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Abstract

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Keywords

directions, liner, scheduling, routing, shipping, overview, future, containership, research

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Containership Routing and Scheduling in Liner Shipping: Overview and Future Research Directions

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Keywords: liner shipping; routing and scheduling; containership; maritime transportation
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1. Introduction

There are generally three modes of operations in shipping: industrial, tramp, and liner (Lawrence 1972). In industrial shipping, cargo owners control the ships and seek to transport their cargo at minimal cost. In tramp shipping, the ship operator does not own the cargo, but selects available cargoes to transport so as to maximize revenue. Liner shipping companies publish their service routes, with fixed sequences of ports of call at a regular service frequency, to attract cargo. A liner ship service route forms a round trip and hence no origins or destinations need to be explicitly specified. Ships can pick up and deliver cargo at any port of call, and may never be empty during a voyage. Unlike in the case of tramp shipping, a single shipper seeking liner shipping services usually has much less than a full shipload of cargo, but liner ships have to keep to their published departure dates even when a full payload is not available.

Liner shipping mainly involves transporting containerized cargo (containers) on the regularly scheduled service routes. United Nations Conference on Trade and Development (UNCTAD 2011) reports that the liner shipping market accounted for about 16% of the world's goods loaded in tons, and total containerized trade was estimated to be 140 million twenty-foot equivalent units (TEUs) in 2010. According to UNCTAD (2011), container trade expanded at an average rate of 8.2% per year between 1990 and 2010. The rapid growth in containerized cargo over the last two decades is a result of economic globalization, increasing world trade volume, dedicated purpose-built large containerships, and more efficient container handling facilities in ports. At the same time, the low costs, fast speeds, reliable schedules, and reduced damage and pilferage in container liner shipping have given impetus to world trade.

Table 1 lists the nomenclature used in this study. As shown in Figure 1, there are three decision-making levels for liner container shipping companies: strategic, tactical, and operational (Pesenti 1995). At the strategic level, a liner container shipping company makes long-term decisions such as ship fleet size and mix, alliance strategies, and network design. Tactical-level decisions are made every three to six months in view of changing container shipment demand. A liner

Table 1 Nomenclature

Nomenclature	Definition/explanation
Fleet size and mix	The types of ships and the number of ships of each type in the ship fleet owned by a liner container shipping company
Port of call	A port visited by a ship together with its calling sequence in a ship's round-trip journey
Itinerary = loop = port rotation = sequence of ports of call	Fixed port calling sequence in a ship's round-trip journey
Liner service route = liner service = liner ship route = ship route	A port rotation with deployed ships and published schedules
Liner shipping service network = liner shipping network = liner network	A set of ship routes that are operated to transport containers from origins to destinations
Fleet deployment	Assignment of ships to port rotations
Schedule	The planned arrival and departure time at each port of call
Frequency = service frequency	The headway (in days) between two consecutive ships on a ship route, or the round-trip time if there is only one ship deployed on the ship route
Transshipment = relay	When containers are shipped to an intermediate destination, and then from there to another destination, the handling operation at the intermediate location is called transshipment
Bunker	The fuel that the main engine of a ship burns

container shipping company needs to set the frequency of its services, deploy ships on its itineraries, determine the sailing speeds of those ships, and design schedules. At the operational level, a liner

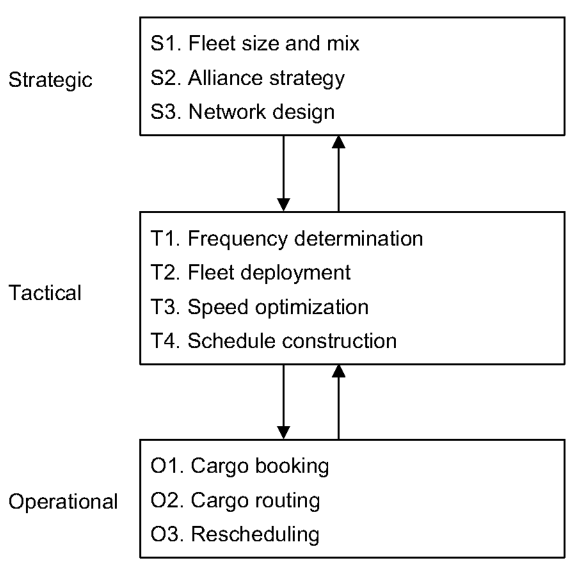

Figure 1 Three Levels of Decision Making for Liner Container Shipping Companies

container shipping company determines whether to accept or reject cargoes, how to route accepted cargoes, and how to reroute or reschedule ships to cope with unexpected incidents such as adverse weather and sea conditions or port congestion. There is some interplay between the decisions made at the three different planning levels. For example, fleet size and mix are necessary inputs for ship fleet deployment, and cargo routing is dependent on the shipping services offered. In addition to the classification of strategic, tactical, and operational levels, the decision problems can be classified according to other criteria (e.g., Kjeldsen 2011). Also, similar problems are addressed by airlines, such as aircraft routing (e.g., Barnhart et al. 1998; Cordeau et al. 2001; Lan, Clarke, and Barnhart 2006), competition over flight frequencies (Vaze and Barnhart 2012), airline fleet assignment (e.g., Lohatepanont and Barnhart 2004; Sherali, Bish, and Zhu 2005; Gao, Johnson, and Smith 2009), aircraft schedule planning (e.g., Jiang and Barnhart 2009; Dunbar, Froyland, and Wu 2012), crew scheduling (e.g., Klabjan et al. 2002; Saddoune et al. 2012), aircraft maintenance (e.g., Liang et al. 2011), and revenue management (e.g., Wright, Groenevelt, and Shumsky 2010). However, the problems associated with liner container shipping are generally more challenging because of its more complex operations. For instance, a flight generally has only one or two legs and a liner service route may have 10–20 legs.

In this study, we use the term "routing and scheduling" in the context of the broader class of logistics problems associated with liner container shipping. Because of the high fixed costs and high daily operating costs of containerships, and the scale (global network, large ship fleet, alliance) and complexity (container transshipment, frequency requirement) of the routing and scheduling problems, we can expect that operations research (OR) methods will bring considerable cost reductions for liner container shipping companies. Therefore, we focus on literature that applies OR methods to address routing and scheduling problems in liner container shipping.

Maritime transportation has attracted much less research effort than other transportation areas (Psaraftis 1999), such as public transit analysis, airline management, and general vehicle routing problems. Furthermore, the existing reviews (Ronen 1983, 1993; Christiansen, Fagerholt, and Ronen 2004; Christiansen et al. 2007) on ship routing and scheduling have mainly focused on industrial and tramp shipping. Therefore, even fewer studies are devoted to liner shipping operations. In reality, the liner container shipping industry is more conservative than other transportation industries, such as the airline industry, and global liner container shipping companies have been reluctant to share their data and concerns

Table 2 Abbreviations

Abbreviation	Full name
B&B	Branch and bound
B&C	Branch and cut
ECR	Empty container repositioning
FD	Fleet deployment
GA	Genetic algorithm
H&S	Hub and spoke
IP	Integer programming
LP	Linear programming
MILP	Mixed-integer linear programming
MINLP	Mixed-integer nonlinear programming
MPC	Multiport call
O-D	Origin-to-destination
SAA	Sample average approximation
SOCP	Second-order cone programming
TEU	Twenty-foot equivalent unit

with researchers in the past. Recently, however, several leading liner container shipping companies have sought to use OR methods to make better decisions because of the increased market competition and high bunker prices in the container shipping industry. We find that there is a gap between academic studies and industrial practices on containership routing and scheduling. It is therefore worthwhile reviewing the literature on containership routing and scheduling problems and elaborating on the needs of the liner container shipping industry.

This paper is organized as follows: In §2, we illustrate the methodology used to search for relevant papers and summarize the problem, model, and algorithm of each paper. In §3, we review studies on strategic planning problems in liner container shipping. Section 4 gives an overview of literature on the tactical-level routing and scheduling problems. Section 5 is dedicated to studies on operational problems. In §6, we discuss issues that have not been extensively explored in the literature but that are vital to the liner container shipping industry. The abbreviations used in the paper are summarized in Table 2.

2. Literature Search Method and Summary of Literature

We used a computerized literature search approach to find relevant studies. First, the databases of Scopus, the Sciences Citation Index, and Google Scholar were searched using the following key words: liner, container, shipping (maritime, sea, or waterway; transportation or transport; ship or vessel; and routing, schedule, or scheduling). We also looked at the personal websites of researchers who are active within maritime transportation and reviewed our own research on the topic. Furthermore, we retrieved studies by tracking the references cited in papers we had already found. In the end we identified 70 papers that use OR methods to examine containership routing and scheduling problems. Table 3 lists these papers, the problems they solve and the main topics they address, and the model and solution algorithms they use. Half of the studies are published in *Transportation Research Part E* (15 papers), *Maritime Policy and Management* (13 papers), *Maritime Economics and Logistics* (formerly known as *International Journal of Maritime Economics*, six papers), or *European Journal of Operational Research* (five papers).

The research topic involving the use of mathematical modeling techniques to address containership routing and scheduling problems has begun to draw more academic attention in recent years. There are three possible reasons for this phenomenon: (i) many liner container shipping companies, such as Maersk Line and Orient Overseas Container Line (OOCL), have recently started to collaborate with the research community to develop better decision support systems, (ii) the increasing volume of containerized trade resulting from an increasingly globalized economy has drawn much attention from academic researchers, and (iii) advancements in computer technology have enabled researchers to solve practical problems on a much larger scale than ever before.

3. Strategic Plans

Strategic problems in liner container shipping are related to long-term decisions that may cover a planning horizon of up to 30 years. Strategic decisions clearly affect the decision making at the tactical and operational levels by defining the boundaries for these decisions. At the same time, liner container shipping companies may need to incorporate tactical-level decisions when making strategic plans. In this section, we review studies of three strategic planning problems: fleet size and mix, alliance strategy, and network design.

3.1. Fleet Size and Mix

The fleet size and mix problem is concerned with the type and number of ships that a liner container shipping company keeps in its ship fleet. With larger and larger containerships being built and higher competition in the market, the importance of this problem is increasing. For example, Maersk Line has recently ordered 10 mega-containerships with a volume capacity of 18,000 TEUs. These mega-containerships have high fixed and daily operating costs and generally remain in service for a period of 20–30 years.

The fleet size and mix problem is usually investigated in combination with the tactical decision of fleet deployment. In fact, the fleet size and mix problem could also be examined in combination with network design. However, as the network design problem is strongly NP-hard, studies looking at the fleet size and

Table 3 Summary of Literature on Containership Routing and Scheduling in Liner Shipping

Paper	Problem and major considerations	Approach
Agarwal and Ergun (2008)	Shipping network design; transshipment; heterogeneous fleet; container routing	Space-time network; Benders' decomposition
Agarwal and Ergun (2010)	Alliance strategy	Game theory
Álvarez (2009)	Network design; transshipment cost; heterogeneous fleet; container routing; speed optimization	Tabu search; column generation
Álvarez (2012)	Connection time at transshipment ports	Analytical
Baird (2006)	Hub location	Case study
Bell et al. (2011)	Container routing; random ship arrivals	LP
Bendall and Stent (2001)	Frequency determination; fleet size; fleet deployment	MILP
Boffey et al. (1979)	Containership route design; container selection	LP; heuristic
Brouer, Pisinger, and Spoorendonk (2011)	Container routing; empty containers	LP; column generation
Brouer et al. (2013)	Ship repositioning	Space-time network
Cheaitou and Cariou (2012)	Speed optimization; elastic demand	Analytical
Cho and Perakis (1996)	Fleet planning; fleet deployment; container routing; single planning period	LP; MILP
Chuang et al. (2010)	Containership route design; fuzzy container shipment demand	Fuzzy theory; GA
Corbett, Wang, and Winebrake (2009)	Emission; speed optimization	Analytical
Du et al. (2011)	Speed optimization; joint planning of shipping operations and port operations	SOCP
Fagerholt (1999)	Feeder network design; homogeneous fleet	MILP
Fagerholt (2004)	Feeder network design; heterogeneous fleet	MILP
Fagerholt, Johnsen, and Lindstad (2009)	Fleet deployment	Multistart local search heuristic
Gelareh and Meng (2010)	Fleet deployment; speed optimization; transit time	MILP
Gelareh, Nickel, and Pisinger (2010)	H&S network design; competition	Lagrangian relaxation
Gelareh and Pisinger (2011)	Liner hub-and-spoke network design; main ship route design	Benders' decomposition
Golias et al. (2010)	Speed optimization; joint planning of shipping operations and port operations	GA
Hoff et al. (2010)	Fleet size and mix; routing	Review
Imai, Shintani, and Papadimitriou (2009)	Hub-and-spoke network; multiport call network; empty container repositioning	Case study
Jaramillo and Perakis (1991)	Fleet deployment	LP
Karlaftis, Kepaptsoglou, and Sambracos (2009)	Feeder network design; heterogeneous fleet; pickup and delivery; time window	Hybrid GA
Kontovas and Psaraftis (2011a)	Emission; speed reduction; port operations	Analytical; case study
Kontovas and Psaraftis (2011b)	Emission; speed reduction	Qualitative
Lane, Heaver, and Uyeno (1987)	Multiple liner route design	Enumeration; IP
Lang and Veenstra (2010)	Speed optimization; joint planning of shipping operations and port operations	Simulation
Liu, Ye, and Yuan (2011)	Fleet deployment; container routing	MILP
Meng and Wang (2010)	Fleet deployment; uncertain container shipment demand; level of service	MILP
Meng and Wang (2011a)	Network design; transshipment; container routing; empty container repositioning	MILP
Meng and Wang (2011b)	Speed optimization; transit time; frequency	B&B
Meng and Wang (2011c)	Fleet planning; fleet deployment	Dynamic programming; MILP
Meng and Wang (2012)	Fleet deployment; week-dependent demand	Bilevel programming
Meng, Wang, and Liu (2012a)	Intermodal liner shipping network design	MILP; heuristic
Meng, Wang, and Wang (2012b)	Fleet deployment; uncertain demand	SAA; Lagrangian relaxation
Mourão, Pato, and Paixão (2001)	Fleet deployment; hub-and-spoke network; transshipment; weekly service frequency; inventory cost	MILP
Notteboom (2006)	Schedule reliability	Survey
Notteboom and Vernimmen (2009)	Speed optimization	Case study
Perakis and Jaramillo (1991)	Fleet deployment	LP
Powell and Perakis (1997)	Fleet deployment	IP
Psaraftis (2012)	Emission	Qualitative; analytical
Psaraftis and Kontovas (2010)	Emission; speed	Analytical; logit model
Qi and Song (2012)	Schedule design; uncertain port time	Stochastic approximation

Table 3 (Continued)

Paper	Problem and major considerations	Approach
Rana and Vickson (1988)	Single liner route design; fixed port calling sequence; single ship	MILP; Benders' decomposition
Rana and Vickson (1991)	Multiple liner route design; fixed port calling sequence; heterogeneous fleet; container routing	Lagrangian relaxation; decomposition
Reinhardt and Pisinger (2012)	Network design; transshipment; butterfly ship route	B&C
Ronen (2011)	Speed optimization	Analytical
Sambracos et al. (2004)	Feeder network design; homogeneous fleet	Metaheuristic
Shintani et al. (2007)	Single liner route design; empty containers	GA
Song and Dong (2012)	Container routing	IP and heuristic
Song and Panayides (2002)	Alliance strategy	Game theory
Ting and Tzeng (2003)	Ship scheduling	Dynamic programming
Vernimmen, Dullaert, and Engelen (2007)	Schedule reliability	Case study
Wang and Meng (2011)	Schedule design; transshipment; transit time; container routing	Hybrid GA
Wang, Wang, and Meng (2011)	Fleet deployment	IP
Wang and Meng (2012a)	Schedule design; transshipment; transit time; uncertain port time; sea time contingency	Stochastic MINLP
Wang and Meng (2012b)	Fleet deployment; transshipment	MILP
Wang and Meng (2012c)	Speed optimization; speed-bunker consumption rate relation	MINLP; MILP
Wang and Meng (2012d)	Schedule design; uncertain port time	MINLP; MILP; SAA
Wang, Meng, and Wang (2012)	Fleet deployment; uncertain demand; risk	MILP; robust optimization
Wang, Meng, and Bell (2013)	Fleet planning; fleet deployment; utilization	Tailored optimization approach
Wang, Meng, and Liu (2013)	Speed optimization; joint planning of shipping operations and port operations	Quadratic outer-approximation
Wang, Meng, and Sun (2013)	Container routing	MIP
Xinlian, Tangfei, and Daisong (2000)	Fleet planning	Dynamic programming
Yan, Chen, and Lin (2009)	Container routing; transshipment	Space-time network; Lagrangian relaxation
Yao, Ng, and Lee (2012)	Speed optimization; bunkering port; bunkering volume	MILP
Zacharioudakis et al. (2011)	Fleet deployment; speed optimization	GA

mix problem generally assume that the network is given a priori.

Hoff et al. (2010) presented an overview of the fleet composition and routing problems in maritime and land transportation. Their survey focused on industrial applications and contrasted the scientific literature with the needs of the industry. Even though almost 100 papers were reviewed, only a few concern the fleets of containerships.

Cho and Perakis (1996) presented a model dealing with fleet size and the choice of optimal liner routes for a container shipping company. They considered a single planning horizon by assuming that the shipment demand over this planning horizon was uniform. The problem was formulated and solved as a LP model, where the columns represented the candidate ship routes. They then extended the model to a MILP model that also considered investment alternatives for expanding fleet capacity, namely, building, purchasing, and chartering in ships.

Xinlian, Tangfei, and Daisong (2000) extended the single-period model of Cho and Perakis (1996) by examining the fleet planning problem in a multiperiod setting. They developed a fleet planning model aimed at determining both the ship types to add to the existing fleet and the optimal fleet deployment plan. They divided the problem into several smaller ones dealing with each stage in turn and searched for the optimal solution to each small problem separately. A dynamic programming approach was used to find these optimal solutions.

Meng and Wang (2011c) also analyzed a multiperiod fleet planning problem. They assumed that container shipment demand varied between periods, and that the liner shipping company could sell, purchase, charter in, and charter out ships at the beginning of each period. To simplify the problem, they assumed that the possible fleet size and mix scenarios for each period were given a priori. A dynamic programming approach was proposed for obtaining the optimal fleet planning decisions.

Wang, Meng, and Bell (2013) analyzed the capacity utilization of a ship route in the context of the megacontainerships with a capacity of 18,000 TEUs ordered by Maersk Line. The uncertain future demand vector of different O-D pairs is modeled as a bounded polyhedral set, and the maximum and minimum capacity utilizations are computed by a tailored global optimization approach. The maximum and minimum capacity utilizations provide valuable information for fleet planning and deployment decisions.

One of the main challenges with fleet size and mix decisions is that there are too many uncertainties in a period of up to 30 years. These uncertainties include political considerations, international trade volume, the bunker price, the freight rate, ship construction and chartering prices, the interest rate, and the currency exchange rate.

3.2. Alliance Strategy

Collaborations and alliances are a common phenomenon among liner shipping operators. Factors that drive carriers to adopt solutions outside of their traditional business practices and collaborate with their competitors include the following (Agarwal and Ergun 2010): (i) liner shipping is a capital-intensive industry; (ii) large containerships produce economies of scale, however, they require a longer period for container accumulation, resulting in a less frequent service; (iii) alliances help carriers to explore new markets and enhance their service scope. It should be mentioned that many other factors, such as strategy, governance, and culture, contribute significantly to the success of alliances.

Song and Panayides (2002) applied cooperative game theory to analyze cooperation among members of liner shipping strategic alliances, producing a conceptual framework that enhanced understanding of interorganizational relationships and decision-making behavior in the liner shipping sector. Agarwal and Ergun (2010) assumed that, once the collaborative optimal service routes and the ships that would operate on them had been decided centrally, then the carriers would individually operate their ships, incurring operational costs and making their own cargo accept or reject routing decisions, thus determining the revenue they earned. Concepts from inverse programming and game theory were utilized and a mechanism was designed to guide the liner shipping companies in an alliance in the pursuit of an optimal collaborative strategy. The mechanism provides side payments to the liner shipping companies as an added incentive to motivate them to act in the best interests of the alliance, whereas maximizing their own profits.

3.3. Liner Container Shipping Network Design

The aim of liner container shipping network design is to determine which ports the ships should visit and in what order. The network design problem is associated with the tactical-level problems and thus cannot be investigated in isolation. The fleet size and mix is often an input to the network design, restricting the number and types of ships that can be used when designing the network. Most existing literature is devoted to itinerary design and ship deployment, assuming a fixed sailing speed and weekly service frequency, and not considering schedules.

The liner container shipping network design problem is NP-hard (Agarwal and Ergun 2008), and we cannot expect to find a polynomial-time algorithm that will produce the optimal solution for a general liner shipping network design problem unless P = NP. Research on this topic can be classified into four categories, and illustrative networks for these four categories are shown in Figure 2. The first category examines the feeder container shipping network design problem, which consists of a hub port and many feeder ports, as shown in Figure 2(a). Containers either originate from or are destined for the hub port, and transshipment is excluded within the feeder network. Fagerholt (1999) contributed a pioneering study in this category. He proposed a set-partitioning model by enumerating all possible shipping service routes and combining these single shipping service routes into multiple shipping service routes if possible. The model relied on the assumption that all ships have the same sailing speed. Fagerholt (2004) later extended the set-partitioning model to address a heterogeneous ship fleet with a given cost structure, capacity, and, in particular, sailing speed for each type of ship. He reported results for 40 ports and 20 ships. Sambracos et al. (2004) carried out a case study on the feeder ship route design used to dispatch small

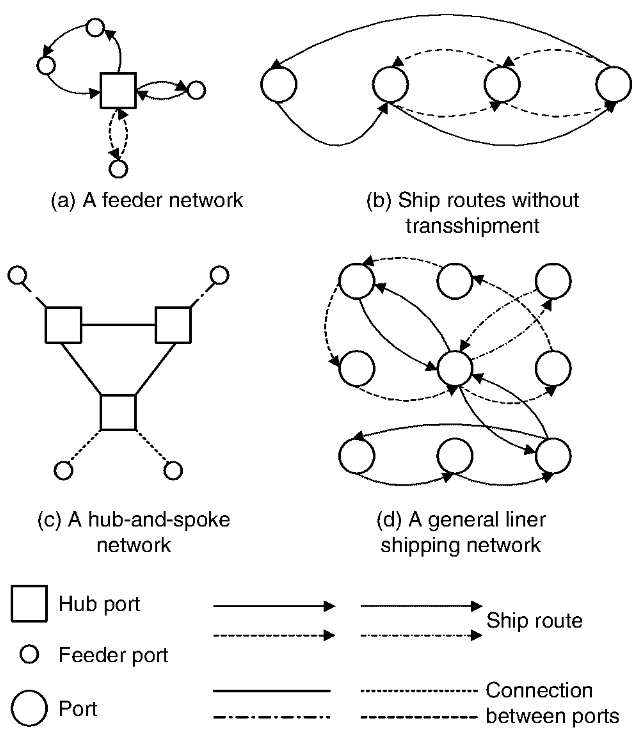

Figure 2 **Liner Shipping Network Design Categories**

containers in the Aegean Sea, from one depot port (Piraeus) to 12 other ports (islands). They assumed a homogeneous fleet that aimed to meet container shipment demand with minimum operating costs, including fuel consumption and port charges. They used a list-based threshold acceptance meta-heuristic method. Their results showed that at least a 5.1% cost saving could be realized over existing shipping practices. This problem was later generalized by Karlaftis, Kepaptsoglou, and Sambracos (2009) to account for container pickup and delivery operations as well as time deadlines. They formulated this extended problem as a vehicle routing problem with pickup and delivery and time windows, and used a hybrid GA to solve the problem.

The second category aims to design one or a few liner service routes without container transshipment operations, as shown in Figure 2(b). In this category of research, Boffey et al. (1979) developed an interactive computer program and a heuristic optimization model for designing the route of a containership on the North Atlantic. The value of the route was obtained by maximizing the total freight revenue, formulated as a LP model. Lane, Heaver, and Uyeno (1987) proposed an analytical model for planning liner container shipping operations. They first enumerated all possible ship routes and then developed a set-partitioning model to choose the optimal set of ship routes that would satisfy the shipping requirements. Rana and Vickson (1988) built a MINLP model for routing a single containership. They then linearized the model by enumerating all possible round trips and solved the resulting MILP model using Benders' decomposition technique. Rana and Vickson (1991) later extended this model to a design with multiple ship routes. They employed Lagrangian relaxation and decomposed the problem into several subproblems—one for each ship. Both models assume that the port-calling sequence for a given ship is predetermined. Shintani et al. (2007) relaxed the assumption of port calling precedence relations and also considered empty container repositioning to design a single ship route. They assumed that all container demand emanating from a port was satisfied if that port was visited. The problem was formulated as a bilevel model, where the upper level was a knapsack problem choosing the best set of calling ports, and the lower level identified the optimal calling sequence of ports for those calling ports chosen in the upper level. A GA is employed to solve the upper-level and lower-level problems simultaneously. Chuang et al. (2010) designed a liner ship route by assuming that the container shipment demand was not a crisp number, but a fuzzy number. Therefore, the profit of the ship route was also fuzzy. They proposed a fuzzy GA to design the ship route, in which the fitness degree of a chromosome (ship route) was a crisp number derived from the fuzzy total profit.

The third group of studies seeks to design a H&S liner shipping network similar to those used by airlines and in telecommunication systems, as shown in Figure 2(c). Baird (2006) compared container transshipment hub locations in northern Europe. Transport distances and associated shipping costs were calculated for existing hub locations and compared with a new proposed transshipment location in the region. Imai, Shintani, and Papadimitriou (2009) compared the efficiency of H&S networks and MPC networks using a simple six-port example, with three ports in one service area (e.g., Asia), and the other three in the other area (e.g., America). In the H&S network, one port in each area is chosen as a hub, and the other four ports are connected to the hubs via feeder services. In the MPC network, all six ports are visited sequentially. They found the MPC network to be superior to the H&S network in most scenarios of European or North American trade lanes. It should be noted that this conclusion might change with the cost structure of liner shipping companies. Gelareh, Nickel, and Pisinger (2010) examined a H&S network design problem in a competitive environment with a newcomer liner shipping company and an existing dominating operator. The newcomer chooses hub ports so as to maximize its market share, which depends on cost and transit time. A mixed-integer programming formulation and a Lagrangian method combined with a primal heuristic were developed. Based on this work, Gelareh and Pisinger (2011) presented a MILP formulation for the simultaneous design of a H&S network and deployment of containerships. A Benders' decomposition-based algorithm was developed that outperformed general-purpose MILP solvers.

The fourth line of research investigates the general liner shipping network design problem, which usually involves more ports in the network and allows for container transshipment operations, as shown in Figure 2(d). Agarwal and Ergun (2008) proposed a multicommodity-based space-time network model for the liner shipping service network design problem with cargo routing. The model incorporated a heterogeneous fleet, a weekly service frequency, multiple ship routes, and cargo transshipment operations, but transshipment costs were not considered in the network design stage. A MILP formulation with an exponential number of decision variables indicating whether a ship route is used was proposed. A greedy heuristic, a column generation-based algorithm, and a two-phase Benders' decomposition-based algorithm were developed, and their computational efficiency (in terms of the solution quality and the computational time taken) was tested on networks with up to 20 ports and 100 ships. Álvarez (2009) extended the problem addressed by Agarwal and Ergun (2008) in two aspects. First, the transshipment cost was explicitly incorporated into the network design. Second, because a containership may vary its speed within a certain range, Álvarez (2009) discretized the speed range and considered each combination of ship type and speed interval as a separate ship type. Similar to the concept of the "cycle" in Agarwal and Ergun (2008), Álvarez (2009) also introduced the notion of a "run", defined as a combination of vessel type, speed, and ports of call, to facilitate model formulation. He applied a combined tabu search and column generation-based heuristic to design a network with 120 ports and five types of ships. Meng and Wang (2011a) presented a network design model that captured a combination of a H&S network and a MPC network and ECR. A set of candidate port rotations were given a priori and the objective was to choose the optimal port rotations and assign containerships to them. Laden containers were allowed to be transshipped only at hub ports, whereas empty containers could be transshipped at any port. The problem was formulated as a MILP model, and a case study with 46 ports was reported. Reinhardt and Pisinger (2012) presented a model to design butterfly ship routes, in each of which one port was visited twice and container transshipment was allowed at that port. Their model also incorporated transshipment costs and a heterogeneous fleet. They developed an exact B&C algorithm to solve instances with up to 15 ports. Meng, Wang, and Liu (2012a) developed a model for a large-scale intermodal liner shipping service network design. The model captured essential practical issues including consistency with current services, slot purchasing, both inland and maritime transportation, multiple-type containers, and origin-to-destination transit time. It used a liner shipping hub-and-spoke network to facilitate laden container routing from one port to another. Laden container routing in the inland transportation network is combined with the maritime network by defining a set of candidate export and import ports. Empty container flow was described on the basis of path flow and leg flow in the inland and maritime networks, respectively. The intermodal liner shipping service network design problem was formulated as a mixed-integer linear programming model. The proposed model was applied to design the shipping services for a global liner shipping company.

4. Tactical Decisions

We now review studies of frequency determination, fleet deployment, ship sailing speed optimization, and schedule design at the tactical planning level. These problems are interrelated and some studies address more than one topic and are consequently discussed in more than one subsection. Strategic decisions, such as the fleet size and mix and the design of the service network, are considered to be already fixed, and therefore restrict the decisions at the tactical level.

4.1. Frequency Determination

Service frequency is the headway (in days) between two consecutive ships on a ship route. A higher frequency (a shorter headway) means a shorter waiting time for containers at their origin port. However, liner container shipping companies need more ships to provide a high service frequency and cannot take advantage of the economies of scale that come from a larger ship size. Bendall and Stent (2001) presented a MILP model that determined the number of high speed containerships a company should deploy, the spoke ports that they should service, and the frequencies of service in a H&S network. The container shipment demand was modeled as a function of the frequency of visits to individual spoke ports. Meng and Wang (2011b) optimized the frequency of a ship route and the sailing speed on each voyage leg by assuming that the average wait time at the origin port was half the headway, and that each O-D port pair had a maximum allowable transportation time that includes the wait time at the original port.

Unlike the studies by Bendall and Stent (2001) and Meng and Wang (2011b), most research efforts in the 1980s and 1990s either made no requirements regarding the service frequency, or only required that a minimum service frequency be maintained. Recent research efforts on liner container shipping have generally adopted the weekly service frequency because global liner shipping companies usually provide weekly shipping services. A weekly service frequency means that each port of call is visited on the same day every week. The establishment of the convention of a weekly service in the industry happened for the following reasons: First, shippers like more frequent services and shipping companies wish to accumulate more cargo by providing less frequent services. A weekly service is a trade-off between the two conflicting interests. Second, a weekly service means that ships on the same ship route arrive at each port of call at the same time each week (e.g., 9:00 A.M. on a Tuesday). Consequently, container terminal operators also allocate berth time windows on a weekly basis. If a ship route does not have a weekly service, then it is difficult to allocate suitable time windows because consecutive arrivals do not occur at the same time every week. It should be noted that there are exceptions, e.g., Maersk Line provides a daily Asia–Europe shipping service called Daily Maersk, which is more competitive than weekly services.

Table 4 **Classification of Literature on FD According to Transshipment and Container Shipment Demand**

	Without transshipment	With transshipment
Deterministic demand	Perakis and Jaramillo (1991); Jaramillo and Perakis (1991); Cho and Perakis (1996); Powell and Perakis (1997); Gelareh and Meng (2010); Wang, Wang, and Meng (2011); Zacharioudakis et al. (2011)	Mourão, Pato, and Paixão (2001); Liu, Ye, and Yuan (2011); Meng and Wang (2012); Wang and Meng (2012b)
Stochastic demand	Meng and Wang (2010)	Meng, Wang, and Wang (2012); Wang, Meng, and Wang (2012)

4.2. Fleet Deployment

Fleet deployment (FD) seeks to assign ships to port rotations to maximize profits or minimize costs. A number of pure or mixed-integer LP models for the FD problem have been developed to account for the various restrictions arising in liner shipping operations. Table 4 classifies the literature on liner ship fleet deployment by container transshipment and demand pattern. In a pioneering piece of modeling work on FD, Perakis and Jaramillo (1991) and Jaramillo and Perakis (1991) built a LP model incorporating ship capacity constraints, minimum service frequency requirements, and ship chartering issues. The objective of this LP model was to minimize the total operating costs of the fleet, including fuel consumption costs, daily operating costs, port charges, and canal fees. It implicitly and unrealistically assumed that the number of ships allocated to a service route was a continuous rather than an integer decision variable. To remedy this unrealistic assumption, Powell and Perakis (1997) presented an integer LP model. These three studies all assumed a service route-based port-to-port shipment demand pattern; the number of containers between a pair of ports on each service route was known a priori. To relax this assumption, Cho and Perakis (1996) formulated a MILP model for the FD problem, where the container shipment demand between two specific ports could be served by any service route passing through both ports. Because the sailing speed of ships has a direct effect on bunker consumption, Gelareh and Meng (2010) developed a MILP model for the FD problem in which the sailing speed of a ship is a decision variable. Wang, Wang, and Meng (2011) presented an efficient FD model that eliminates symmetrical solutions suggested by Gelareh and Meng (2010). Zacharioudakis et al. (2011) gave a practical solution to the modern shipping company's fleet deployment problem. They developed a generic cost model that aimed to minimize total operating costs by using a GA to optimize fleet deployment and various predefined attributes such as operational speed. The final model could be used by liner shipping companies to optimize liner networks, or to simulate and examine possible scenarios and what-if analyses. Unlike the aforementioned models that had deterministic container shipment demand, Meng and Wang (2010) developed a chance-constrained programming model for the FD problem with uncertain container shipment demand. They assumed that a certain level of service had to be maintained on each route. The level of service was defined as the probability that all container shipment demand on the service route would be fulfilled. The chance constraints could then be transformed into equivalent deterministic linear constraints.

In the previous models, containers must be delivered from their origin port to their destination port by a direct service, and transshipment is not allowed. In the literature that takes into account container transshipment operations, Mourão, Pato, and Paixão (2001) proposed a simple model for a specific FD problem defined on a small H&S network consisting of two routes—a feed route and a main route—and one pair of ports, by assuming that all containers must be transshipped at the hub port in the feeder route. Liu, Ye, and Yuan (2011) developed a FD model with container routing where the revenue is a concave increasing function of the volume of containers shipped to account for discounts for customers. Wang and Meng (2012b) developed a MILP model for the FD problem in which containers may be transshipped at any port. The container flow decisions are represented by origin-based variables. Meng and Wang (2012) examined a FD problem with week-dependent container shipment demand and transit time constraint. The problem was formulated as a bilevel programming model. In view of the difficulty of the problem, two relaxation models providing lower bounds were built: one required known container shipment demand at the FD stage, and the other assumed constant container shipment demand over the planning horizon. A global optimization algorithm exploiting the prior lower bounds was proposed. In addition, Fagerholt, Johnsen, and Lindstad (2009) developed a FD model that required ships to fulfill a given number of voyages, without explicitly considering the container flow. They further integrated the model into a decision support system.

There are also studies on FD problems with container transshipment and uncertain container shipment demand. Meng, Wang, and Wang (2012) assumed the uncertain demand as a random variable with known probability distribution. A two-stage stochastic integer programming model was formulated. A solution algorithm, integrating the sample average approximation (SAA) with a dual decomposition and Lagrangian relaxation approach, was then proposed.

Wang, Meng, and Wang (2012) extended the model of Meng, Wang, and Wang (2012) by considering not only the expected cost, but also the variance of the cost (namely, the risk for the liner shipping company) in the objective function.

Compared with the network design problem, FD is easier to tackle because the number of ship types is limited and not all ship types are compatible with each port rotation because of commercial and physical restrictions. Even though the FD topic has been extensively investigated, modeling and solving realistically sized problems remains a challenge, especially in the richer versions of the problem, for example when speed design and schedule construction are incorporated.

4.3. Optimization of Ship Sailing Speed

The sailing speeds of ships have a significant impact on the total operating costs because an increase of just a couple of knots results in a dramatic increase in bunker consumption (Notteboom and Vernimmen 2009), and bunker costs may constitute more than 75% of the total operating costs of a container ship (Ronen 2011). At the same time, higher speeds mean shorter transit times and fewer ships required to maintain weekly services. Sailing speed is an important decision that affects all levels of decision making. At the strategic level, there is a trade-off between the fleet composition and the speed of the ships; fewer ships means that each ship must sail faster. When there is flexibility in the delivery timescales, speed decisions become important in the fleet deployment phase. At the operational level, weather and currents greatly influence speed.

The relationship between sailing speed and bunker consumption rate is an important input when optimizing the speed of container ships. Many researchers have used the power of three relation in their studies, namely, that the daily bunker consumption is approximately proportional to the speed cubed. Wang and Meng (2012c) calibrated the relation using historical operating data for containerships and found that the exponent was between 2.7 and 3.3, supporting the power of three approximation. They also found that the relation varies for different voyage legs. Du et al. (2011) used an exponent of 3.5 for feeder containerships, 4 for medium-sized containerships, and 4.5 for jumbo containerships, based on the suggestions of a ship engine manufacturing company. Kontovas and Psaraftis (2011a) suggested using an exponent of 4 or higher when the speed is greater than 20 knots. Overall, all of the studies have suggested the importance of sailing speed for bunker consumption.

Most studies have assumed that ships sail at a predetermined speed. This might be attributable to the nonlinear relation between sailing speed and bunker consumption rate. Notteboom and Vernimmen (2009) developed a cost model for analyzing the effect of high fuel costs on liner service configuration in container shipping. The cost model demonstrates—for a typical North Europe, East Asia loop—that high bunker prices have a significant impact on the cost per TEU, even when using large, post-Panamax vessels. The model also shows that shipping lines are reacting quite late to increases in bunker costs because of inertia, transit time concerns, schedule integrity problems, and fleet management issues. Ronen (2011) analyzed the relationship between bunker price, sailing speed, service frequency, and the number of vessels operating on a ship route; and devised a model that helps determine the sailing speed, round-trip time, and number of containerships that minimize the total operating costs.

Notteboom and Vernimmen (2009) and Ronen (2011) looked at speed optimization in a simple setting with a single ship route. These two studies demonstrated the importance of optimizing the speed of containerships, especially when the bunker price is high. Cheaitou and Cariou (2012) extended the works of Notteboom and Vernimmen (2009) and Ronen (2011) by incorporating the dependence of the container shipment demand on transit time. To optimize the sailing speed in more general settings, different approaches have been used. The first approach bypasses nonlinearity by assuming that bunker consumption varies linearly with sailing speed (Lang and Veenstra 2010). This approach is a good approximation only when the possible speed range is very narrow. The second approach is to use heuristic methods; for example, Golias et al. (2010) applied the GA, which cannot guarantee optimality. Both Lang and Veenstra (2010) and Golias et al. (2010) optimized the speed of containerships arriving at a port, from the viewpoint of the joint planning of shipping and port operations. The third approach was presented by Álvarez (2009), Gelareh and Meng (2010), Yao, Ng, and Lee (2012). Álvarez (2009) considered ships of different speeds as different types of ships in the network design. Gelareh and Meng (2010) optimized the speed in the FD problem. Yao, Ng, and Lee (2012) studied not only the speed of containerships, but also the selection of bunkering ports and the amount of bunker to take at the refill port. In this category of approaches, the sailing speed is discretized into many small intervals, and additional binary decision variables are introduced to indicate the adopted sailing speed interval. Nevertheless, the addition of these binary decision variables significantly increases the computational burden.

Du et al. (2011) investigated a similar setting to that of Lang and Veenstra (2010) and Golias et al. (2010), and proposed a fourth approach by exploiting the property of the power relation between sailing speed and bunker consumption rate. They transformed the constraints with power functions to SOCP constraints and took advantage of state-of-the-art solvers to solve the SOCP problem. This exact algorithm is efficient when the bunker consumption rate is proportional to the sailing speed to the power of specific values, such as 3.5, 4.0, or 4.5. In the case of other values, for example 3.311, each power function constraint has to be represented by a substantial number of SOCP constraints and the problem can no longer be solved efficiently. Wang, Meng, and Liu (2013) overcame this deficiency by proposing a static quadratic outer-approximation method and a dynamic quadratic outer-approximation method. In the fifth approach, Meng and Wang (2011b) considered the optimization of speed along with ship deployment and frequency determination. They proposed a B&B-based ε-optimal algorithm to obtain the optimal sailing speed on each voyage leg. The algorithm uses a piecewise linear function to approximate the nonlinear relationship between sailing speed and bunker consumption rate because the relationship is convex. Wang and Meng (2012c) generated the piecewise linear functions a priori and developed a MILP approximation model to optimize the speed of containerships in a liner shipping network with container routing.

The speed of containerships not only determines the bunker consumption rate, but also the pollutant emissions. Containerships are among the top fuel-consuming and hence air-polluting categories of ships, and the main reason is their high service speed. Some studies have focused on the CO_2 emissions of ships. Psaraftis and Kontovas (2010) analyzed the implications of various maritime emission-reduction policies for maritime logistics. They concluded that important trade-offs may have to be made between the environmental benefits associated with such measures as a reduction in steaming speed and changes in the number of vessels in the fleet, and more conventional logistics attributes such as in-transit inventory holdings. Corbett, Wang, and Winebrake (2009) evaluated whether vessel speed reduction was a potentially cost-effective CO_2 mitigation option for ships calling at U.S. ports. By applying a profit-maximizing equation to estimate route-specific, economically efficient speeds, they explored the policy impacts of a fuel tax and a speed reduction mandate on CO_2 emissions. They found that a fuel tax of about \$150/ton of fuel would lead to average speed-related CO_2 reductions of about 20–30%. Meanwhile, a speed reduction mandate targeted to achieve a 20% CO_2 reduction in container shipping would cost between \$30 and \$200 per ton of CO_2 abated, depending on how the ship fleet responded to the mandate.

Kontovas and Psaraftis (2011a) examined the operational use of a speed reduction to reduce fuel consumption and curb emissions. Because time at sea increases with slow steaming, they investigated possible ways to decrease the time spent in port, one being to reduce the port service time, and the other to enable the prompt berthing of vessels upon arrival. Emissions reduction along the maritime intermodal container chain was investigated vis-à-vis a reduction in operational costs and other service attributes. Kontovas and Psaraftis (2011b) discussed the lessons learned from slow steaming, providing a link between the economy and the environment. They pointed out that the main incentives for speed reduction are (i) higher or volatile bunker prices leading to increased fuel costs; (ii) higher bunker costs because of the need to use the more expensive low-sulphur fuel oil, e.g., when operating in areas with controls on sulphur emissions; (iii) to make savings in other components of running costs (e.g., port dues and local taxes); (iv) over-capacity resulting in reduced freight rates; (v) mandatory emission-related regulations; and (vi) voluntary emission-related regulations, mainly adopted by companies that want to take responsibility for their impact on society. Psaraftis (2012) discussed the general concept of market-based measures for greenhouse gases. He reviewed 10 distinct proposals for market-based measures, under consideration by the International Maritime Organization and analyzed their pros and cons according to specific criteria such as administrative burden and likelihood of fraud. Psaraftis and Kontovas (2013) presented a survey of models in which speed is one of the decision variables in maritime transportation. They gave a taxonomy of such models according to a set of parameters, such as optimization criterion, decision maker, fuel consumption function, and whether inventory costs and emissions are included.

4.4. Schedule Design

The schedule of liner services is made up of the planned arrival and departure times at each port of call. Once the schedule is designed, the speeds of the containerships are largely determined. Therefore, schedule design is usually interwoven with speed optimization. The schedule of liner services also determines the O-D transit times for containers. Transit time (on a port-to-port or door-to-door basis) is an important service factor in liner shipping because shippers demand a fast service so they can reduce their inventories. Offering short transit times is a competitive factor, particularly when the goods involved are time sensitive (Notteboom 2006). When containers are delivered from the origin port to the destination port without transshipment, the port-to-port transit time is basically dependent on the intermediate port calls and the sailing speed. Karlaftis, Kepaptsoglou, and Sambracos (2009); Gelareh and Meng (2010); and Meng and Wang (2011b) have all considered the transit time constraint for direct deliveries without transshipment. When containers are transshipped, the transit time not only comprises the onboard time, but also the connection times at transshipment ports. Wang and Meng (2011) and Álvarez (2012) presented mathematical formulations to describe the relation between the connection times at transshipment ports and the schedules of liner services.

One line of study investigated the schedule design problem in a deterministic environment. In the model of Mourão, Pato, and Paixão (2001) mentioned earlier, the feeder route had two possible schedules: Tuesday and Thursday departures from the hub. The two schedules were examined and compared on the basis of the inventory costs of the containers to be shipped. Ting and Tzeng (2003) proposed a dynamic programming model for scheduling a single ship route under time window restrictions. Wang and Meng (2011) designed schedules by assuming that each O-D pair has a market-level transit time and a penalty or a benefit is incurred depending on whether the real transit time is longer or shorter than it. They proposed a hybrid GA to minimize the container routing cost and the cost associated with the transit time.

However, liner shipping services are not as reliable as one might imagine. As acknowledged by Psaraftis (2004, pp. 195–196), the former CEO of the Piraeus Port Authority, "the name of the game of all major container lines is their ability to meet their schedules, as they incur enormous costs, both real and intangible, in case they do not." Therefore, the second line of research examines the schedules of liner services taking uncertain factors into consideration. Notteboom (2006) conducted a survey and concluded that 93.6% of delayed schedules are attributable to port access and terminal operations. He further analyzed how liner shipping companies deal with the trade-offs linked to managing the time factor in liner service design and discussed the range of measures and planning tools container carriers deploy to maximize schedule reliability. Vernimmen, Dullaert, and Engelen (2007) presented a case study to illustrate the impact of schedule unreliability on the level of safety stock that needs to be kept by a manufacturer who sources spare parts from overseas. The results showed that an improvement in schedule reliability could lead to significant cost savings for the company under consideration. Qi and Song (2012) designed an optimal containership schedule on a liner ship route to minimize the total expected fuel consumption. The time spent at port was treated as a random variable and a certain level of service, in terms of the probability that the containership would arrive at a port no later than the published arrival time, had to be maintained. The problem is tackled with simulation-based stochastic approximation methods. Wang and Meng (2012d) designed the schedule of a liner ship route. The designed schedule was robust in that uncertainties in port operations and schedule recovery by fast steaming were captured endogenously. This problem was formulated as a mixed-integer nonlinear stochastic programming model. A solution algorithm that incorporated an SAA method, a linearization technique, and a decomposition scheme, was proposed. Wang and Meng (2012a) designed the optimal schedules of containerships in a liner shipping network. They assumed that there was a maximum allowable transit time for each O-D that had to be fulfilled. Uncertain port time and sea time contingencies were also captured. They formulated a stochastic MINLP and proposed a cutting-plane-based algorithm.

5. Operational Problems

There are a number of operational-level decision problems in liner shipping, for example, cargo booking, cargo routing, ship rescheduling, and crew scheduling. The operational-level problems are generally less structured than the strategic and tactical ones. Cargo booking and routing decisions are often incorporated into tactical-level plans. In this section, we review the literature on cargo booking and routing, and ship rescheduling.

5.1. Cargo Booking and Routing

Container cargo booking is not as evolved as it is for airlines, where many classes (e.g., economy and business) exist. It is generally assumed that the containers of the same O-D are homogeneous in the eyes of the liner shipping company, and the company simply determines how many containers to transport between each O-D, subject to its shipping capacity, to maximize profit. Container routing problems are very similar to multicommodity network-flow problems, and are usually formulated as LP models where the number of containers is treated as a continuous decision variable. Some studies have modeled container routing using O-D-based link flow formulations (e.g., Agarwal and Ergun 2008; Brouer, Pisinger, and Spoorendonk 2011), origin-based link flow formulations (e.g., Alvarez 2009; Wang and Meng 2012b), or segment-based formulations, where a segment is a sequence of consecutive links (e.g., Bell et al. 2011; Meng and Wang 2011a). Other studies have adopted path-based formulations (e.g., Brouer, Pisinger, and Spoorendonk 2011; Wang and Meng 2011, 2012c; Wang, Meng, and Sun 2013). Song and Dong (2012) mentioned how to generate the paths in a simple setting, and Meng and Wang (2012) and Wang, Meng, and Sun (2013) developed models to generate the paths for general application contexts.

Yan, Chen, and Lin (2009) developed an operational-level container routing model from the perspective of a liner shipping company. Their objective was to maximize operating profit, subject to related operating constraints. They constructed a space-time network to facilitate model formulation. They then developed a Lagrangian-based algorithm and performed a case study utilizing operating data from a major Taiwanese marine shipping company.

Bell et al. (2011) applied the frequency-based transit assignment model to minimize sailing time plus container dwell time at the origin port and any intermediate transshipment ports, for liner services with a given frequency. The model assumed that ships arrived at ports randomly, and that the dwell time at the origin port was half the average headway. A number of practical extensions were also discussed. Their model was more tactical level than operational level.

Brouer, Pisinger, and Spoorendonk (2011) investigated the cargo allocation problem, taking into consideration the repositioning of empty containers, for a liner shipping company. The aim was to maximize the profit from transporting cargos in a network, subject to the cost and availability of empty containers. The problem was formulated as a multicommodity flow model with additional interbalancing constraints to control the repositioning of empty containers. It was found that solving the LP-relaxed path-flow model with delayed column generation was very successful compared with solving the arc-flow model with the CPLEX barrier solver. The column generation algorithm was found to be at least two orders of magnitude faster for one time period and three orders of magnitude faster for three time periods.

Song and Dong (2012) considered the problem of joint cargo routing and empty container repositioning at the operational level for a shipping network with multiple service routes, multiple deployed vessels, and multiple regular voyages. They minimized the total relevant costs in the planning horizon that include container lifting on and off costs at ports, customer demand backlog costs, demurrage (or waiting) costs at the transshipment ports for temporarily storing laden containers, the empty container inventory costs at ports, and the empty container transportation costs. They assumed that the laden container routing from the original port to the destination port was limited with at most three service routes. A two-stage shortest-path-based integer programming method and a heuristic-rules-based method were proposed. The heuristic-rules-based method had advantages in its applicability to large-scale realistic systems.

5.2. Ship Rescheduling

In container liner shipping, disruptions can occur because of adverse weather conditions, port contingencies, and many other issues. A common scenario for recovering a schedule is to either increase the speed at the cost of a significant increase in the fuel consumption or to delay the delivery of cargo. Advanced recovery options might exist by swapping two ports of call or even omitting one. Brouer et al. (2013) proposed a vessel schedule recovery problem to evaluate a given disruption scenario and to select a recovery action balancing the tradeoff between increased bunker consumption and the impact on cargo in the remaining network and the customer service level. A space-time network model was presented. The model was applied to four real-life cases from Maersk Line and cost savings of up to 58% were achieved by the suggested solutions compared to realized recoveries of the real-life cases.

6. Future Research Perspectives with Practical Relevance

Despite the aforementioned advancements in the research on containership routing and scheduling, there are still some practically significant issues that have seldom been addressed. In this section, we examine these issues and suggest future research directions.

6.1. Intermodal Container Transportation Network Design

The origins and destinations of containerized cargo are usually inland locations. Sometimes shippers arrange the inland transportation from the origin to the export port and from the import port to the destination. Under these circumstances, liner shipping companies can take the ports as the origin and destination. Otherwise, the liner shipping companies must not only provide maritime transportation services, but also take charge of inland transportation to fulfill the supply chain management requirements of the shippers.

The literature on containership routing and scheduling in liner shipping focuses mainly on the ocean side. Although there are a few studies on the inland transportation of containers, little research has been directed at the optimization of both inland and maritime transportation systems. The interaction between inland and maritime transportation lies in the choice of load (export) port and discharge (import) port as well as the origin–destination transit time considerations (Meng, Wang, and Liu 2012). It is evident that a holistic optimization of the intermodal transportation network will have implications for a liner shipping company. Considering that the maritime liner shipping network design problem is already NP-hard, efficient heuristic methods might be expected to address the intermodal container transport network design problem.

6.2. Joint Planning Between Liner Shipping Companies and Port Operators

In general, liner shipping companies and port operators make decisions independently. Nevertheless, a holistic optimization approach may improve the operating efficiency of both parties. For example, when a port is congested, a ship may lower its speed to save bunker because it will have to wait for a berth even if it arrives early at the port. Another example is that the liner shipping companies and port operators will agree on berth time windows for ships over a planning horizon. However, in practice, ships frequently miss the allocated time slots because liner shipping companies build too little buffer time in their schedules. This adversely affects both berth and yard planning for the port operators. A major challenge here is how to design mechanisms to coordinate the different parties involved in both the decision making and the execution of the decisions.

6.3. Shipping Network Reliability and Vulnerabilities

Maintaining a high quality of service is a great concern for liner shipping companies, and maintaining reliable schedules has proven to be a challenge. Schedule unreliability has extensive adverse effects. First, customers have to maintain a high inventory level to hedge against the unexpected late arrival of cargo. Second, port operators need to make frequent adjustments to their berthing plans, quay crane allocations, and yard operations. Third, liner shipping companies face low customer satisfaction and incur high costs because of fast steaming to catch up with a delayed schedule. Understanding and correctly formulating models that take reliability and vulnerability into account is an important topic for future research.

6.4. Green Shipping

Designing shipping networks that are not only efficient but also minimize environmental impact is becoming more important. Emissions from commercial shipping are currently the subject of intense scrutiny. In fact, the era of nonregulation for shipping-related greenhouse gases officially came to an end in July 2011, when, after considerable debate and fierce opposition from a number of developing countries, the Marine Environment Protection Committee adopted the Energy Efficiency Design Index for new ships (Psaraftis 2012). Moreover, further measures to curb future greenhouse gas growth in shipping are being sought with a high sense of urgency. The new regulations will affect all levels of decision making, from deciding on fleet compositions and ports of call (e.g., some ports offer a discount on dockage fees to vessels that sail at a low speed, according to Kontovas and Psaraftis 2011b) to selecting the right sailing route between two ports in the presence of a storm or favorable currents. It will therefore be important to consider possible regulation scenarios in future models.

6.5. Better Benchmarks and Unifying Models

Many studies of liner ship routing and scheduling are based on real-world applications, which often means that the models are customized to a particular application. To enhance development, general models and benchmarks need to be proposed and made available. The problems need to be interesting and challenging, while incorporating many aspects unique to liner ship routing and scheduling. The benchmarks should be based on real data from the industry and be rich enough to properly address the unique industrial aspects. A first attempt in this direction has been made by researchers from the Technical University of Denmark. They share benchmarking instances that consist of data on ship fleets, demand, ports, and distances. Hopefully, more studies in the future will use the same data set for comparison.

6.6. Applications by Practitioners

For several reasons, only a few research efforts have actually been implemented by liner shipping companies. First, liner shipping companies are sensitive about their operating data, and hence, even if some research is applied in practice, the results may not be reported. Second, academic models cannot capture all of the operating features of liner shipping, and liner shipping companies thus often prefer their traditional planning approaches. Third, the computational experiments reported in the literature are generally not large enough to handle the global shipping network of a liner shipping company. Some companies, such as OOCL and Maersk Line, have started to work with academia to improve their shipping operations. We believe that there is a significant opportunity for academic research to address practical containership routing and scheduling problems.

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