even for a ten-year-old ship (Stopford,  
12 2009).

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

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24 In this paper we focus on MFSMPs for shipping companies that are pri-  
25 marily interested in the ships for transportation purposes. That is, we will  
26 not include literature where the MFSMP has been studied under the per-  
27 spective of asset play (see, e.g. , Alizadeh and Nomikos (2007), Marcus et al.  
28 (1991), Bendall and Stent (2005), and Sødal et al. (2009)).  
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### 34 3. Literature review

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36 In the following literature review on the MFSMP we distinguish between  
37 single-period MFSMPs which will be referred to simply as MFSMPs, and  
38 multi-periods MFSMPs which will be referred to as *maritime fleet renewal*  
39 *problems* (MFRP). The former category of problems focus on the design of  
40 a fleet of ships transportation systems whose characteristics are meant to  
41 remain unchanged over time and therefore do not to take into account the  
42 the evolution from a point in time to another. They may also represent  
43 short-term operations. The latter is an extension of the MFSMP in which a  
44 dynamic adjustment of the fleet in response to the evolution of the service  
45 requirements is sought. In this case the problem implies an existing fleet to  
46 renew from time to time and a planning horizon which is to be considered  
47 as succession of time periods. A variant of the MFSMP is the *maritime fleet*  
48 *size problem* (MFSP) which consists of determining the number of ships in a  
49 homogenous fleet, i.e. where all the ships have identical characteristics.  
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53 For each of the papers reviewed, Tables 2 to 5 report the following infor-  
54 mation: the way ships are acquired or disposed of, the mode of operations,  
55 the industry the study deals with, the methodology applied, and the type  
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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 operate on customers' callings. In addition to cargoes whose transportation is agreed through long-term contracts, they typically try to increase the profit by carrying optional spot cargoes. In liner shipping ships sail according to a public fixed schedule. Their profits are therefore influenced by the schedule and frequency published. Finally, in the industrial mode the owner of the goods to transport operates its own ships and seeks to minimize transportation cost. Table 1 reports the notation and the abbreviations, other than those introduced when needed throughout the text, used in the tables.

Section 3.1 describes the available papers on the MFSMP. Papers on the MFSP are presented in Section 3.2, while Section 3.3 reports the available papers on the MFRP. Finally, Section 3.4 presents some papers in which the fleet size and mix is corrected within the frame of tactical problems.

Table 1: Notation used in the following tables

Acquisition/ disposal of	Mode	Methodology	Operating decision
CI=Charter in	LI=Liner	HEU=Heuristic	D=Deployment
CO=Charter out	TR=Tramp	StP=Stochastic programming	R=Routing
P=Purchase	IN=Industrial	SIM=Simulation	S=Scheduling
B=Building		QM=Queue modeling	--=Not reported
CP=Choose from a pool		NLP=Non-linear programming	
LU=Lay up		OC=Optimal control	
SE=Sale		RO=Robust optimization	
SC=Scrapping			
--=Not reported			

### 3.1. Maritime fleet size and mix problems

In this section we first present the available studies on the MFSMP as a strategic problem, and second studies that consider the fleet size and mix on

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9 a tactical level only. Table 2 summarizes the ones belonging to the former  
10 category.

11 The first contribution to this category of problems was given by [Everett et al.](#)  
12 (1972) who presented the problem of composing the U.S. merchant marine  
13 fleet. A linear programming (LP) problem was used to obtain the best ship  
14 designs and sizes for a fleet of tanker and bulkers supposed to carry 15% of  
15 the U.S. foreign trade (e.g. grain, oil, coal and ores). The problem was later  
16 slightly modified and re-proposed by [Bradley et al.](#) (1977). During the same  
17 period, [Murotsu and Taguchi](#) (1975) combined dynamic programming (DP)  
18 and non-linear programming to determine the optimal fleet size and mix for  
19 a fleet of crude oil carriers. They assumed only one origin port and one  
20 destination port. The characteristics of the ships (size and speed) were also  
21 variables of the problem and hence determined by their procedure instead of  
22 being fixed in advance.

23 Later, a number of authors proposed heuristic procedures for the solution  
24 of the problems they illustrated. [Larson](#) (1988) studied the problem of trans-  
25 porting sludge from waste water treatment plants in the city of New York to  
26 an offshore dumping site. Among other strategic issues, the number and the  
27 size of the vessels to employ were to be determined. [Pesenti](#) (1995) proposed  
28 a heuristic procedure to support purchasing and use of container ships. The  
29 algorithm consists of exchange of information and decisions between all plan-  
30 ning levels. Strategic decisions are passed to the tactical level to be tested  
31 and receive a feedback. Then the strategic level can emend its solution or  
32 make it final. [Sigurd et al.](#) (2005) studied the problem of establishing a new  
33 liner shipping system for container transportation from Norway to Central  
34 Europe. They evaluated the possibility of building up to 15 different ships to  
35 ensure the desired service speed and frequency. The problem was formulated  
36 as a set partitioning problem and solved by means of a heuristic branch-  
37 and-price algorithm. Finally, [Zeng and Yang](#) (2007) described the problem  
38 of deciding both fleet size and mix and ship schedules for a Chinese coal  
39 shipping system. Coal was transported by rail to three outbound ports and  
40 then shipped to demand ports. A tabu search heuristic was used to solve the  
41 original integer programming (IP) formulation of the problem. [Crary et al.](#)  
42 (2002) aimed to determine the U.S. destroyers fleet size and mix in sight of  
43 a potential conflict on the Korean peninsula. Each mission had a random  
44 weight dependent on the actual war dynamics. They solved multiple times  
45 a mixed integer programming (MIP) problem under different realization of  
46 the weights of the missions in order to estimate the war winning probability  
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and to find the fleet performing the best.

Two papers describe the use of simulation to evaluate alternative fleets. The first one, proposed by [Darzentas and Spyrou \(1996\)](#), treats the development of a ferry system in the Aegean Sea. They simulated the ferry traffic under different setting of the system (e.g. port layouts and ferry routes), including different ferry fleet configurations. Key indicators were for example the passenger’s delay and the number of ships in queue at ports. A similar approach was used by [Fagerholt et al. \(2010\)](#). A set of different strategic decisions were given as input to a simulation tool. The tool first draws realizations for a set of elements not under the company’s control (e.g. cargo quantities and time windows) and then solves short term ship routing and scheduling problems during the simulation. The set of strategic decisions may include fleet size and mix decisions, although the case study presented did not.

Table 2: Papers on the strategic MFSMP

Paper	Acquisition/ disposal	Mode	Industry	Methodology	Operating decisions
<a href="#">Bradley et al. (1977)</a>	P	IN	Bulk shipping	LP	D
<a href="#">Crary et al. (2002)</a>	P	IN	Navy	MIP	D
<a href="#">Darzentas and Spyrou (1996)</a>	–	LI	Passengers transportation	SIM	–
<a href="#">Everett et al. (1972)</a>	P	IN	Bulk shipping	LP	D
<a href="#">Fagerholt et al. (2010)</a>	–	TR or IN	General shipping	SIM	R+S
<a href="#">Larson (1988)</a>	–	IN	Refuse transportation	HEU	D
<a href="#">Murotsu and Taguchi (1975)</a>	B	TR or IN	Oil shipping	DP+NLP	–
<a href="#">Pesenti (1995)</a>	P	TR	Container shipping	MIP+HEU	D
<a href="#">Sigurd et al. (2005)</a>	P	LI	Container shipping	MIP+HEU	R+S
<a href="#">Zeng and Yang (2007)</a>	-	TR	Coal shipping	IP+HEU	R

In the short-term MFSMP a fleet of ships needs to be arranged to fulfill a short-term task. Typically, ships are chosen from an available pool (e.g. a pool of ships shared between more transportation tasks) or chartered in for

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9 the length of the transportation task. From this it is understood that these  
10 are not strategic problems. Table 3 summarizes the papers on the short-term  
11 MFSMP.  
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13 To the best of our knowledge, the earliest paper in this category belongs  
14 to [Schwartz \(1968\)](#). A bargeline company is to move given cargoes from ori-  
15 gins to destinations in its district at given times. The problem consists of  
16 determining the number of barges and towboats of each size to move the car-  
17 goes. Barges and boats can be chosen from an available pool. The problem  
18 is modeled by means of an IP problem but it could not be solved with the  
19 algorithms available at that time. In the paper proposed by [Mehrez et al.](#)  
20 [\(1995\)](#), bulk products are to be shipped to transshipment ports along the  
21 Atlantic Coast and the decision maker is to decide the number and the type  
22 of ships to charter in each time period to perform the shipments. They devel-  
23 oped a heuristic algorithm to solve the IP model proposed for the problem.  
24 [Meng and Wang \(2010\)](#) presented a short-term MFSMP for a container liner  
25 shipping company that consists of deciding which of the available ships to use  
26 and their deployment as well as the number of charters (in or out). They pro-  
27 posed a chance constrained problem to tackle demand uncertainty. Lately,  
28 [Meng et al. \(2012\)](#) extended this problem including transshipment. They  
29 proposed a two-stage stochastic IP model as well as a solution algorithm.  
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32 [Fagerholt and Lindstad \(2000\)](#) studied the supply service for an offshore  
33 installation with the scope of finding which vessels to operate (charter) on  
34 weekly schedules. They first generated a number of feasible ship routes and  
35 then, by solving an IP problem, chose the schedule and the corresponding  
36 vessels to use. Later, [Halvorsen-Weare et al. \(2012\)](#) studied a similar problem  
37 including more realistic elements such as spreads of departures and maximum  
38 and minimum duration of voyages. Their optimization model was then used  
39 by [Halvorsen-Weare and Fagerholt \(2011\)](#) in combination with simulation to  
40 ensure more robust routes and fleet solutions with respect to the weather.  
41 A liner shipping service in the Pacific Sea was considered by [Lane et al.](#)  
42 [\(1987\)](#). A MIP problem selects among a set of candidate ship schedules  
43 found by a forward-looking heuristic. Ship schedules are associated to ships  
44 therefore the fleet size and mix emerges from the selection of schedules. A  
45 similar approach was used by [Fagerholt \(1999\)](#). The context was that of  
46 the development of a new liner shipping system from the Norwegian Sea to  
47 ports in Europe and U.S. The focus was on finding the optimal fleet of feeder  
48 vessels to hire for fixed periods in order to move cargoes from Norway to a  
49 central depot. Complete ship routes are generated and then a set partitioning  
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problem selects the most convenient routes and the associated vessels.

Table 3: Papers on the short-term MFSMP

Paper	Acquisition/ disposal	Mode	Industry	Methodology	Operating decisions
<a href="#">Fagerholt (1999)</a>	CI	LI	General shipping	IP	R
<a href="#">Fagerholt and Lindstad (2000)</a>	CI	IN	Offshore services	IP	R+S
<a href="#">Halvorsen-Weare and Fagerholt (2011)</a>	CI	IN	Offshore services	IP+SIM	R
<a href="#">Halvorsen-Weare et al. (2012)</a>	CI	IN	Offshore services	IP+HEU	R
<a href="#">Lane et al. (1987)</a>	CP	LI	General shipping	IP	R+S
<a href="#">Mehrez et al. (1995)</a>	CI	IN	Bulk shipping	MIP+HEU	R
<a href="#">Meng and Wang (2010)</a>	CP,CI,CO	LI	Container shipping	StP	D
<a href="#">Meng et al. (2012)</a>	CP,CI,CO	LI	Container shipping	StP	D
<a href="#">Schwartz (1968)</a>	CP,CI	TR	River system	MIP	R+S

### 3.2. Maritime fleet size problems

The MFSP is a special case of MFSMP, in which there is only one ship type. Hence, the problem is to decide the number of ships required to perform some transportation task. Table 4 summarizes the research papers related to the MFSP.

The first contribution on MFSPs dates back to 1954 ([Dantzig and Fulkerson, 1954](#)). The authors applied an LP model to determine the minimum number of tankers in order to guarantee a shipping service with a fixed schedule. Later, [Bellmore et al. \(1968\)](#) modified this problem by including a utility for each delivery and assessing the possibility to cancel some deliveries by giving up the corresponding utility. An LP model was used in that paper as well.

[Bendall and Stent \(2001\)](#) presented the problem of finding the number of identical container ships to be assigned to a high speed service in a major hub and spoke system based in Singapore. The MIP model also provided optimal deployment for the ships. The number of ferries was to be chosen in the framework of ferry network design studied by [Lai and Lo \(2004\)](#). The

Table 4: Papers on the MFSP

Paper	Acquisition/ disposal	Mode	Industry	Methodology	Operating decisions
<a href="#">Bendall and Stent (2001)</a>	–	TR,LI or IN	Container shipping	MIP	S
<a href="#">Dantzig and Fulkerson (1954)</a>	–	LI or IN	Oil shipping	LP	S
<a href="#">Jaikumar and Solomon (1987)</a>	–	LI	River system	MIP	R
<a href="#">Koenigsberg and Lam (1976)</a>	–	TR,LI or IN	LNG shipping	QM+SIM	–
<a href="#">Koenigsberg and Meyers (1980)</a>	–	TR,LI or IN	LNG shipping	QM+SIM	–
<a href="#">Lai and Lo (2004)</a>	CI,P	LI	Passengers transportation	MIP+HEU	R+S
<a href="#">Larson et al. (1991)</a>	P	IN	Refuse transportation	SIM	R
<a href="#">Richetta and Larson (1997b)</a>	P	IN	Refuse transportation	SIM	R
<a href="#">Sambracos et al. (2003)</a>	–	LI	Container shipping	MIP	R
<a href="#">Shyshou et al. (2010)</a>	CI	IN	Offshore services	SIM	–

objective was that of finding an optimal ferry network configuration taking into account set up and operating costs as well as passengers’ performance measures (e.g. waiting time). They used a heuristic algorithm to solve the MIP formulation for the problem. [Sambracos et al. \(2003\)](#) investigated the introduction of small containers in a coastal shipping system in the Aegean Sea. They proposed a MIP model to determine the number of similar container vessels to use while ship operations were modeled as a vehicle routing problem.

Two studies dealt with barge-tugs systems. [Jaikumar and Solomon \(1987\)](#) studied the minimization of the number of tugs to acquire in order to move a given number of barges between ports in a river system. By exploiting the particular structure of the problem they proposed a polynomial exact algorithm to solve the IP formulation of the problem. On commission of the New York City department of sanitation [Larson et al. \(1991\)](#) developed a simulation tool for supporting the task determining the number of barges to transport refuse to an offshore landfill. The performance of different fleet sizes was tested for example in terms of tonnage of delayed refuse and time spent

at the dumping site. This work was later extended by [Richetta and Larson \(1997a\)](#) to adapt the simulation tool to the changes occurred in the marine transport system due to new environmental regulations and technologies.

Some other studies described the use of simulation. [Shyshou et al. \(2010\)](#) dealt with supply vessels for anchor handling operations. Such vessels are hired either on long-term charters or on spot charters which are usually more expensive. The objective was that of finding the cost optimal fleet of vessels on long-term charter. Different fleet sizes were evaluated in a discrete event simulation framework. A fleet of liquid natural gas vessels was to be assembled in the papers of [Koenigsberg and Lam \(1976\)](#) and [Koenigsberg and Meyers \(1980\)](#). The former considered gas transportation between one loading and one or two discharge ports while the latter applied the model to the transportation of gas between Alaska and Los Angeles. In both papers different fleet sizes were evaluated in a simulation tool and the underlying operations were described by means of queuein models.

### 3.3. Maritime fleet renewal problems

In this section we report on the available papers on the MFRP. The papers reviewed are summarized in Table 5.

Table 5: Papers on the MFRP

Paper	Acquisition/ disposal	Mode	Industry	Methodology	Operating decisions
<a href="#">Alvarez et al. (2011)</a>	P,CI,CO,SE,SC,LU	TR or IN	Bulk shipping	RO	D
<a href="#">Cho and Perakis (1996)</a>	P,B,CI,LU	LI	General shipping	MIP	D
<a href="#">Jin and Kite-Powell (2000)</a>	B,SC	TR,LI or IN	General shipping	OC	–
<a href="#">Meng and Wang (2011)</a>	P,CI,CO,SE,LU	LI	Container shipping	DP	D
<a href="#">Nicholson and Pullen (1971)</a>	CI,SE	TR,LI or IN	General shipping	DP	–
<a href="#">Wijsmuller and Beumee (1979)</a>	B,CI,SE,LU	LI	General shipping	LP	–
<a href="#">Xie et al. (2000)</a>	P,LU	TR,LI or IN	General shipping	DP	D

[Xie et al. \(2000\)](#) studied the development of the fleet over time in order to meet a given demand pattern. In every year ships can be added to the

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9 initial fleet or laid up. The fleet development was modeled by means of DP  
10 while the underlying fleet deployment was found by solving LP problems. A  
11 similar structure was employed by [Meng and Wang \(2011\)](#) who developed a  
12 multi-period fleet planning model for liner shipping companies. Also in this  
13 case DP is applied to model the fleet evolution but here the fleet deployment  
14 is found by solving a MIP problem for each time period. In the DP model  
15 each status represents one of a number of scenarios proposed by experts,  
16 where a scenario consists of the number of ships owned, bought, chartered in  
17 or chartered out in the correspondent period of time.

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19 Some papers aimed at finding the best replacement schedule for the avail-  
20 able ships while also allowing the fleet size and mix to vary from between  
21 periods. [Wijsmuller and Beumee \(1979\)](#) presented an LP model for a ship  
22 investment and replacement problem. The fleet size could vary within an  
23 upper and a lower bound and also the fleet mix could be adjusted while  
24 finding the replacement schedule. [Jin and Kite-Powell \(2000\)](#) aimed at de-  
25 termining optimal strategies for using, building and scrapping ships in order  
26 to maximize the profit. The number of vessels was allowed to vary over  
27 time and ships could be bought or scrapped not only for replacement pur-  
28 poses. They employed optimal control theory for its formulation and solution.  
29 [Nicholson and Pullen \(1971\)](#) studied the problem of scaling down a fleet of  
30 ships due to major technology changes. In this problem the size of the fleet  
31 is given (i.e. the number of ships to use in each period) but the mix of owned  
32 and chartered ships must be determined. Charters are adopted in case of  
33 premature sale of available ships. A heuristic procedure schedules the sales  
34 of the ships while the optimal number of charters are found by means of DP.

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36 [Cho and Perakis \(1996\)](#) studied the problem of expanding a current liner  
37 shipping fleet by evaluating a set of ships to include (build, purchase or  
38 charter). They did not run experiments but suggested the Lagrangian re-  
39 laxation for solving the MIP formulation proposed for the problem. At last,  
40 [Alvarez et al. \(2011\)](#) explicitly considered uncertainty while studying the fleet  
41 evolution. A robust optimization model was proposed to find solutions which  
42 are feasible against random variations in the selling and purchasing prices of  
43 ships. Their method is suitable for companies with varying degrees of risk  
44 tolerance in managing and modifying the fleet. In order to solve the model,  
45 it was transformed into a MIP problem.  
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### 3.4. Fleet adjustment in tactical problems

At a tactical level of planning a fleet of ships is given and the focus is on the best way of using the available ship in order to meet the transportation demand. Typical problems faced at this level are fleet deployment and ship routing and scheduling problems. The former consists of finding the minimum cost allocation of the available ships to services (e.g. trades and routes). Generally, the decision is about the number of times each ship (or type of ships) will operate a given service. The latter is usually faced in tramp and industrial shipping operations and consists of sequencing the ports to call (ship routing) and sometimes of assigning a time to each port call (ship routing and scheduling).

In most cases, when the fleet size and mix is planned (that is an MFSMP is solved), the actual realization of the demand is not known for sure. Therefore, in a tactical planning context, given the actual demand, decision makers evaluate the need to charter in additional ships. Similarly, if the transportation demand can be met by a subset of the available ships, decision makers can decide to charter out ships to other companies or just lay them up at port.

Numerous studies include the possibilities to charter in or out or laying up ships when dealing with tactical planning. We limit ourselves to report a few examples on how the fleet is adjusted within the frame of tactical problems. A more thorough discussion of the literature on fleet deployment and ship routing and scheduling problems is provided by [Christiansen et al. \(2004, 2007\)](#).

Table 6 summarizes the papers we include here. We report the main tactical problem studied in the paper, the type of action that modifies the fleet size and mix (e.g. charter in or charter out), the operations mode and the shipping industry dealt with.

The most common alternative to adjust the fleet is the lay up. It consists of excluding ships from operations for a period of time by stopping them at port. During this period the operating cost of the ships laid up is reduced due mainly to engines kept at least regimes and reduced crew. [Perakis and Jaramillo \(1991\)](#) and [Jaramillo and Perakis \(1991\)](#) introduced lay up possibilities in a fleet deployment problem. The former presented an LP formulation for the problem while the latter presented its implementation and results. Later, this work was modified by [Powell and Perakis \(1997\)](#), who introduced an IP model to eliminate rounding errors likely to occur when using the LP formulation of the former authors.

Table 6: Papers including tactical corrections to the fleet size and mix

Paper	Operating decisions	Acquisition/disposal	Mode	Industry
<a href="#">Alvarez (2009)</a>	D	CO	LI	Container shipping
<a href="#">Gelareh and Meng (2010)</a>	D	CI,CO,LU	LI	General shipping
<a href="#">Hwang et al. (2008)</a>	S	CO	TR or LI	General shipping
<a href="#">Jaramillo and Perakis (1991)</a>	D	LU	LI	General shipping
<a href="#">Perakis and Jaramillo (1991)</a>	D	LU	LI	General shipping
<a href="#">Powell and Perakis (1997)</a>	D	LU	LI	General shipping
<a href="#">Rana and Vickson (1988)</a>	R	CI	LI	Container shipping
<a href="#">Sherali et al. (1999)</a>	R+S	CI	IN	Oil shipping
<a href="#">Wang et al. (2011)</a>	D	CI,CO	LI	General shipping
<a href="#">Wang and Meng (2012)</a>	D	CI,CO	LI	Container shipping

Charters (in or out) and lay up periods are included in the fleet deployment problem studied by [Gelareh and Meng \(2010\)](#). Their MIP model was later reformulated by [Wang et al. \(2011\)](#) in order to eliminate its combinatorial behavior. Finally, [Wang and Meng \(2012\)](#) considered only charter in and charter out possibilities to correct the fleet structure. The problem they proposed is a fleet deployment problem for a liner shipping company and includes handling of transshipment operations.

Fleet modifications have also been treated in ship routing and scheduling problems. [Rana and Vickson \(1988\)](#) provided an IP model to help liner shipping companies evaluating whether individual container ships should be chartered in or not within the framework of a ship routing problem. An exact specialized algorithm was proposed to solve the problem. [Sherali et al. \(1999\)](#) included time charter options in a ship routing and scheduling problem where tankers are transporting oil from Kuwait to Asia, America, and Europe. The MIP model presented is initially reformulated in a more tractable model and then solved by means of a specialized rolling horizon heuristic algorithm. [Hwang et al. \(2008\)](#) included the possibility to charter out some of the available ships when capacity surplus occurs. They presented a quadratic model to the variance of shipping profit caused by volatility in the spot market. The model is solved by means of a Branch-and-Price-and-Cut algorithm.

#### 4. Research contributions and future perspectives

The first element we point out is the general scarcity of papers dealing with the maritime fleet size and mix problems (MFSMP) and its variants presented in Sections 3.1 to 3.3. We count 36 papers produced from 1954 to 2012. This number is small if compared to the 60 papers mostly on ship routing and scheduling published only in the decade before 2004 and reviewed by Christiansen et al. (2004). Possible motivations to this shortage of papers might be: (1) the difficulty to plan for long periods of time and thus to having access to market information which in most cases is imprecise or even not available, (2) the ocean shipping industry, due to its long tradition, is conservative, especially with regard to investment decisions which are typically made based on past experience, entrepreneurial spirit, and taking advantage of different national laws (Ronen, 1983). However, the frequent tonnage imbalances discussed in Section 1 and the scarcity of papers suggest more effort to improve decision support systems and make the MFSMP an open field for new research initiatives.

Most of the papers reviewed studied single-period problems (see Sections 3.1 and 3.2). The methods proposed fit shipping contexts which are meant to be stable or short-term problems where changes and uncertainties are cut off by the limited planning horizon. The research literature covers this kind of problems with a number of different analytic methodologies and simulation models. Furthermore, the available papers address or can fit the start-up of completely new shipping systems. They in fact implicitly do not assume an existing fleet.

However, given the dynamic nature of the shipping market and the long lifetime of ships, most real life problems need to take into account the evolution of the market status rather than a single, unchangeable, period. Furthermore, only in rare occasions a completely new fleet needs to be determined. More often shipping companies need to adjust the current fleet according to the market evolution and their beliefs about the future. Only in seven of the 36 reviewed papers, the authors assume that there is an initial fleet that should be adjusted, over time, by including or excluding ships (see Section 3.3).

Moreover, 10 of the 36 papers address the dimensioning of a homogeneous fleet (see Section 3.2). As far as ocean transportation is concerned more often than not fleets are heterogeneous, varying at least in size, technology, cost function and operating restrictions.

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Additional research should be encouraged to capture an increasing number of realistic elements of the problem. This could be done by better addressing the process of having a step-by-step evolution of the fleet in response to the market dynamics rather than a static configuration of the fleet. The emphasis should be on the best modification of the current fleet, taking into account future market challenges. This effort needs to consider the heterogeneous characteristics of ocean going fleets and a possible challenge could be the definition of ship types and the evaluation of the effects of different clustering strategies (i.e. how ships are grouped by similar characteristics).

Most reviewed papers propose methods for planning in a deterministic context. Although some papers include stochastic elements – see Table 7 – in most cases they still propose methods that are fitted for deterministic problems. Uncertain data is typically replaced by average or extreme values. As an example, in [Crary et al. \(2002\)](#) the importance (weight) of each mission of a potential war is stochastic. They test different fleets with different realizations of the random weights of the missions. Each test consists of solving a deterministic MIP to estimate the war winning probability. After a number of trials the best performing fleet is chosen. Another example is given by [Jaikumar and Solomon \(1987\)](#). When they incorporate stochastic demand they solve an IP problem planning for the highest value of demand.

Decision problems which can be reasonably considered deterministic are rather scarce in maritime transportation. This is especially true for strategic planning problems with a long planning horizon such as the strategic MFSMP. Only few papers explicitly treat uncertainty. If only strategic problems are considered the only exception is the robust optimization model presented by [Alvarez et al. \(2011\)](#) (see Section 3.3). [Fagerholt et al. \(2010\)](#), and [Shyshou et al. \(2010\)](#) faced uncertainty by means of simulation tools. The former included uncertainty in the quantity and timing of the cargoes while the latter considered uncertain weather conditions in offshore operations. Finally, [Halvorsen-Weare and Fagerholt \(2011\)](#), [Meng and Wang \(2010\)](#) and [Meng et al. \(2012\)](#) included and tackled uncertainty in short-term MFSMPs (see Section 3.1).

Future research needs to increase the attention towards more sophisticated methods to handle uncertainty or at least better investigate in which cases deterministic programming approaches may perform well. A possible challenge can be the modeling of the complex shipping market behavior.

As far as the cost function is concerned the most common modeling approach is that of incurring a fixed cost when adding a ship to the fleet and a

Table 7: Papers including uncertain elements in the problem

Paper	Problem	Planning against uncertainty	Simulation
<a href="#">Alvarez et al. (2011)</a>	MFRP	x	-
<a href="#">Crary et al. (2002)</a>	MFSMP	-	-
<a href="#">Fagerholt et al. (2010)</a>	MFSMP	-	x
<a href="#">Halvorsen-Weare and Fagerholt (2011)</a>	MFSMP	-	x
<a href="#">Jaikumar and Solomon (1987)</a>	MFSP	-	-
<a href="#">Larson et al. (1991)</a>	MFSP	-	-
<a href="#">Meng et al. (2012)</a>	MFSMP	x	-
<a href="#">Meng and Wang (2010)</a>	MFSMP	x	-
<a href="#">Pesenti (1995)</a>	MFSMP	-	-
<a href="#">Shyshou et al. (2010)</a>	MFSP	-	x
# of papers	10	3	3
% of the 36 papers reviewed	27.7%	8.3%	8.3%

variable cost associated to the sailing of the ships. The fixed cost is described in more or less detail from one study to another, and a number of them do not specify its meaning. However, in almost all cases the cost is univocal and no comparison between different alternatives is given. Real life problems typically offer a wealth of options when it comes to include or exclude ships from the fleet. Ships can be built, bought in the second-hand market, chartered in or taken as bare boat charter (i.e. the ship is chartered for a given period at an agreed rate, the owning company pays the capital cost and the charterer all other costs). Each of these options is associated to different needs and outcomes. As an example, second-hand ships are available in short time, but their characteristics must be chosen among what is available in the market. On the opposite, new buildings can be designed according to the company’s specifications, but are available after several months to years. Similarly, when ships are to be disposed of a shipping company can charter them out, lay them up, scrap or sell them. Therefore, a potential venue for research is to better address the type of fleet modification by comparing different acquisition or disposal options.

Almost all the reviewed papers use the underlying ship operation to estimate the total capacity needed to meet the demand. However, different

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9 levels of detail in the routing aspects can be found in literature. Tables 2  
10 to 5 report the operating decisions on which the tonnage estimation of the re-  
11 ported papers is based. Operating decisions vary from ship scheduling to ship  
12 deployment. The former alternative implies much more information (e.g. the  
13 exact sequencing of port calls and their timing) while the latter is at a higher  
14 level of abstraction. Open questions may be how different levels of detail in  
15 model of the operations of the ships influence the resulting fleet size and mix  
16 decisions, and what is the least amount of information needed to make sound  
17 strategic decisions. The answer to these questions will surely vary between  
18 different shipping segments and operation modes. Future research may set  
19 out to explore and better describe these aspects.  
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23 Finally, with regard to computation issues, difficulties arise in making a  
24 fair comparison between the methodologies proposed in the literature. The  
25 first obstacle is the wealth of different shipping networks and fleet operations  
26 described which makes it hard to evaluate and compare the complexity of the  
27 different problems. However, a significant number of papers did not apply  
28 heuristic procedure (see Tables 2 and 5), solving the problems to optimal-  
29 ity. A possible interpretation of this is that the field is ready to add extra  
30 complexity by including more real life elements. On the other hand, stan-  
31 dardized benchmark problems are needed in order to allow a more thorough  
32 evaluation of the computational efficiency. This can in turn trigger new re-  
33 search initiatives on better solution methods and on variants of the problem  
34 obtained by including additional problem features.  
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## 40 5. Conclusions

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42 Due to the changeable and stochastic behavior of the seaborne economy,  
43 decisions on the composition of the fleet of ships are crucial in maritime  
44 transportation. Furthermore, frequent tonnage imbalances call for better de-  
45 cision support systems. We surveyed the available literature on the maritime  
46 fleet size and mix problem and discussed the state of the art on the deci-  
47 sion support for such problem. We pointed out the available methodologies  
48 and the characteristics of the problems they are devised for. Furthermore,  
49 we highlighted points of weakness, where the available methodologies fail to  
50 capture important real life aspects of the problem and suggested possible  
51 future research directions to enhance the state of the art.  
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55 The available research papers have been focusing on shipping systems  
56 which can be considered as static and not characterized by volatility. They  
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9 have also well addressed the start-up of new shipping systems. However,  
10 important aspects of real life problems deserve further attention. Future re-  
11 search should especially focus more on the renewal of the fleet where the  
12 continual adaption of the fleet to changes in the market situation is sought.  
13 Important characteristics of the problem to better take into account are the  
14 uncertain market behavior and the large number of alternative ways for the  
15 shipping companies to renew their fleet. Furthermore, open research ques-  
16 tions can be found, such as the appropriate description of the operations of  
17 the ships and opportune methodologies to include and tackle uncertainty.  
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