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Vessel scheduling in liner shipping: a critical literature review and future research needs

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Abstract

Liner shipping plays a major role for freight transportation and international seaborne trade. The economic development of different countries is significantly dependent on the movement of a containerized cargo. One of the most challenging decision problems, tackled by liner shipping companies, is the design of vessel schedules. At the vessel scheduling stage, the liner shipping company aims to determine vessel sailing speeds at voyage legs of a given liner shipping route, port times, vessel handling rates at ports, the minimum number of vessels required in order to provide the agreed service frequency at ports, and other factors. Considering the existing pollution levels, the environmental impacts of liner shipping have to be captured in the vessel scheduling models as well. This study conducts a comprehensive survey of the existing research on vessel scheduling in liner shipping. The collected vessel scheduling studies are classified into different categories, including general vessel scheduling, uncertainty in liner shipping operations, collaborative agreements, vessel schedule recovery, and green liner shipping. Based on a detailed analysis of the collected literature, findings are discussed, and limitations in the state-of-the-art are identified for each category of studies. The study concludes with a number of future research opportunities, taking into account the recent developments and trends in liner shipping.

Keywords Maritime transportation · Liner shipping · Vessel scheduling · Critical literature review · Modeling drawbacks · Future research needs

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1 Introduction

Maritime transportation is considered as a vital mode for international trade. According to the study, conducted by Lloyd's Marine Intelligence Unit, maritime transportation accounts for ≈ 75% of the total volume and ≈ 60% of the total value of global trade (Lee and Song 2017). Maritime transportation is the most economical mode of transportation and, therefore, is preferable for the movement of large cargo volumes, despite being slower than other modes, such as road, rail, and air (Chang and Thai 2017). International seaborne trade has experienced a tremendous escalation over the past decades. More specifically, global seaborne trade increased by about 295% from 1970 to 2016 (UNCTAD 2017). United Nations Conference on Trade and Development (UNCTAD) projected an annual growth of 3.2% in international seaborne trade between 2017 and 2022. The economic importance of maritime transportation emphasizes the need to focus on the improvement of shipping operations in order to facilitate the seaborne trade (Chew et al. 2015; Andersen et al. 2017; Diz et al. 2018).

Maritime transportation of freight has three modes of operation, including the following: (1) industrial shipping; (2) liner shipping; and (3) tramp shipping (Lawrence 1972). In industrial shipping, the owners of cargoes are in control of the vessels and intend to ship their cargoes at a minimal cost. When the cargo owners are not in charge of the vessels, two shipping modes are available: liner shipping and tramp shipping. Liner shipping companies operate their vessels on fixed routes and schedules. Details regarding the routes and schedules are posted by liner shipping companies and are available to shippers. Vessels, deployed for service of a given liner shipping route, perform round trips and can load and unload cargo at the ports that belong to the route or port rotation (i.e., the sequence of ports to be called). Any deviations from the published arrival times of vessels at ports are not desirable, even if the vessels are not fully loaded. Violation of published vessel schedules may result in additional penalties, which can be imposed by the marine container terminal (MCT) operators. In contrast to liner shipping, tramp shipping does not have any fixed schedules or port rotations. The vessels can sail from any port to another on short notice. Tramp vessels usually sail when they are fully or close to fully loaded. Furthermore, tramp vessels transport the cargo for a very limited number of clients only; therefore, loading and discharging generally occur only at a few ports (Reddy 2017). Also, tramp shipping companies offer their services at freight rates, which are typically negotiable, while liner shipping companies usually have fixed freight rates for their services (Reddy 2017).

Liner shipping companies deal with three levels of decision problems (Pesenti 1995; Meng et al. 2014), which include: (1) strategic decisions; (2) tactical decisions; and (3) operational decisions (Fig. 1). The strategic-level decisions consist of long-term decisions, which are generally made with a frequency, varying from 6 months to several years, such as vessel fleet size and mix, alliance strategies, and network design. Based on changing shipment demand, tactical-level decisions are made every 3–6 months. These decisions include determination of the

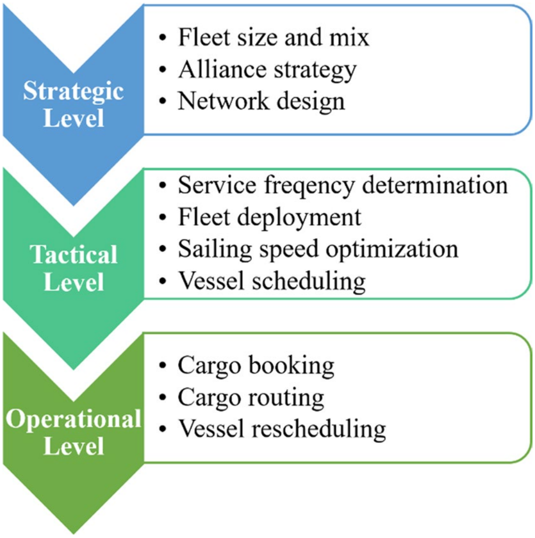

Fig. 1 Liner shipping decision problems at different levels

frequency of liner shipping services, deployment of vessels on the respective port rotations, determination of vessel sailing speeds, and design of vessel schedules. The operational-level decision problems include cargo booking, cargo routing, and vessel rescheduling due to disruptions, such as congestion at ports, adverse weather, malfunctioning of vessel engines, and others.

The design of vessel schedules (i.e., the vessel scheduling problem) is a challenging decision problem in liner shipping. Throughout the vessel schedule design, the liner shipping company has to focus on determination of sailing speeds at voyage legs of a port rotation. The liner shipping company also has to explicitly capture the MCT operations at ports [i.e., determination of arrival and departure times, waiting time, potential vessel arrival delays, arrival time windows (TWs) and handling rates at each port]. Furthermore, the liner shipping company should allocate a sufficient number of vessels in order to maintain the agreed service frequency at each port (in general, weekly or bi-weekly). Some of the aforementioned decisions are to be made by the liner shipping company (e.g., determination of vessel sailing speeds, determination of the required number of vessels), while certain decisions have to be negotiated with the MCT operators at ports of the given liner shipping route (arrival TWs at ports, handling rates at ports).

Efficient vessel schedules are critical not only for the liner shipping company but also for other key supply chain players, including MCT operators, shippers, alliance partners, and others. For instance, having access to the updated vessel schedules is important for exporters. If exporters are not updated regarding changes in vessel schedules, they can make inaccurate bookings. Truckers also should be notified of any changes in vessel schedules. Failure to inform truckers regarding the updated vessel schedules can lead to substantial financial losses due to demurrage penalties. Without a proper notification, several parties can miss the critical cut-off times, ultimately delaying the cargoes and violating the schedules. Another group, affected by changes in vessel schedules, is importers. Their production and sales plans are based on vessel schedules. In order to adjust the production cycles, any changes in the vessel arrival times must be known. Improper notifications might lead to missed sale dates, late deliveries, or even customer losses and factory shutdowns.

Certain decisions, which have to be made by liner shipping companies throughout the design of vessel schedules, are conflicting in nature. For example, slow steaming or speed reduction is a common strategy adopted by liner shipping companies when they try to minimize the total fuel cost. Application of a slow steaming strategy allows reducing the fuel consumption and the associated cost but increases the sailing time at each voyage leg and, consequently, the total vessel turnaround time. In order to maintain the service frequency, negotiated between the liner shipping company and the MCT operators, the liner shipping company will have to deploy more vessels (Meng et al. 2014). The latter action would further lead to an increase in the total vessel operational cost. In addition, slow steaming may cause violation of transit times for certain types of cargoes and incur an additional inventory cost. The total vessel turnaround time can be lowered by requesting a handling rate with higher handling productivity at ports [generally measured in twenty-foot equivalent units (TEUs) per hour]. However, a handling rate with higher handling productivity will increase the total port handling cost. Therefore, the liner shipping company has to directly consider the conflicting decisions in order to design cost-effective vessel schedules.

Increasing fuel consumption also increases the amount of emissions, produced by vessels. In 2007, it was estimated that the total fuel consumption of the global vessel fleet ranged between 279 million tons and 400 million tons (IMO 2009). Consequently, the amount of carbon dioxide (CO_2), sulfur oxide (SO_x), and nitrogen oxide (NO_x) gases and particulate matter (PM) emissions from liner shipping is substantial. International Maritime Organization (IMO), the international authority responsible for regulation of pollution from maritime transportation, enforced a global maximum limit of 3.5% sulfur content in vessel fuel since 2012 (IMO 2018a). The fuel sulfur content of 3.5% was targeted to be reduced to 0.5% by 2020 (IMO 2018a). IMO established several Emission Control Areas (ECAs), which impose special restrictions on emissions from vessels sailing within ECAs. Some of the areas that are designated as ECAs include: (1) the Baltic Sea area with restrictions on SO_x—effective since 2006; (2) the North Sea area with restrictions on SO_x—effective since 2007; (3) the U.S.—Canadian coastal zone with restrictions on NO_x, SO_x, and PM—effective since 2012; and (4) the U.S. Caribbean Sea area with restrictions on NO_x, SO_x, and PM—effective since 2014 (IMO 2018b). Special restrictions on SO_x are imposed within ECAs, where the maximum sulfur content of fuel was restricted to 1.00% after July 01, 2010 and to 0.10% after January 01, 2015 (IMO 2018b). It should be noted that the price of low-sulfur fuel (e.g., marine gas oil—MGO) is much higher than the regular fuel (i.e., heavy fuel oil—HFO), which causes additional challenges in the design of cost-efficient and environment-friendly vessel schedules.

A significant number of studies focused on the vessel scheduling problem in order to assist liner shipping companies with the design of vessel schedules. This study presents a detailed review of the research efforts, which investigated different aspects of the vessel scheduling problem in liner shipping. Moreover, representative mathematical models, capturing these aspects, are provided as well. The present study complements the previous liner shipping literature survey efforts, conducted by Meng et al. (2014) and Lee and Song (2017). The contributions of this work to the state-of-the-art can be summarized as follows:

(1) The present study performs a recent and broader survey of the studies with a specific focus on the vessel scheduling problem. In particular, the present survey provides a detailed review of 108 studies, which specifically deal with the vessel scheduling problem and the aspects that may influence the vessel scheduling decisions.
(2) The present study provides mathematical formulations for five vessel scheduling problems, including the following: (1) general vessel scheduling problem; (2) vessel scheduling problem with uncertainties in liner shipping operations; (3) collaborative vessel scheduling problem; (4) vessel schedule recovery problem; and (5) green vessel scheduling problem. The presented mathematical models can serve as a foundation for the future studies on vessel scheduling.
(3) The present survey provides a comprehensive and systematic review of the critical vessel scheduling attributes adopted within the collected studies, including the following data: (1) assumptions regarding the vessel sailing speed; (2) assumptions regarding the port time; (3) model objective; (4) objective components; (5) solution approach; and (6) notes/major considerations.
(4) Considering an increasing attention of the community to environmental concerns, a strong emphasis is given to the green vessel scheduling problems in liner shipping.
(5) The present survey provides a review of the studies, which did not propose any mathematical models for vessel scheduling but discussed certain important environmental aspects, which should be considered by the future green vessel scheduling studies (e.g., explicit evaluation of the effects from fuel/emission taxation schemes on vessel scheduling; environmental regulations and vessel scheduling within ECAs; the impacts of the existing technologies and methods, which are used for reducing emissions, on vessel scheduling).
(6) New trends in the vessel scheduling literature are identified. In the meantime, the existing research gaps in the prior and recent vessel scheduling studies are determined, and future research needs are highlighted.

The rest of the paper is organized as follows. The next section presents a detailed description of the vessel scheduling problem, while the third section discusses the literature survey that was performed as a part of this study. The fourth section presents a detailed description of the reviewed studies, summary of findings, existing research gaps, and future research needs. The fifth and the final section provides necessary conclusions.

2 Vessel scheduling problem description

This section of the manuscript presents a detailed description of the main features of the vessel scheduling problem, including the following: (a) liner shipping route description; (b) service of vessels at ports; (c) fuel consumption; (d) port service frequency; (e) container inventory; (f) sailing speed selection; and (g) revenue estimation. Furthermore, an illustrative example of a vessel schedule is provided at the end of this section.

2.1 Liner shipping route description

A given liner shipping route can be either served by one liner shipping company or multiple liner shipping companies (i.e., liner shipping alliance). The liner shipping routes consist of multiple ports. The number of ports to be visited by vessels of a given liner shipping company may vary from one route to another. Denote $P = \left\{1, \dots, m^1\right\}$ as the set of ports to be visited by vessels for a given liner shipping route. The sequence of ports to be called (the latter term is generally referred to as "port rotation" in the liner shipping literature—Meng et al. 2014) is determined by each liner shipping company at the strategic level. Certain ports in a port rotation can be visited more than once during a voyage. The consecutive ports are connected by voyage legs (e.g., voyage leg p connects ports p and $p+1$). Generally, details regarding the port rotations are publicly available and are provided by liner shipping companies. These details may include, but are not limited to: (a) name of the port; (b) country; (c) distance to the next port to be visited; (d) names/specifications of the vessels, serving a given liner shipping route; and others.

2.2 Service of vessels at ports

The liner shipping company negotiates a port arrival TW with the MCT operator at each port of the liner shipping route. Each port arrival TW can be defined using two attributes: (a) $\tau_p^{st}, p \in P$—TW start at port p (hours); and (b) $\tau_p^{end}, p \in P$—TW end at port p (hours). Each vessel is expected to arrive at a given port within the negotiated arrival TW. Certain studies relied on a "soft TW" concept (Fagerholt 2001; Alharbi et al. 2015), where the vessels are allowed to arrive before the TW start or after the TW end at a given port. The vessels, arriving at the port before the negotiated arrival TWs, usually wait for service in the dedicated waiting area, located in a vicinity of the port. Service of the vessels, arriving at the port after the negotiated arrival TWs, may start upon the vessel arrival (if the designated MCT berthing position is still available and the MCT operator has sufficient handling resources for the vessel service). Late vessel arrivals may result in substantial disruptions of berth schedules, developed by the MCT operators. Therefore, the total late vessel arrival cost (***LAC***—USD) will be imposed by the MCT operators to the liner shipping company at ports of call, which is calculated based on the unit late vessel arrival cost ($c_p^{late}, p \in P$—USD/hour) and the late arrival hours ($\boldsymbol{\tau}_p^{late}, p \in P$—hours) using the following relationship:

$$\boldsymbol{LAC} = \sum_{p \in P} c_p^{late} \boldsymbol{\tau}_p^{late} \tag{1}$$

Along with the port arrival TWs, the liner shipping company negotiates a handling rate with the MCT operator at each port of the liner shipping route. The port handling productivity, which is associated with the negotiated handling rate, defines the total number of TEUs that will be handled per hour for a given vessel. The handling time at port p ($\boldsymbol{\tau}_p^{hand}, p \in P$—hours) can be calculated based on the negotiated handling productivity ($ph_p, p \in P$—TEUs/hour) and the container demand ($\boldsymbol{QC}_p^{PORT}, p \in P$—TEUs) using the following relationship:

$$\boldsymbol{\tau}_p^{hand} = \frac{\boldsymbol{QC}_p^{PORT}}{ph_p} \quad \forall p \in P \tag{2}$$

Note that the container demand ($\boldsymbol{QC}_p^{PORT}, p \in P$—TEUs) is treated as a variable in Eq. (2), as it is generally sensitive to the transit time of containers (Cheaitou and Cariou 2019). In order to provide the negotiated handling productivity, the MCT operator at each port should allocate the appropriate amount of handling recourses. A unit port handling cost ($c_p^{hand}, p \in P$—USD/TEU) is imposed to the liner shipping company based on the requested handling productivity. The total port handling cost (***PHC***—USD) can be calculated using the following relationship:

$$\boldsymbol{PHC} = \sum_{p \in P} c_p^{hand} \boldsymbol{QC}_p^{PORT} \tag{3}$$

2.3 Fuel consumption

One of the common assumptions in the published-to-date vessel scheduling studies is a homogenous nature of the vessel fleet, allocated for service of a given liner shipping route (Wang and Meng 2012a, b; Wang et al. 2014a; Alharbi et al. 2015). The latter assumption is also in line with real-life liner shipping operations (CMA CGM 2018a, b). Homogeneous vessels are assumed to burn fuel at the same rate, which can be justified by similarities in their technical specifications (e.g., configurations and capacity of the main and auxiliary vessel engines). An increase in the sailing speed of vessels increases the fuel consumption (Wang and Meng 2012a, b, c; Bialystocki and Konovessis 2016). Several factors impact the fuel consumption, including sailing speed, payload, weather conditions, and vessel geometric characteristics (Bialystocki and Konovessis 2016). A number of studies highlighted that the vessel sailing speed and the vessel payload are the major factors, which directly influence the fuel consumption (Psaraftis and Kontovas 2013; Kontovas 2014). The fuel consumption by the main vessel engines per nautical mile (nmi) at voyage leg p ($\boldsymbol{f}_p, p \in P$—tons/nmi) can be calculated using the following relationship (Psaraftis and Kontovas 2013; Kontovas 2014):

$$\boldsymbol{f}_p = k_1\left(k_2 + (\boldsymbol{s}_p)^{k_3}\right)\left(\boldsymbol{w}_p + A\right)^{2/3} \quad \forall p \in P \tag{4}$$

where $k_1 > 0, k_2 \geq 0, k_3 \geq 3$—are the coefficients of the fuel consumption function; $\boldsymbol{s}_p, p \in P$—is the vessel sailing speed at voyage leg p (knots); $\boldsymbol{w}_p, p \in P$—is the vessel payload at voyage leg p (tons); A—is the "lightship weight" component, estimated as a summation of the vessel weight (tons) if empty, fuel, and other consumables.

The total fuel cost ($\boldsymbol{FCC}$—USD) at a given liner shipping route can be calculated based on the voyage leg length ($l_p, p \in P$—nmi), the unit fuel cost (c^{fuel}—USD/ton), and the total fuel consumption using the following relationship:

$$\boldsymbol{FCC} = c^{fuel}\sum_{p\in P} l_p \boldsymbol{f}_p \tag{5}$$

The fuel consumption by the auxiliary vessel engines, which are used for providing power on board the vessels, does not change substantially throughout the vessel voyage and is typically included in the vessel operational cost in the vessel scheduling studies (Kontovas 2014; Dulebenets 2018a). The sailing speed at a given voyage leg of the liner shipping route is assumed to remain constant, while the vessel is sailing at that leg. The sailing time at voyage leg p ($\boldsymbol{\tau}_p^{sail}, p \in P$—hours) can be calculated based on the vessel sailing speed and the voyage leg length using the following relationship:

$$\boldsymbol{\tau}_p^{sail} = \frac{l_p}{\boldsymbol{s}_p} \quad \forall p \in P \tag{6}$$

2.4 Port service frequency

The port service frequency is another tactical-level decision to be determined by the liner shipping company, which is generally used as an input for the vessel scheduling problem (Meng et al. 2014). In order to maintain the port service frequency, negotiated with the MCT operators, the liner shipping company needs to ensure that the following relationship is maintained (Wang et al. 2014a; Alharbi et al. 2015; Dulebenets and Ozguven 2017):

$$\sum_{p\in P}\boldsymbol{\tau}_p^{sail} + \sum_{p\in P}\boldsymbol{\tau}_p^{wait} + \sum_{p\in P}\boldsymbol{\tau}_p^{hand} = 24\phi\boldsymbol{q} \tag{7}$$

where $\boldsymbol{q}$—is the total number of vessels to be deployed for service of the liner shipping route (vessels); ϕ—is the port service frequency (days); 24—is the total number of hours in one day (hours/day); $\boldsymbol{\tau}_p^{wait}, p \in P$—is the vessel waiting time at port p (hours).

The left-hand-side of equality (7) denotes the total vessel turnaround time at the given liner shipping route. More specifically, it represents the total time required by the vessels to visit all the ports of the given liner shipping route and return at the first port. The total vessel turnaround time includes the following time components:

(a) the total vessel sailing time over all the voyage legs; (b) the total port waiting time over all the ports; and (c) the total port handling time over all the ports. In order to determine the total number of vessels, necessary for service of the given liner shipping route, the total turnaround time should be divided by the negotiated port service frequency and integer "24" (representing the total number of hours in a 1 day). The total vessel operational cost (***VOC***—USD) can be calculated based on the unit vessel operational cost (c^{oper}—USD/day), port service frequency, and the total number of deployed vessels using the following relationship:

$$\boldsymbol{VOC} = c^{oper}\phi\boldsymbol{q} \tag{8}$$

2.5 Container inventory

The liner shipping company has to account for the inventory cost, associated with the movement of containers along all the voyage legs of the liner shipping route. The total container inventory cost (***CIC***—USD) can be calculated based on the unit container inventory cost (c^{inv}—USD/TEU/hour), the number of containers to be transported at voyage legs ($\boldsymbol{QC}_p^{SEA}, p \in P$—TEUs), and the total vessel sailing time using the following relationship (Wang et al. 2014a; Giovannini and Psaraftis 2018):

$$\boldsymbol{CIC} = c^{inv}\sum_{p\in P}\boldsymbol{QC}_p^{SEA}\boldsymbol{\tau}_p^{sail} \tag{9}$$

Note that the total container inventory cost is included in many of the vessel scheduling models, which have been presented to date in the literature (Wang et al. 2014a; Dulebenets and Ozguven 2017; Giovannini and Psaraftis 2018). However, the total container inventory cost in not a direct cost for liner shipping companies and is primarily endured by shippers.

2.6 Sailing speed selection

Sailing speed is one of the major decision variables in the vessel scheduling problem. Selection of high vessel sailing speeds at voyage legs of the liner shipping route will reduce the transit time of containers between ports and the associated container inventory cost. Furthermore, increasing vessel sailing speed will decrease the total vessel turnaround time; and, therefore, the liner shipping company will need to deploy less vessels for service of the given liner shipping route (see Eq. 7 in Sect. 2.4 of the manuscript). The latter will also result in a reduction of the total vessel operational cost. However, increasing vessel sailing speed will increase the fuel consumption and the associated total fuel cost. Moreover, selection of the vessel sailing speed is also affected with technical characteristics of the main vessel engines (Psaraftis and Kontovas 2013, 2014).

2.7 Revenue estimation

The total revenue (***REV***—USD), which will be generated by the liner shipping company, can be calculated based the unit freight rate ($c_p^{rev}, p \in P$—USD/TEU) and the quantity of containers to be delivered to the ports of the given liner shipping route using the following relationship (Chuang et al. 2010; Giovannini and Psaraftis 2018):

$$\boldsymbol{REV} = \sum_{p \in P} c_p^{rev} \boldsymbol{QC}_p^{PORT} \tag{10}$$

2.8 Typical vessel schedule example

Figure 2 illustrates an example of a typical vessel schedule for the liner shipping route that includes four ports. It is assumed that the arrival time at the first port ($\boldsymbol{\tau}_1^{arr}$), which is port "1" in this example, is zero. Based on the designed schedule, a vessel arrives at port "1" within the negotiated arrival TW (therefore, $\boldsymbol{\tau}_1^{wait} = 0$ hours). Upon the TW start at port "1", the vessel will be served for $\boldsymbol{\tau}_1^{hand} = 24$ hours and will depart port "1" at time $\boldsymbol{\tau}_1^{dep} = \boldsymbol{\tau}_1^{arr} + \boldsymbol{\tau}_1^{wait} + \boldsymbol{\tau}_1^{hand} = 0 + 0 + 24 = 24$ hours. If the distance from port "1" to port "2" (l_1) is 2240 nmi, and the vessel sails at constant speed $\boldsymbol{s}_1 = 16.0$ knots, the sailing time will be $\boldsymbol{\tau}_1^{sail} = \frac{2240}{16.0} = 140$ hours. So, the arrival time at port "2" will be $\boldsymbol{\tau}_2^{arr} = \boldsymbol{\tau}_1^{dep} + \boldsymbol{\tau}_1^{sail} = 24 + 140 = 164$ hours. Since the vessel arrives at port "2" before the TW start ($\tau_2^{st} = 168$ hours), it will be required to wait in the dedicated area of port "2" for $\boldsymbol{\tau}_2^{wait} = 168 - 164 = 4$ hours. Upon the

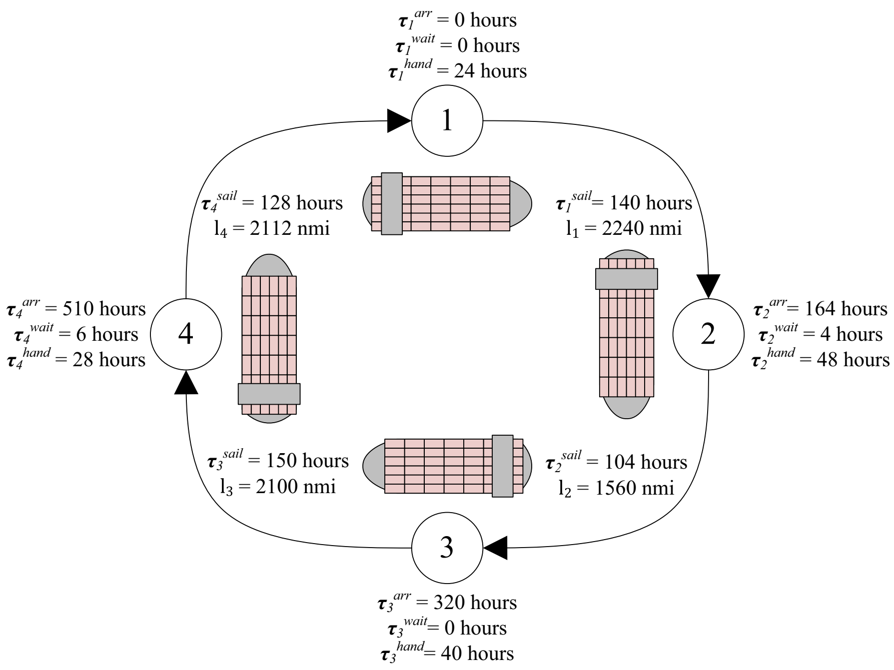

Fig. 2 A typical vessel schedule example

TW start at port "2", the vessel will be served for $\tau_2^{hand} = 48$ hours and will depart port "2" at time $\tau_2^{dep} = 164 + 4 + 48 = 216$ hours. If the distance from port "2" to port "3" (l_2) is 1560 nmi, and the vessel sails at constant speed $s_2 = 15.0$ knots, the sailing time will be $\tau_2^{sail} = \frac{1560}{15.0} = 104$ hours. So, the arrival time at port "3" will be $\tau_3^{arr} = 216 + 104 = 320$ hours. Based on the designed schedule, the vessel arrives at port "3" within the negotiated arrival TW (therefore, $\tau_3^{wait} = 0$ hours). Upon the TW start at port "3", the vessel will be served for $\tau_3^{hand} = 40$ hours and will depart port "3" at time $\tau_3^{dep} = 320 + 0 + 40 = 360$ hours.

If the distance from port "3" to port "4" (l_3) is 2100 nmi, and the vessel sails at constant speed $s_3 = 14.0$ knots, the sailing time will be $\tau_3^{sail} = \frac{2100}{14.0} = 150$ hours. So, the arrival time at port "4" will be $\tau_4^{arr} = 360 + 150 = 510$ hours. Since the vessel arrives at port "4" before the TW start ($\tau_4^{st} = 516$ hours), it will be required to wait in the dedicated area of port "4" for $\tau_4^{wait} = 516 - 510 = 6$ hours. Upon the TW start at port "4", the vessel will be served for $\tau_4^{hand} = 28$ hours and will depart port "4" at time $\tau_4^{dep} = 510 + 6 + 28 = 544$ hours. If the distance from port "4" to port "1" (l_4) is 2112 nmi, and the vessel sails at constant speed $s_4 = 16.5$ knots, the sailing time will be $\tau_4^{sail} = \frac{2112}{16.5} = 128$ hours. So, the vessel is expected to return to port "1" at time $\tau_1^{arr} = 544 + 128 = 672$ hours. The total vessel turnaround time for this liner shipping route will be $24 + 140 + 4 + 48 + 104 + 40 + 150 + 6 + 28 + 128 = 672$ hours. If the negotiated port service frequency is 1 week (i.e., $\phi = 7$ days), the liner shipping company will have to allocate $q = \frac{672}{24 \cdot 7} = 4$ vessels. Also, the vessel arrival time at port "1" will have to be adjusted as follows: $\tau_1^{arr} = \tau_4^{dep} + \tau_4^{sail} - 24\phi q = 544 + 128 - 24 \cdot 7 \cdot 4 = 0$ hours. The latter adjustment is required in order to account for the round voyage of a vessel (Dulebenets 2018a).

3 Literature search

The literature search in this study was conducted using the major scientific publishers (e.g., Elsevier, Springer, ASCE, Wiley) in order to gather the existing literature related to the vessel scheduling problem. A number of keywords and phrases, directly related to the theme of this study, were used to guide the search process. More specifically, the following keywords and phrases were used to identify the relevant studies: liner shipping, liner shipping companies, vessel scheduling, vessel schedule design, green vessel scheduling, vessel schedule recovery, and collaborative vessel scheduling. A total of 108 studies, found to be the most relevant to the theme of the conducted literature survey, were extracted for a detailed review from all the studies that were identified as a result of a structured keyword search. The selected studies were classified into the following categories: (1) general vessel scheduling; (2) uncertainties in liner shipping operations; (3) collaborative agreements; (4) vessel schedule recovery; and (5) green liner shipping. Figure 3 shows the distribution of the selected studies by the study category and year of publication, while the distribution of the selected studies by the study category is illustrated in Fig. 4.

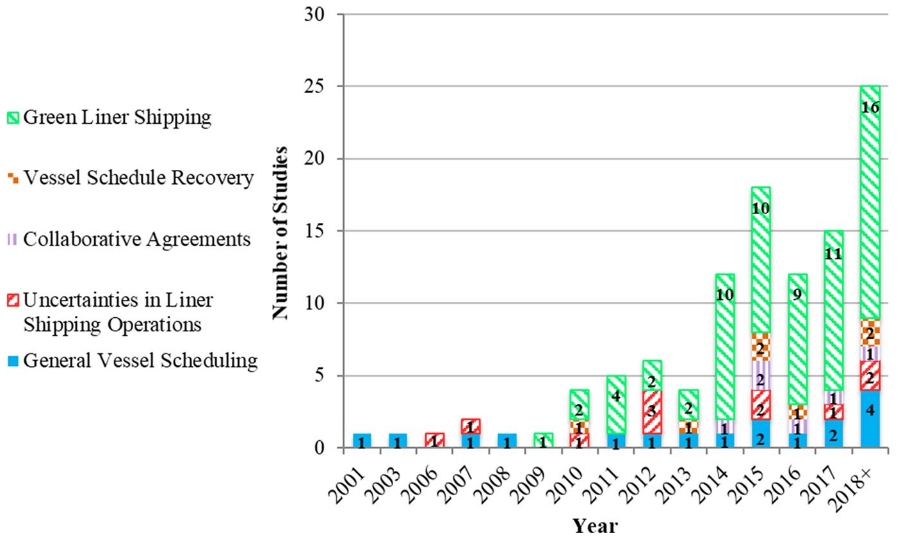

Fig. 3 Distribution of studies by the study category and year of publication

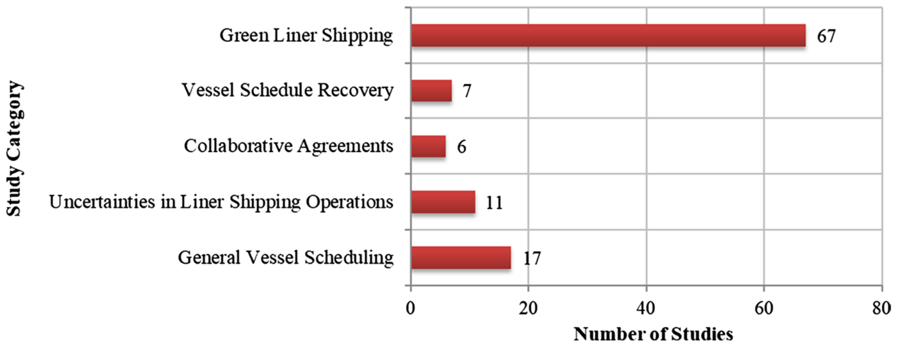

Fig. 4 Distribution of the selected studies by the study category

The results from the conducted literature survey indicate that vessel scheduling in liner shipping continues receiving increasing attention from the community, especially over the last 10 years. The latter tendency can be explained by rapidly increasing volumes of international seaborne trade and the needs of liner shipping companies for the decision support methodologies, which can be used for the design of cost-effective vessel schedules. Furthermore, a significant portion of the studies focused on green vessel scheduling and environmental aspects in vessel scheduling (a total of 67 studies were identified under the green liner shipping group). A detailed description of the collected studies for each one of the aforementioned categories will be presented in the following sections of the manuscript.

4 Detailed review of the collected studies

This section of the manuscript provides a detailed review of the studies, which were collected as a result of the conducted literature survey. Each one of the study categories will be analyzed with a primary focus on the following aspects: (1) description of the study category and a representative mathematical model (if applicable); (2) description of the relevant studies; (3) summary of findings; and (4) existing limitations and future research needs. A full list of notations that were used in the proposed mathematical models is provided in "Appendix". The summary of findings for each study category will be presented in a table format and will include the following data: (1) author(s); (2) year of publication; (3) assumption regarding the vessel sailing speed; (4) assumption regarding the port time; (5) model objective; (6) objective components (cost-related components will be considered); (7) solution approach; and (8) notes/ major considerations.

4.1 General vessel scheduling

This section of the manuscript focuses on general vessel scheduling, which aims to design basic vessel schedules (i.e., determine sailing speeds at voyage legs of a given liner shipping route, port waiting times, late vessel arrivals at ports, the minimum number of vessels required in order to provide the agreed service frequency at ports) without explicitly modeling certain operational factors, such as the existing environmental regulations, emissions produced by vessels, uncertainty in liner shipping and MCT operations, collaborative agreements between the liner shipping company and the MCT operators, and others. A detailed description of the general vessel scheduling problem is provided in Sect. 2 of the manuscript. Denote $\boldsymbol{TP}$ as the total profit, which will be generated by the liner shipping company (USD); s^{max} as the maximum vessel sailing speed (knots); s^{min} as the minimum vessel sailing speed (knots); and q^{max} as the maximum number of vessels that can be allocated for service of the given liner shipping route (vessels). Then, a typical mixed-integer nonlinear mathematical model for the general vessel scheduling problem (**VSP**) can be formulated as follows:

General Vessel Scheduling Problem (**VSP**):

$$max\ \boldsymbol{TP} = [\boldsymbol{REV} - (\boldsymbol{PHC} + \boldsymbol{LAC} + \boldsymbol{FCC} + \boldsymbol{VOC} + \boldsymbol{CIC})] \tag{11}$$

Subject to:

$$\boldsymbol{\tau}_p^{sail} = \frac{l_p}{\boldsymbol{s}_p} \quad \forall p \in P \tag{12}$$

$$\boldsymbol{s}_p \le s^{max} \quad \forall p \in P \tag{13}$$

$$\boldsymbol{s}_p \ge s^{min} \quad \forall p \in P \tag{14}$$

$$\boldsymbol{f}_p = k_1(k_2 + (\boldsymbol{s}_p)^{k_3})(\boldsymbol{w}_p + A)^{2/3} \quad \forall p \in P \tag{15}$$

$$\boldsymbol{\tau}_{p+1}^{arr} = \boldsymbol{\tau}_p^{dep} + \boldsymbol{\tau}_p^{sail} \quad \forall p \in P, p < m^1 \tag{16}$$

$$\boldsymbol{\tau}_1^{arr} = \boldsymbol{\tau}_p^{dep} + \boldsymbol{\tau}_p^{sail} - 24\phi\boldsymbol{q} \quad \forall p \in P, p = m^1 \tag{17}$$

$$\boldsymbol{\tau}_p^{hand} = \frac{\boldsymbol{QC}_p^{PORT}}{ph_p} \quad \forall p \in P \tag{18}$$

$$\boldsymbol{\tau}_{p+1}^{wait} \geq \tau_{p+1}^{st} - \boldsymbol{\tau}_p^{dep} - \boldsymbol{\tau}_p^{sail} \quad \forall p \in P, p < m^1 \tag{19}$$

$$\boldsymbol{\tau}_1^{wait} \geq \tau_1^{st} - \boldsymbol{\tau}_p^{dep} - \boldsymbol{\tau}_p^{sail} + 24\phi\boldsymbol{q} \quad \forall p \in P, p = m^1 \tag{20}$$

$$\boldsymbol{\tau}_p^{late} \geq \boldsymbol{\tau}_p^{arr} - \tau_p^{end} \quad \forall p \in P \tag{21}$$

$$\boldsymbol{\tau}_p^{dep} = \boldsymbol{\tau}_p^{arr} + \boldsymbol{\tau}_p^{wait} + \boldsymbol{\tau}_p^{hand} \quad \forall p \in P \tag{22}$$

$$\sum_{p \in P} \boldsymbol{\tau}_p^{sail} + \sum_{p \in P} \boldsymbol{\tau}_p^{wait} + \sum_{p \in P} \boldsymbol{\tau}_p^{hand} = 24\phi\boldsymbol{q} \tag{23}$$

$$\boldsymbol{q} \leq q^{max} \tag{24}$$

$$\boldsymbol{REV} = \sum_{p \in P} c_p^{rev} \boldsymbol{QC}_p^{PORT} \tag{25}$$

$$\boldsymbol{PHC} = \sum_{p \in P} c_p^{hand} \boldsymbol{QC}_p^{PORT} \tag{26}$$

$$\boldsymbol{LAC} = \sum_{p \in P} c_p^{late} \boldsymbol{\tau}_p^{late} \tag{27}$$

$$\boldsymbol{FCC} = c^{fuel} \sum_{p \in P} l_p \boldsymbol{f}_p \tag{28}$$

$$\boldsymbol{VOC} = c^{oper} \phi\boldsymbol{q} \tag{29}$$

$$\boldsymbol{CIC} = c^{inv} \sum_{p \in P} \boldsymbol{QC}_p^{SEA} \boldsymbol{\tau}_p^{sail} \tag{30}$$

The objective function (11) of the **VSP** mathematical model aims to maximize the total profit, which will be generated by the liner shipping company. Constraint set (12) estimates the vessel sailing time at voyage legs of the liner shipping route. Constraint sets (13) and (14) impose bounds on the vessel sailing speed at voyage legs of the liner shipping route. Constraint set (15) computes the fuel consumption at voyage legs of the liner shipping route. Constraint sets (16–22) calculate the arrival time, the handling time, the waiting time, the late arrival time, and the departure time for each port of the liner shipping route. Constraint set (23) guarantees that the negotiated service frequency will be maintained at each port of the liner shipping route. Constraint set (24) imposes the restriction on the maximum number of vessels that can be deployed at the given liner shipping route. Constraint sets (25–30) compute the cost components of the objective function (11), including the total revenue, the total port handling cost, the total late vessel arrival cost, the total fuel cost, the total vessel operational cost, and the total container inventory cost, respectively.

4.1.1 Description of studies

Fagerholt (2001) proposed a mathematical model for a vessel scheduling problem, which imposed inconvenience penalties for the vessels arriving outside the agreed TWs at ports in order to control violations. The latter assumption was inspired by the idea that controlled TW violations could improve the quality of vessel schedules and yield notable cutbacks in transportation costs. The analysis results indicated that the proposed methodology reduced the total route service costs when compared to the cases with fixed port arrival TWs. Ting and Tzeng (2003) examined a vessel scheduling problem with port arrival TW constraints. The objective minimized the total variation from the agreed port arrival TWs. A dynamic programming algorithm was applied to solve the problem. The computational experiments were conducted for the Trans-Atlantic liner shipping route. It was found that the proposed solution methodology could decrease the total fuel cost and the port handling time.

Chen et al. (2007) studied a vessel scheduling problem with bi-directional flows, where the containers with cargo were shipped from the origin port to the destination port, while the empty containers were shipped from the destination port to the origin port. The objective of the proposed model minimized the total vessel operational cost and the total container inventory cost. A three-step heuristic was designed to solve the problem, which had *NP*-hard complexity. Findings from the numerical experiments indicated that the developed heuristic outperformed CPLEX in terms of the computational time with acceptable optimality gaps. Boros et al. (2008) focused on optimizing the cycle time that was required by the liner shipping company to return the empty containers, considering the conflicting objectives of the liner shipping company and the MCT operator. Both supply chain players aimed to maximize their total profits. An iterative heuristic was developed to solve the problem. The computational experiments indicated that the proposed heuristic returned near-optimal solutions within a reasonable computational time for the considered problem instances.

Ronen (2011) indicated that an increase in the unit fuel cost would require the liner shipping company reducing the vessel sailing speed. However, the vessel sailing speed reduction would increase the total vessel turnaround time; and, hence, the liner shipping company would have to deploy more vessels for service of the given liner shipping route. The study presented a cost model for analysis of the latter tradeoff. Álvarez (2012) treated the container inventory cost as an indicator of the level of service in liner shipping. A two-tier mathematical model was formulated, where fleet deployment, vessel routing, and vessel sailing speed were determined at the upper tier, while the merchandise flows and transshipment quantities were determined at the lower tier. The study highlighted that the proposed methodology would assist the liner shipping company with achieving a balance between the liner shipping network design costs and the level of service. Wang et al. (2013) addressed the vessel scheduling problem with transit-time-sensitive demand, which was modeled as a decreasing continuous function of transit time. A mixed-integer nonlinear mathematical formulation was presented, and the objective maximized the total profit of the liner shipping company. The problem was solved using a Branch-and-Bound-based algorithm. It was found that the demand function influenced the number of vessels deployed as well as the vessel sailing speed.

Wang et al. (2014b) focused on simultaneous optimization of the vessel schedule coordination and cargo allocation for liner shipping networks. It was highlighted that liner shipping companies should consider extra demurrage costs for the additional waiting time of containerized cargo at ports of call. The objective of the proposed model aimed to maximize the total profit. CPLEX was used as a solution approach. Two case studies, which were performed for the Asia-Europe trade lines, demonstrated efficiency of the proposed methodology. Dulebenets (2015) proposed a metaheuristic approach for solving the vessel scheduling problem, which aimed to minimize the total route service cost. The conducted numerical experiments demonstrated that the developed metaheuristic was more efficient in terms of the solution quality and the computational time when compared to the static secant approximation method.

Wang et al. (2015a) conducted a study, aiming to assess the perceived value of container transit times in liner shipping. The objective of the presented mathematical model minimized the sum of the total fuel cost and the time-associated cost of containers. The problem was solved using an iterative optimization algorithm. The numerical experiments demonstrated how the perceived transit time values could be used in the design of optimal vessel schedules. Zhen et al. (2016) focused on the vessel scheduling problem and vessel service at a transshipment hub, aiming to minimize the total fuel cost and the total container inventory cost at the hub. A local branching-based solution approach was developed to solve the problem. The conducted computational experiments indicated that the proposed solution approach was promising as compared to CPLEX.

Dulebenets and Ozguven (2017) modeled transportation of perishable assets on board the vessels and explicitly accounted for the asset decay cost. A mixed-integer nonlinear programming model was formulated, aiming to minimize the total route service cost, which included the deterioration cost of perishable assets throughout the voyage. The original model was linearized using piecewise secant approximations and solved using CPLEX. The results from numerical experiments suggested that deployment of smaller vessels would be more advantageous when transporting perishable assets. He et al. (2017) focused on optimizing the vessel sailing speed between consecutive ports of call. The objective of the presented mathematical model aimed to minimize the total route service cost, considering port arrival TWs and speed limit constraints. An iterative optimization algorithm was developed to solve the problem. A case study was performed for the Asia-North Europe liner shipping route. It was found that the proposed optimization algorithm could solve the problem instances with up to 10,000 nodes within several seconds.

Dulebenets (2018a) proposed a multi-objective mixed-integer nonlinear programming model for the vessel scheduling problem, taking into account the main route service cost components. The model divided the route service cost components into two conflicting groups. A Global Multi-Objective Optimization Algorithm was designed to solve the linearized vessel scheduling problem. The results showed that negotiation of port arrival TWs and port handling rates between liner shipping companies and MCT operators could significantly impact the total route service cost components. The vessels, assigned to a given port rotation, may not be of the same type in some cases. Taking into account the latter operational feature, Dulebenets (2018b) studied the vessel scheduling problem, considering heterogeneous nature of the vessel fleet. The objective minimized the total vessel turnaround cost, and the problem was solved using BARON. The computational experiments indicated that introduction of larger vessels in the fleet substantially influenced the vessel schedule as compared to increasing unit fuel cost.

Mallidis et al. (2018) examined the effects of speed reduction on the total route service cost and on the shipper's total landed logistics costs. An activity-based model was developed to determine the vessel voyage cost per container. Furthermore, a continuous review inventory-planning model was proposed to calculate the shipper's total landed logistics cost at the intermediate ports of the network. The computational results showed that the impact of slow steaming on the total route service cost depended on the breakpoint distance. Moreover, the shipper's logistics cost increased with a reduction in the sailing speed of vessels. Wang et al. (2019) focused on a single intercontinental service design problem, aiming to maximize the total service profit. An iterative algorithm, which was inspired by the Branch-and-Cut algorithm, was presented to solve the proposed mathematical model. The developed methodology was applied for the Asia–Europe shipping service, which was provided by the CKYH alliance. It was found that application of the additional cuts within the proposed solution approach improved the solution quality and reduced the computational time. Also, the results showed that changes in the unit fuel cost influenced the vessel sailing speed and the fleet size.

4.1.2 Summary of findings

Table 1 presents a summary of findings from the studies that addressed the general vessel scheduling problem. The majority of the reviewed studies assumed variable vessel sailing speeds (76.5% of studies) and variable port times (58.8% of studies).

Table 1 Summary of findings: studies on general vessel scheduling

References	Sailing speed	Port time	Model objective	Objective components	Solution approach	Notes/major considerations
Fagerholt (2001)	V	F	Minimize the total cost	TOC; TFC; TPC; TVC	Heuristic	Soft port arrival TWs
Ting and Tzeng (2003)	V	V	Minimize the total variation in port arrival time	TVC	Dynamic programming	Quay crane dispatching decisions
Chen et al. (2007)	F	F	Minimize the total cost	TOC; TIC	Heuristic	Bi-directional flows, return of empty containers
Boros et al. (2008)	F	V	Maximize the total profit	REV; TVC; MSC	Heuristic	Iterative procedure to determine the vessel cycle time
Ronen (2011)	V	F	Minimize the total cost	TOC; TFC	Analytical method	Tradeoff between sailing speed and fleet size
Álvarez (2012)	F	V	Minimize the total cost	TIC	Analytical method	Two-tier optimization model
Wang et al. (2013)	V	V	Maximize the total profit	REV; TOC; TFC	Branch-and-bound-based algorithm	Transit-time-sensitive demand
Wang et al. (2014b)	F	F	Maximize the total profit	REV; TOC; TFC; TPC; TIC; MSC	CPLEX	Cargo allocation decisions
Dulebenets (2015)	V	V	Minimize the total cost	TOC; TFC; TPC; TVC	Metaheuristic	The proposed algorithm outperformed the static secant approximation
Wang et al. (2015a)	V	F	Minimize the total cost	TFC; TIC	Iterative optimization algorithm	Perceived value of container transit times
Zhen et al. (2016)	V	V	Minimize the total cost	TFC; TIC	Local branching algorithm	Transshipment
Dulebenets and Ozguven (2017)	V	V	Minimize the total cost	TOC; TFC; TPC; TVC; TIC; MSC	CPLEX	Transport of perishable assets
He et al. (2017)	V	F	Minimize the total cost	TFC	Iterative optimization algorithm	Sailing speed optimization at voyage legs
Dulebenets (2018a)	V	V	Minimize the total cost	TOC; TFC; TPC; TVC; TIC; TEC	Iterative optimization algorithm	Conflicting route service cost components

Table 1 (continued)

References	Sailing speed	Port time	Model objective	Objective components	Solution approach	Notes/major considerations
Dulebenets (2018b)	V	V	Minimize the total cost	TOC; TFC; TPC; TVC; TIC	BARON	Heterogeneous fleet
Mallidis et al. (2018)	V	F	Minimize the total cost	TOC; TFC; TPC; TVC; TIC; MSC	Analytical method	Slow steaming
Wang et al. (2019)	V	V	Maximize the total profit	REV; TOC; TFC; TPC; MSC	Branch-and-cut-based algorithm	Intercontinental service design

Sailing speed/port time: *V* variable, *F* fixed

Objective components: *REV* total revenue, *TOC* total vessel operational cost, *TFC* total fuel cost, *TPC* total port handling cost, *TVC* total cost for violation of port arrival TWs, *TIC* total container inventory cost, *TEC* total emission cost, *MSC* miscellaneous cost

The mathematical models, proposed for the general vessel scheduling problem, typically aimed to either minimize the total route service cost (70.6% of studies) or to maximize the total profit (23.5% of studies). The following major cost components were primarily captured: the total vessel operational cost (64.7% of studies), the total fuel cost (76.5% of studies), the total port handling cost (47.1% of studies), the total cost for violation of port arrival TWs (47.1% of studies), and the total container inventory cost (52.9% of studies). The studies, aiming to maximize the total profit, also accounted for the total revenue in the respective mathematical models. As for the solution approaches, iterative optimization algorithms and heuristics were found to be the most common methods.

4.1.3 Limitations and future research needs

A number of limitations have been identified in the existing studies on general vessel scheduling. These limitations and future research needs with respect to general vessel scheduling include the following:

- The vessel scheduling problem could be incorporated with other decision problems (e.g., routing, empty container repositioning, fleet deployment, and others). Holistic mathematical models (i.e., the ones that incorporate multiple decision problems) would be more beneficial to liner shipping companies for planning their operations.
- The majority of the reviewed studies assigned the same type of vessels to serve the liner shipping route (i.e., the vessel fleet is homogeneous), which may not be the case for certain routes. Hence, the future research should focus on the development of the vessel scheduling models, where the liner shipping route is served by vessels with different technical characteristics (i.e., the vessel fleet is heterogeneous).
- Certain studies applied their methodologies to one liner shipping route only. These methodologies should be evaluated for different liner shipping routes.
- The factors related to port operations (e.g., port availability, arrival TWs at ports, delays at ports for larger vessels) should be explicitly accounted for in the vessel scheduling models.
- The heuristics, developed by a significant number of the reviewed studies, could not provide the optimal solutions for the large-size problem instances. Therefore, there is a need to develop more efficient solution algorithms for complex vessel scheduling problems.
- The future research should be directed towards the important operational aspects in vessel scheduling (e.g., inland transport, transshipment, empty container repositioning, decay of perishable assets, changes in market conditions).
- As highlighted by Dulebenets (2018a), many decisions that have to be made by liner shipping companies are conflicting in their nature. However, the existing vessel scheduling studies generally combine the conflicting components into one objective function, which imposes limitations in the analysis of important trade-offs. Only a limited number of studies proposed multi-objective mathematical

models for vessel scheduling. The future research should focus on the development of comprehensive multi-objective vessel scheduling models.

4.2 Uncertainties in liner shipping operations

This section of the manuscript focuses on review of the vessel scheduling studies, which specifically modeled uncertainties in liner shipping operations (such as uncertainties in vessel sailing times, port waiting times, port handling times, and other factors that may significantly impact the vessel schedule design) and proposed different approaches for improving the vessel schedule reliability. Denote $\widetilde{\boldsymbol{\tau}_p^{sail}}, p \in P$ as the expected sailing time at voyage leg p (hours); $\widetilde{\boldsymbol{s}_p}, p \in P$ as the expected vessel sailing speed at voyage leg p (knots); $\widetilde{\boldsymbol{f}_p}, p \in P$ as the expected fuel consumption at voyage leg p (tons/nmi); $\widetilde{\boldsymbol{\tau}_p^{hand}}, p \in P$ as the expected handling time at port p (hours); and $\widetilde{\boldsymbol{\tau}_p^{wait}}, p \in P$ as the expected vessel waiting time at port p (hours). Note that uncertainty in the vessel sailing speed can be caused by natural disruptions (e.g., adverse weather) and/or man-made disruptions (e.g., errors of the vessel crew, technological issues on board the vessel). Uncertainty in the vessel sailing speed will further cause uncertainties in the vessel sailing time and the fuel consumption. Similarly, uncertainty in the port waiting and handling times can be caused by a large number of different factors (e.g., adverse weather, port congestion, container demand uncertainty). The mathematical model for the vessel scheduling problem with uncertainties in vessel sailing times, port waiting times, and port handling times (**UVSP**) can be formulated as follows:

Vessel Scheduling Problem with Uncertainties in Liner Shipping Operations (**UVSP**):

$$max\ \boldsymbol{TP} = [\boldsymbol{REV} - (\boldsymbol{PHC} + \boldsymbol{LAC} + \boldsymbol{FCC} + \boldsymbol{VOC} + \boldsymbol{CIC})] \tag{31}$$

Subject to:

Constraint sets (21), (24–27), (29)

$$\widetilde{\boldsymbol{\tau}_p^{sail}} = \frac{l_p}{\widetilde{\boldsymbol{s}_p}} \quad \forall p \in P \tag{32}$$

$$\widetilde{\boldsymbol{f}_p} = k_1\left(k_2 + \left(\widetilde{\boldsymbol{s}_p}\right)^{k_3}\right)\left(\boldsymbol{w}_p + A\right)^{2/3} \quad \forall p \in P \tag{33}$$

$$\boldsymbol{\tau}_{p+1}^{arr} = \boldsymbol{\tau}_p^{dep} + \widetilde{\boldsymbol{\tau}_p^{sail}} \quad \forall p \in P, p < m^1 \tag{34}$$

$$\boldsymbol{\tau}_1^{arr} = \boldsymbol{\tau}_p^{dep} + \widetilde{\boldsymbol{\tau}_p^{sail}} - 24\boldsymbol{\phi q} \quad \forall p \in P, p = m^1 \tag{35}$$

$$\boldsymbol{\tau}_p^{dep} = \boldsymbol{\tau}_p^{arr} + \widetilde{\boldsymbol{\tau}_p^{wait}} + \widetilde{\boldsymbol{\tau}_p^{hand}} \quad \forall p \in P \tag{36}$$

$$\sum_{p\in P}\widetilde{\boldsymbol{\tau}_p^{sail}}+\sum_{p\in P}\widetilde{\boldsymbol{\tau}_p^{wait}}+\sum_{p\in P}\widetilde{\boldsymbol{\tau}_p^{hand}}=24\phi\boldsymbol{q} \tag{37}$$

$$\boldsymbol{FCC}=c^{fuel}\sum_{p\in P}l_p\widetilde{\boldsymbol{f}_p} \tag{38}$$

$$\boldsymbol{CIC}=c^{inv}\sum_{p\in P}\boldsymbol{QC}_p^{SEA}\widetilde{\boldsymbol{\tau}_p^{sail}} \tag{39}$$

The objective function (31) of the **UVSP** mathematical model aims to maximize the total profit, which will be generated by the liner shipping company. Constraint set (32) estimates the expected vessel sailing time at voyage legs of the liner shipping route, considering uncertainty in the vessel sailing speed. Constraint set (33) computes the expected fuel consumption at voyage legs of the liner shipping route. Constraint sets (34–36) calculate the vessel arrival and departure times for each port of the liner shipping route. Constraint set (37) guarantees that the negotiated service frequency will be maintained at each port of the liner shipping route. Constraint sets (38) and (39) compute the total fuel cost and the total container inventory cost, respectively.

4.2.1 Description of studies

Notteboom (2006) analyzed the factors that could affect the liner shipping service reliability, as well as the measures that could be used to improve the liner shipping service reliability. Port congestion due to increasing volumes and capacity constraints was found to be the major source of the vessel schedule unreliability. A number of measures, which are typically used by liner shipping companies to improve the vessel schedule reliability, were highlighted in the study, including reshuffling the order of ports, port skipping, early departure of vessels from ports (some containers may wait for the next vessels), sailing speed adjustment, and increasing vessel fleet size. Vernimmen et al. (2007) also studied the vessel schedule unreliability and its effects on the hinterland supply chain operations. Inclement weather conditions in sea, port congestion, and delayed departures from previous ports were listed as the common factors, influencing the vessel schedule reliability. Based on the presented case study, it was found that unreliability of the vessel schedules caused significant disruptions in the MCT operations planning, increased the inland transportation cost, and resulted in higher inventory level requirements to avoid disruptions in production processes.

Chuang et al. (2010) developed a Fuzzy Evolutionary Algorithm for the vessel routing and scheduling problem, considering uncertainties in handling times at ports, sailing times, and demand at ports, in order to generate a long-term profit. In contrast to the previous studies that assumed that the market demand was crisp, the study addressed uncertainty in demand using the fuzzy sets theory. Applicability of the proposed methodology was demonstrated based on a numerical example. Qi and Song (2012) considered uncertain nature of handling times at ports in vessel scheduling. The objective of the presented model was to minimize the total fuel cost and the total cost due to late vessel arrivals at ports. The problem was solved using the sample average approximation method. The results from numerical experiments indicated that the port handling time uncertainty could substantially affect the fuel consumption, service levels, and the optimal schedule design. Wang and Meng (2012a) presented a mixed-integer nonlinear vessel scheduling problem, where the port waiting and handling times were subject to uncertainty. The objective of the model minimized the total route service cost. The sample average approximation method was used to solve the problem. The analysis results showed that increasing vessel fleet could enhance the reliability of vessel schedules.

Wang and Meng (2012b) considered uncertainties in sea and at ports (i.e., port waiting and handling times) at the vessel scheduling stage. A mixed-integer nonlinear mathematical model, minimizing the total route service cost, was formulated and solved using a cutting plane-based solution algorithm. The results from computational experiments demonstrated that a reduction of the sailing speeds of vessels decreased the total route service cost for the cases with higher unit fuel cost. Song et al. (2015) studied a vessel scheduling problem, taking into account uncertain nature of port handling times. The objective of the presented mathematical model aimed to optimize three key performance indicators, including the following: annual vessel operational cost, service reliability, and CO_2 emissions. A multi-objective Evolutionary Algorithm was applied to solve the vessel scheduling problem. A set of computational experiments were conducted to present how the proposed solution approach could be used for the development of Pareto Fronts for the considered key performance indicators.

Wang (2015) argued that there might be differences in the capacities of vessels in a string. Due to demand uncertainty, the sequence of vessels in a string might cause delay of containers at ports. To address the latter issue, the study aimed to determine the optimal sequence of vessels in a string with the objective of minimizing the total delay of containers at ports. The analysis results indicated that the optimal sequence of vessels in a string would save more than $6 million per year for liner shipping companies around the world. Aydin et al. (2017) proposed a mathematical model for optimizing vessel sailing speed for a liner shipping service, taking into account stochastic nature of vessel service times (i.e., port waiting and handling times). The objective aimed to minimize the total fuel cost and the total late vessel arrival cost. A dynamic programming method was adopted to solve the problem. The numerical experiments were conducted using the data from one of the European liner shipping companies. The findings indicated that consideration of uncertainty in the vessel service times while making sailing speed decisions allowed significantly reducing the total fuel cost.

Gürel and Shadmand (2018) focused on the vessel scheduling problem with a heterogeneous fleet, considering uncertain port waiting and handling times. The authors presented a chance-constrained mixed-integer nonlinear programming formulation, aiming to minimize the total fuel cost and achieving the target service level (defined based on the on-time vessel departure probabilities). CPLEX was used to solve the problem. It was found that assigning different service levels to port-vessel pairs could be advantageous for the liner shipping company. Tan et al. (2018)

studied a joint vessel schedule design and sailing speed optimization problem for a single inland shipping service, capturing uncertainty in dam transit time. A bi-objective mathematical model was formulated, aiming to minimize the total fuel consumption and the total vessel turnaround time. The Pareto optimal solutions were derived analytically. The computational experiments were presented for the Yangtze River (China). The findings demonstrated that uncertainty in dam transit time could significantly impact the total vessel turnaround time.

4.2.2 Summary of findings

Table 2 presents a summary of findings from the studies that modeled uncertainty in liner shipping operations. A total of 45.5% of studies assumed variable vessel sailing speeds, while 27.3% of studies captured uncertainty in vessel sailing speeds. Uncertainty in port times was modeled by 72.7% of studies. The majority of the mathematical models, capturing uncertainty in liner shipping operations, aimed to minimize the total route service cost (54.5% of studies). Only Song et al. (2015) proposed a multi-objective formulation, while the remaining mathematical models were single-objective. The total fuel cost was accounted for by 72.7% of studies. As for the solution approaches, sample average approximation and heuristics/metaheuristics were found to be the most common methods.

4.2.3 Limitations and future research needs

A number of limitations have been identified in the existing studies on uncertainties in vessel scheduling. These limitations and future research needs with respect to modeling uncertainties in vessel scheduling include the following:

- Only a limited number of vessel scheduling studies explicitly accounted for uncertainties in liner shipping operations. Since uncertainties in liner shipping operations may substantially affect the design of vessel schedules (Notteboom 2006; Vernimmen et al. 2007; Qi and Song 2012), more emphasis should be given to modeling uncertainties in the future vessel scheduling studies.
- The future vessel scheduling studies should focus on a comprehensive assessment of different factors that may influence the vessel schedule reliability (e.g., the average size of vessels deployed, the average age of vessels deployed, collaborative agreements between supply chain players).
- More accurate and detailed historical data are needed for the liner shipping services of interest in order to model uncertainties in liner shipping operations and evaluate various strategies, which can be used to mitigate the negative effects from these uncertainties.
- The majority of the collected studies considered only a specific type of uncertainty (e.g., either uncertainty in port waiting time or port handling time or vessel sailing time or container demand at ports). The future vessel scheduling studies should concentrate on capturing multiple sources of uncertainty to make the developed models more applicable in practice.

Table 2 Summary of findings: studies on uncertainties in liner shipping operations

References	Sailing speed	Port time	Model objective	Objective components	Solution approach	Notes/major considerations
Notteboom (2006)	N/A	N/A	N/A	N/A	Survey	Schedule reliability
Vernimmen et al. (2007)	N/A	N/A	N/A	N/A	Case study	Schedule reliability
Chuang et al. (2010)	U	U	Maximize the total profit	REV; TOC; TFC; TPC	Metaheuristic	Uncertainty in port handling times, sailing times, and demand
Qi and Song (2012)	V	U	Minimize the total cost	TFC; TVC	Sample average approximation	Uncertainty in port handling times
Wang and Meng (2012a)	V	U	Minimize the total cost	TOC; TFC; TVC	Sample average approximation	Uncertainty in port waiting and handling times
Wang and Meng (2012b)	U	U	Minimize the total cost	TOC; TFC	Cutting-plane algorithm	Uncertainty in port and sailing times
Song et al. (2015)	V	U	Minimize the total cost; minimize the schedule unreliability; minimize the total CO_2 emissions	TFC; TVC; TEC; MSC	Metaheuristic	Uncertainty in port handling times
Wang (2015)	F	U	Minimize the total delay	N/A	Heuristic	Uncertainty in demand; heterogeneous fleet
Aydin et al. (2017)	V	U	Minimize the total cost	TFC; TVC	Dynamic programming	Uncertainty in port waiting and handling times
Gürel and Shadmand (2018)	V	U	Minimize the total cost	TFC	CPLEX	Uncertainty in port waiting and handling times; heterogeneous fleet
Tan et al. (2018)	U	F	Minimize the total fuel consumption; minimize the total turnaround time	TOC; TFC	Analytical method	Uncertainty in dam transit time

Sailing speed/port time: *V* variable, *F* fixed, *U* uncertain

Objective components: *REV* total revenue, *TOC* total vessel operational cost, *TFC* total fuel cost, *TPC* total port handling cost, *TVC* total cost for violation of port arrival TWs, *TEC* total emission cost, *MSC* miscellaneous cost

- Inter-round trip effects and network effects on the vessel schedule reliability should be considered in the future research.

4.3 Collaborative agreements

Collaborative agreements between liner shipping companies and MCT operators may significantly improve the efficiency of liner shipping and supply chain operations. This section of the manuscript focuses on review of the vessel scheduling studies, which specifically modeled various collaborative agreements between liner shipping companies and MCT operators. The collaborative agreements, identified in the collected vessel scheduling studies, assumed that multiple port arrival TWs and/or handling rates were offered by the MCT operators at ports to the liner shipping company (instead of fixed port arrival TWs and handling rates, which are commonly adopted in other vessel scheduling studies). Denote $T_p = \left\{1, \ldots, m_p^2\right\}, p \in P$ as the set of arrival TWs, offered by the MCT operator at port p (TWs); $H_{pt} = \left\{1, \ldots, m_{pt}^3\right\}, p \in P, t \in T_p$ as the set of handling rates, offered by the MCT operator at port p during TW t (handling rates); $\tau_{pt}^{st}, p \in P, t \in T_p$ as the start of TW t at port p (hours); $\tau_{pt}^{end}, p \in P, t \in T_p$ as the end of TW t at port p (hours); $ph_{pth}, p \in P, t \in T_p, h \in H_{pt}$ as the handling productivity at port p during TW t under handling rate h (TEU/hour); and $c_{pth}^{hand}, p \in P, t \in T_p, h \in H_{pt}$ as the unit handling cost at port p during TW t under handling rate h (USD/TEU). Let $\boldsymbol{z}_{pt} = 1, p \in P, t \in T_p$ if TW t is selected at port p (=0 otherwise); and $\boldsymbol{x}_{pth} = 1, p \in P, t \in T_p, h \in H_{pt}$ if handling rate h is selected at port p during TW t (=0 otherwise). Then, the mathematical model for the collaborative vessel scheduling problem (**CVSP**) can be formulated as follows:

Collaborative Vessel Scheduling Problem (**CVSP**):

$$max\ \boldsymbol{TP} = [\boldsymbol{REV} - (\boldsymbol{PHC} + \boldsymbol{LAC} + \boldsymbol{FCC} + \boldsymbol{VOC} + \boldsymbol{CIC})] \tag{40}$$

Subject to:

Constraint sets (12–17), (22–25), (27–30)

$$\sum_{t \in T_p} \boldsymbol{z}_{pt} = 1 \quad \forall p \in P \tag{41}$$

$$\sum_{t \in T_p} \sum_{h \in H_{pt}} \boldsymbol{x}_{pth} = 1 \quad \forall p \in P \tag{42}$$

$$\boldsymbol{x}_{pth} \le \boldsymbol{z}_{pt} \quad \forall p \in P, t \in T_p, h \in H_{pt} \tag{43}$$

$$\boldsymbol{\tau}_p^{hand} = \sum_{t \in T_p} \sum_{h \in H_{pt}} \left(\frac{QC_p^{PORT}}{ph_{pth}} \right) \boldsymbol{x}_{pth} \quad \forall p \in P \tag{44}$$

$$\boldsymbol{\tau}_{p+1}^{wait} \ge \sum_{t \in T_p} \tau_{(p+1)t}^{st} \boldsymbol{z}_{(p+1)t} - \boldsymbol{\tau}_p^{dep} - \boldsymbol{\tau}_p^{sail} \quad \forall p \in P, p < m^1 \tag{45}$$

$$\boldsymbol{\tau}_1^{wait} \geq \sum_{t \in T_p} \tau_{1t}^{st} \boldsymbol{z}_{1t} - \boldsymbol{\tau}_p^{dep} - \boldsymbol{\tau}_p^{sail} + 24\boldsymbol{\phi q} \quad \forall p \in P, p = m^1 \tag{46}$$

$$\boldsymbol{\tau}_p^{late} \geq \boldsymbol{\tau}_p^{arr} - \sum_{t \in T_p} \tau_{pt}^{end} \boldsymbol{z}_{pt} \quad \forall p \in P \tag{47}$$

$$\boldsymbol{PHC} = \sum_{p \in P} \sum_{t \in T_p} \sum_{h \in H_{pt}} c_{pth}^{hand} \boldsymbol{QC}_p^{PORT} \boldsymbol{x}_{pth} \tag{48}$$

The objective function (40) of the **CVSP** mathematical model aims to maximize the total profit, which will be generated by the liner shipping company. Constraint set (41) indicates that only one arrival TW is requested by the liner shipping company at each port. Constraint set (42) ensures that only one handling rate is requested by the liner shipping company at each port. Constraint set (43) guarantees that the selected handling rate will be provided during the requested arrival TW at each port of the liner shipping route. Constraint sets (44–47) calculate the handling time, the waiting time, and the late arrival time for each port of the liner shipping route. Constraint set (48) computes the total port handling cost.

4.3.1 Description of studies

Wang et al. (2014a) studied the vessel scheduling problem with multiple port arrival TWs. The objective of the proposed mathematical model aimed to minimize the total route service cost. The problem was solved using an iterative optimization algorithm. The computational experiments demonstrated that the availability of port arrival TWs, the port handling efficiency, the unit fuel cost, and the unit container inventory cost had significant impacts on the total route service cost, the optimal number of vessels for deployment, and the optimal vessel schedule. Alharbi et al. (2015) evaluated the effects of port arrival TW availability on the efficiency of liner shipping operations. The objective of the vessel scheduling problem aimed to minimize the total route service cost. The numerical experiments revealed that the port arrival TW availability, shorter port handling time, and lower unit fuel cost could decrease the total route service cost and the required number of vessels to be deployed. The study also suggested that liner shipping companies may need to reserve more vessels if there is a predicted increase in the unit fuel cost.

Wang et al. (2015b) studied collaborative agreements between liner shipping companies and MCT operators. The first collaborative agreement assumed no transshipment operations at ports, while the second one focused on modeling transshipment operations. Both collaborative agreements assumed that the liner shipping company should provide a utility value to the MCT operator depending on the port arrival time. Increasing fuel and container inventory costs reduced the utility. The MCT operator had to compensate the liner shipping company for starting the service at the day with the negative utility value. The proposed collaborative agreements were found to be efficient for the design of equitable berthing plans. Conventionally, the vessel scheduling studies assume fixed container handling rates at ports. Liu et al. (2016) discussed that MCT operators might be able to provide handling rates with higher handling productivities at ports for the vessel service, which could lead to additional costs. Selection of a handling rate with higher handling productivity by liner shipping companies might be beneficial if the additional cost is less than the monetary benefits, achieved by the liner shipping company when sailing to the next port at a lower speed. The objective of the mathematical model minimized the total fuel cost and the additional cost due to an increase in handling productivity at ports. A dynamic programming was used to solve the problem. A case study demonstrated remarkable cost reductions that could be attained by the liner shipping company from application of the proposed collaborative agreement, while the MCT operators did not incur any monetary losses.

Venturini et al. (2017) considered collaborative agreements between liner shipping companies and MCT operators. The study presented a mathematical model for the multi-port berth allocation problem, taking into account vessel sailing speed optimization and emissions produced. The objective aimed to minimize the total cost, including the following components: (1) the port waiting cost; (2) the port handling cost; (3) the vessel delay cost; and (4) the vessel fuel consumption cost. The developed mathematical model was solved with CPLEX. The numerical experiments showed that most of the considered problem instances were solved to the global optimality within the time limit imposed (3 hours). Dulebenets (2019a) proposed a new collaborative agreement between liner shipping companies and MCT operators. Based on the agreement, the MCT operators could offer multiple port arrival TWs, start and end times for the available TWs, and port handling rates during the available TWs to the liner shipping company. The objective aimed to minimize the total route service cost. The original model was linearized and solved using CPLEX. The results from computational experiments indicated that reducing the duration of port arrival TWs, increasing weekly vessel operational cost, and increasing unit fuel cost might increase financial gains from the proposed collaborative agreement.

Note that the berth allocation decisions and the associated collaborative agreements between liner shipping companies and MCT operators influence the total vessel waiting times at ports of call, the total vessel handling times at ports of call, the departure times from ports of call, and, therefore, directly impact vessel schedules (Du et al. 2011; Umang et al. 2017; Xiang et al. 2017; Dulebenets 2019b; Kavoosi et al. 2019). The scope of this survey does not include a detailed review of the studies, which solely focused on berth allocation and scheduling without explicitly accounting for the vessel scheduling decisions from the liner shipping perspective. However, for excellent reviews of the literature, focusing on berth allocation and scheduling, this study refers to Bierwirth and Meisel (2015) and Carlo et al. (2015).

4.3.2 Summary of findings

Table 3 presents a summary of findings from the studies that discussed various collaborative agreements between liner shipping companies and MCT operators. All the reviewed studies assumed variable vessel sailing speeds, while 50.0% of studies modeled variable port times. The majority of the mathematical models

Table 3 Summary of findings: studies on collaborative agreements

References	Sailing speed	Port time	Model objective	Objective components	Solution approach	Notes/major considerations
Wang et al. (2014a)	V	F	Minimize the total cost	TOC; TFC; TIC	Iterative optimization algorithm	Multiple port arrival TWs
Alharbi et al. (2015)	V	F	Minimize the total cost	TOC; TFC; TVC	Iterative optimization algorithm	Multiple port arrival TWs
Wang et al. (2015b)	V	F	Maximize the utility	TFC; TPC; TIC; MSC	Case study	Utility associated with the start time of vessel service
Liu et al. (2016)	V	V	Minimize the total cost	TFC; TPC; MSC	Dynamic programming	Multiple handling rates
Venturini et al. (2017)	V	V	Minimize the total cost	TFC; TPC; TVC; MSC	CPLEX	Multi-port berth allocation
Dulebenets (2019a)	V	V	Minimize the total cost	TOC; TFC; TPC; TVC; TIC	CPLEX	Multiple port arrival TWs; multiple start/end times for each TW; multiple handling rates

Sailing speed/port time: *V* variable, *F* fixed

Objective components: *TOC* total vessel operational cost, *TFC* total fuel cost, *TPC* total port handling cost, *TVC* total cost for violation of port arrival TWs, *TIC* total inventory cost, *MSC* miscellaneous cost on collaborative vessel scheduling aimed to minimize the total route service cost (83.3% of studies). All the reviewed studies captured the total fuel cost in the respective mathematical models, while 66.7% of studies also considered the total port handling cost. The majority of collaborative vessel scheduling studies applied iterative optimization algorithms to solve the presented mathematical models.

4.3.3 Limitations and future research needs

A number of limitations have been identified in the existing studies on collaborative vessel scheduling. These limitations and future research needs with respect to collaborative vessel scheduling include the following:

- A port may be occupied by different MCT operators. The future research should focus on modeling collaborative agreements, where the liner shipping company may divert a vessel from one MCT to another at a given port to reduce service delays and the associated costs.
- The future vessel scheduling models should assess the effects of collaboration between MCT operators at different ports, aiming to maximize the utility values for liner shipping companies (Wang et al. 2015b).
- The formation of strategic alliances between liner shipping companies allows sharing the available vessel capacity and dedicated services. Alliances also help liner shipping companies holding steadier market positions. The future research should focus on modeling interactions between liner shipping alliances in the vessel scheduling models.
- As indicated by Liu et al. (2016), the container handling time is dependent on the number of containers handled, the number of quay cranes used (affected by the length of a vessel and also the number of quay cranes available), stowage plan of a vessel, and other factors. The aforementioned factors should be explicitly captured by the vessel scheduling models to accurately estimate the port handling time.
- The future research should focus on the development of game-theoretic models for negotiation of port arrival TWs and/or handling rates between the liner shipping company and the MCT operator at each port of the liner shipping route.
- Collaborative vessel scheduling models generally ignore uncertainties in liner shipping operations. The future research should evaluate the effects of collaborative agreements on vessel schedule reliability.

4.4 Vessel schedule recovery

Disruptions in sea (e.g., inclement weather, malfunctioning of the main vessel engines, piracy) and at ports (e.g., labor strikes, port congestion, handling equipment failure) may significantly affect the planned vessel schedules. This section of the manuscript focuses on review of the vessel scheduling studies, which evaluated various vessel schedule recovery strategies. Although vessel schedule recovery is made by liner shipping companies at the operational level (unlike the design of vessel schedules), it is included in the present review, considering the frequent occurrence of disruptive events and the necessity for efficient vessel schedule recovery strategies.

Denote TP^0 as the total profit based on the original vessel schedule (USD); $s_p, p \in P$ as the planned vessel sailing speed at voyage leg p (knots); $\tau_p^{arr}, p \in P$ as the planned vessel arrival time at port p (hours); q as the total number of deployed vessels based on the original vessel schedule (vessels); $\widetilde{\boldsymbol{\delta}_p^{sea}}, p \in P$ as the expected vessel sailing speed change due to a disruptive event at voyage leg p (knots); $\widetilde{\boldsymbol{\delta}_p^{port}}, p \in P$ as the expected duration of a disruptive event at port p (hours); $\Delta_p^{sea}, p \in P$ as the vessel sailing speed adjustment at voyage leg p (knots); $\overline{\boldsymbol{\tau}^{vtt}}$ as the total vessel turnaround time based on the recovered vessel schedule (hours); and $c_p^{skip}, p \in P$ as the total cost of skipping port p (USD). Let $\boldsymbol{y}_p^{port} = 1, p \in P$ if a disruption occurred at port p (=0 otherwise); $\boldsymbol{y}_p^{sea} = 1, p \in P$ if a disruption occurred at voyage leg p (=0 otherwise); and $\boldsymbol{x}_p^{skip} = 1, p \in P$ if port p is skipped (=0 otherwise). The remaining notations will be adopted from the **VSP** mathematical model, and the accent symbol "–" will be added to denote the recovered vessel schedule. For example, $\overline{\boldsymbol{s}_p}, p \in P$ will be used to denote the vessel sailing speed at voyage leg p based on the recovered vessel schedule (knots). The mathematical model for the vessel schedule recovery problem with the sailing speed adjustment and the port skipping recovery strategies (**VSRP**) can be formulated as follows:

Vessel Schedule Recovery Problem (**VSRP**):

$$min\left[TP^0 - \overline{\boldsymbol{TP}}\right] \tag{49}$$

Subject to:

$$\overline{\boldsymbol{s}_p} \leq s_p + \widetilde{\boldsymbol{\delta}_p^{sea}} \boldsymbol{y}_p^{sea} + \Delta_p^{sea}\left(1 - \boldsymbol{y}_p^{sea}\right) \quad \forall p \in P \tag{50}$$

$$\overline{\boldsymbol{\tau}_p^{sail}} = \frac{l_p}{\overline{\boldsymbol{s}_p}} \quad \forall p \in P \tag{51}$$

$$\overline{\boldsymbol{s}_p} \leq s^{max} \quad \forall p \in P \tag{52}$$

$$\overline{\boldsymbol{s}_p} \geq s^{min} + \widetilde{\boldsymbol{\delta}_p^{sea}} \boldsymbol{y}_p^{sea} \quad \forall p \in P \tag{53}$$

$$\overline{\boldsymbol{f}_p} = k_1\left(k_2 + \left(\overline{\boldsymbol{s}_p}\right)^{k_3}\right)\left(\boldsymbol{w}_p + A\right)^{2/3} \quad \forall p \in P \tag{54}$$

$$\overline{\boldsymbol{\tau}_{p+1}^{arr}} = \overline{\boldsymbol{\tau}_{p}^{dep}} + \overline{\boldsymbol{\tau}_{p}^{sail}} \quad \forall p \in P, p < m^1 \tag{55}$$

$$\overline{\boldsymbol{\tau}_{1}^{arr}} = \overline{\boldsymbol{\tau}_{p}^{dep}} + \overline{\boldsymbol{\tau}_{p}^{sail}} - \overline{\boldsymbol{\tau}^{vtt}} \quad \forall p \in P, p = m^1 \tag{56}$$

$$\overline{\boldsymbol{\tau}_{p}^{hand}} = \left(\frac{\boldsymbol{QC}_p^{PORT}}{ph_p} + \widetilde{\boldsymbol{\delta}_p^{port}} \boldsymbol{y}_p^{port} \right) \left(1 - \boldsymbol{x}_p^{skip} \right) \quad \forall p \in P \tag{57}$$

$$\overline{\boldsymbol{\tau}_{p+1}^{wait}} \geq \tau_{p+1}^{st} - \overline{\boldsymbol{\tau}_{p}^{dep}} - \overline{\boldsymbol{\tau}_{p}^{sail}} \quad \forall p \in P, p < m^1 \tag{58}$$

$$\overline{\boldsymbol{\tau}_{1}^{wait}} \geq \tau_{1}^{st} - \overline{\boldsymbol{\tau}_{p}^{dep}} - \overline{\boldsymbol{\tau}_{p}^{sail}} + \overline{\boldsymbol{\tau}^{vtt}} \quad \forall p \in P, p = m^1 \tag{59}$$

$$\overline{\boldsymbol{\tau}_{p}^{late}} \geq \overline{\boldsymbol{\tau}_{p}^{arr}} - \tau_{p}^{arr} \quad \forall p \in P \tag{60}$$

$$\overline{\boldsymbol{\tau}_{p}^{dep}} = \overline{\boldsymbol{\tau}_{p}^{arr}} + \overline{\boldsymbol{\tau}_{p}^{wait}} + \overline{\boldsymbol{\tau}_{p}^{hand}} \quad \forall p \in P \tag{61}$$

$$\boldsymbol{x}_p^{skip} \leq \boldsymbol{y}_p^{port} \quad \forall p \in P \tag{62}$$

$$\overline{\boldsymbol{\tau}^{vtt}} = \sum_{p \in P} \overline{\boldsymbol{\tau}_{p}^{sail}} + \sum_{p \in P} \overline{\boldsymbol{\tau}_{p}^{wait}} + \sum_{p \in P} \overline{\boldsymbol{\tau}_{p}^{hand}} \tag{63}$$

$$\overline{\boldsymbol{REV}} = \sum_{p \in P} c_p^{rev} \boldsymbol{QC}_p^{PORT} \left(1 - \boldsymbol{x}_p^{skip} \right) \tag{64}$$

$$\overline{\boldsymbol{PHC}} = \sum_{p \in P} c_p^{hand} \boldsymbol{QC}_p^{PORT} + \sum_{p \in P} c_p^{skip} \boldsymbol{x}_p^{skip} \tag{65}$$

$$\overline{\boldsymbol{LAC}} = \sum_{p \in P} c_p^{late} \overline{\boldsymbol{\tau}_{p}^{late}} \tag{66}$$

$$\overline{\boldsymbol{FCC}} = c^{fuel} \sum_{p \in P} l_p \overline{\boldsymbol{f}_p} \tag{67}$$

$$\overline{\boldsymbol{VOC}} = c^{oper} \phi q \tag{68}$$

$$\overline{\boldsymbol{CIC}} = c^{inv} \sum_{p \in P} \boldsymbol{QC}_p^{SEA} \overline{\boldsymbol{\tau}_{p}^{sail}} \tag{69}$$

$$\overline{TP} = \left[\overline{REV} - \left(\overline{PHC} + \overline{LAC} + \overline{FCC} + \overline{VOC} + \overline{CIC}\right)\right] \tag{70}$$

The objective function (49) of the **VSRP** mathematical model aims to minimize the total profit loss, endured by the liner shipping company as a result of disruptions in sea and/or ports. Constraint set (50) estimates the vessel sailing speed at voyage legs of the liner shipping route for the recovered vessel schedule. Note that it is assumed that the liner shipping company will not be able to use the sailing speed adjustment recovery strategy (i.e., increase the sailing speed to reduce the delays, caused by disruptions) at the voyage legs that experience disruptions. Constraint set (51) computes the vessel sailing time at voyage legs of the liner shipping route for the recovered vessel schedule. Constraint sets (52) and (53) impose bounds on the vessel sailing speed at voyage legs of the liner shipping route. Constraint set (54) calculates the fuel consumption at voyage legs of the liner shipping route for the recovered vessel schedule.

Constraint sets (55–61) estimate the arrival time, the handling time, the waiting time, the late arrival time, and the departure time for each port of the liner shipping route for the recovered vessel schedule. Constraint set (62) ensures that a given port can be skipped only if that port experienced a disruption. Constraint set (63) computes the total vessel turnaround time for the recovered vessel schedule. Constraint sets (64–70) compute the cost components of the objective function (49), including the total revenue, the total port handling cost, the total late vessel arrival cost, the total fuel cost, the total vessel operational cost, the total container inventory cost, and the total profit for the recovered vessel schedule, respectively. Note that certain studies used the port swapping strategy as one of the vessel schedule recovery strategies (Brouer et al. 2013). When the port swapping strategy is used to recover a given vessel schedule; then, the **VSRP** mathematical model can be reduced to a typical traveling salesman problem.

4.4.1 Description of studies

Paul and Maloni (2010) designed a decision support system for alleviating the effects from weather and/or terrorism at ports on vessel schedules. A mixed-integer nonlinear programming model was presented, aiming to minimize the total route service cost, which included the vessel operational cost, the transportation cost, the capital cost, and the port handling cost. A Dijkstra's shortest path algorithm was applied to obtain the optimal usage of the port network capacity. The numerical results demonstrated how the proposed methodology could be used for estimating the magnitude of cost increases due to disruptive events. Brouer et al. (2013) studied the vessel schedule recovery problem, where the following types of disruptions were modeled: (1) delays in sea (e.g., due to inclement weather); (2) port closure (e.g., due to labor strikes); (3) berth prioritization (e.g., decision to serve a vessel because of its size); and (4) port congestion (e.g., due to port maintenance or excess capacity). The following vessel schedule recovery strategies were considered: (1) omit a port; (2) swap port calls; and (3) vessel sailing speed adjustment. A space–time network model was presented, which minimized the total vessel operational cost and the cost due to delayed or missed cargo connection. The considered problem instances were solved using CPLEX. The results from numerical experiments indicated that skipping a port or switching ports along the liner shipping route could substantially reduce the total route service cost.

Li et al. (2015) examined three operational-level solutions to delays in vessel schedules, including vessel sailing speed adjustment, port skipping, and port swapping. A nonlinear programming model was proposed for the cases where only speeding up was used for schedule recovery. The objective of the model minimized the total fuel cost and the total late vessel arrival cost. Dynamic programming algorithms were used to solve the problem. The results from computational experiments indicated that vessel sailing speed adjustment could be efficient when the delays were not significant. In case of significant delays, port skipping and port swapping were found to be more efficient vessel schedule recovery strategies. Qi (2015) proposed two vessel schedule recovery models. The first model was developed to recover the schedule for a single vessel, while the second model was proposed to recover the schedule for multiple vessels. The objective aimed to minimize the total fuel cost and the total late vessel arrival cost. The following vessel schedule recovery strategies were considered: (a) vessel sailing speed adjustment; (b) port skipping; and (c) port swapping. A dynamic programming algorithm was recommended as a solution approach. A number of illustrative examples were presented for the proposed vessel schedule recovery strategies.

Li et al. (2016) investigated recovery policies under regular uncertainties and disruptive events in liner shipping. Regular uncertainties were defined as recurring probabilistic events in sea or at ports, while disruptive events were defined as occasional or one-off events mainly occurring at ports. The objective of the presented model minimized the total fuel cost, the total vessel delay cost, and the total cost of accelerated vessel handling at ports. The problem was solved using dynamic programming. The numerical experiments demonstrated advantages of a real-time control policy for vessel schedule recovery. Cheraghchi et al. (2018) focused on a vessel schedule recovery based on the vessel sailing speed adjustment. A multi-objective optimization model was proposed, where the first objective was to minimize the total financial loss, while the second objective was to minimize the total delay in vessel arrivals at ports. A set of computational experiments were conducted using a number of multi-objective metaheuristic algorithms with a focus on the following: (1) scalability analysis; (2) vessel steaming policies; and (3) voyage distance analysis. Among the metaheuristic algorithms applied to solve the problem, the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) exhibited the highest efficiency.

Abioye et al. (2019) proposed a new mathematical model for vessel schedule recovery at the liner shipping routes, which pass through ECAs. The objective of the presented mathematical formulation aimed to minimize the total profit loss as a result of disruptive events that could occur within and/or outside ECAs. A set of linearization techniques were applied to the original nonlinear formulation, and the linearized version of the model was solved using CPLEX. The numerical experiments, which were conducted for one of the liner shipping routes that are served by the OOCL liner shipping company, demonstrated that an increase in the unit fuel cost imposed limitations on the vessel sailing speed adjustment strategy. Furthermore, an increasing number of disruptions required implementation of more radical vessel schedule recovery strategies (i.e., port skipping rather than vessel sailing speed adjustment).

4.4.2 Summary of findings

Table 4 presents a summary of findings from the studies that evaluated various vessel schedule recovery strategies. All the reviewed studies, except Paul and Maloni (2010), modeled disruptions in sea and at ports and evaluated various vessel schedule recovery strategies to compensate for the delays in sea and at ports; therefore, vessel sailing speeds and port times were assumed to be variable. Paul and Maloni (2010) particularly studied disruptions at ports. A total of 85.7% of studies proposed single-objective mathematical models, aiming to minimize the total route service cost. Cheraghchi et al. (2018) developed a multi-objective mathematical model, aiming to minimize the total financial loss and the total port arrival delay. The total fuel cost and the total cost for violation of port arrival TWs (or agreed port arrival times) were the primary objective function components, which were considered by the reviewed studies. As for the solution approaches, dynamic programming and heuristics/metaheuristics were found to be the most common methods.

4.4.3 Limitations and future research needs

A number of limitations have been identified in the existing studies on vessel schedule recovery. These limitations and future research needs with respect to vessel schedule recovery include the following:

- Only a few studies focused on evaluation of various vessel schedule recovery strategies. Although vessel schedule recovery is an operational-level decision problem, it should be studied more in depth to improve reliability of vessel schedules, which are designed at the tactical level.
- The effects of disruptions on liner shipping operations may differ substantially depending on the nature of a given disruption ("inclement weather at a port" vs. "explosion at a port"). An accurate assessment of disruption effects is critical and should be conducted by the future studies in order to select the appropriate vessel schedule recovery strategies.
- Typically, the proposed vessel scheduling recovery strategies are applied individually in the literature. The future vessel schedule recovery studies should focus on application of multiple vessel schedule recovery strategies simultaneously (e.g., vessel sailing speed adjustment and port swapping could be more efficient as compared to just port swapping, especially for the cases when a disruption may cause substantial changes in the original vessel schedule).
- There is a need to assess not only economic but also environmental impacts from deployment of various vessel schedule recovery strategies (e.g., increasing vessel sailing speed not only increases the total fuel cost but also increases the amount of emissions produced by vessels).

Table 4 Summary of findings: studies on vessel schedule recovery

References	Sailing speed	Port time	Model objective	Objective components	Solution approach	Notes/major considerations
Paul and Maloni (2010)	F	V	Minimize the total cost	TOC; TFC; TPC; MSC	Heuristic	Disruptions at ports
Brouer et al. (2013)	V	V	Minimize the total cost	TOC; TFC; TPC; TVC; MSC	CPLEX	Disruptions in sea and at ports
Li et al. (2015)	V	V	Minimize the total cost	TFC; TVC	Dynamic Programming	Disruptions in sea and at ports
Qi (2015)	V	V	Minimize the total cost	TFC; TVC	Dynamic Programming	Disruptions in sea and at ports
Li et al. (2016)	V	V	Minimize the total cost	TFC; TPC; TVC; MSC	Dynamic Programming	Regular uncertainties and disruptive events
Cheraghchi et al. (2018)	V	V	Minimize the total cost; minimize the total delay	TFC; TVC	Metaheuristics	Speed-based vessel schedule recovery
Abioye et al. (2019)	V	V	Minimize the total cost	REV; TOC; TFC; TPC; TVC; TIC	CPLEX	Consideration of emission control areas

Sailing speed/port time: *V* variable, *F* fixed

Objective components: *REV* total revenue, *TOC* total vessel operational cost, *TFC* total fuel cost, *TPC* total port handling cost, *TVC* total cost for violation of port arrival TWs, *TIC* total container inventory cost, *MSC* miscellaneous cost

- The future vessel schedule recovery studies should focus on modeling uncertainties at the consecutive ports after meeting the real-time requirements at a given port.
- Disruptions in sea and/or ports may negatively affect not only liner shipping companies but also other supply chain players. There is a need for more comprehensive models that capture the disruption effects and propose the appropriate recovery strategies for the major supply chain players (e.g., liner shipping companies, inland operators, logistics companies).

4.5 Green liner shipping

Green liner shipping has received increasing attention, especially in the past decade. From the literature survey, it was found that the majority of the collected green liner shipping studies had been published from 2014 to 2018. This section of the manuscript focuses on review of the green vessel scheduling studies, which specifically modeled various types of emissions that are produced by vessels (i.e., greenhouse gas emissions and/or non-greenhouse gas emissions), certain environmental regulations, effects of various environmental countermeasures (e.g., introduction of taxation on emissions produced by vessels), and other important environmental aspects. Furthermore, this section reviews the studies, which did not propose any mathematical models for green vessel scheduling but discussed and/or evaluated certain methods that could be used for reducing the environmental externalities from liner shipping (e.g., vessel hull design measures, power and propulsion system measures, application of alternative fuels, application of alternative energy sources).

Denote $\boldsymbol{EP}_p^{SEA}, p \in P$ as the amount of emissions produced at voyage leg p (tons); EF^{SEA} as the emission factor in sea (tons of emissions/ton of fuel); $\boldsymbol{EP}_p^{PORT}, p \in P$ as the amount of emissions produced at port p (tons); $EF_p^{PORT}, p \in P$ as the emission factor at port p (tons of emissions/TEU); c^{emis} as the unit emission cost (USD/ton); and $\boldsymbol{EC}$ as the total emission cost (USD). Then, the mathematical model for the green vessel scheduling problem (**GVSP**) can be formulated as follows:

Green Vessel Scheduling Problem (**GVSP**):

$$max\ \boldsymbol{TP} = [\boldsymbol{REV} - (\boldsymbol{PHC} + \boldsymbol{LAC} + \boldsymbol{FCC} + \boldsymbol{VOC} + \boldsymbol{CIC} + \boldsymbol{EC})] \tag{71}$$

Subject to:

Constraint sets (12–30)

$$\boldsymbol{EP}_p^{SEA} = EF^{SEA} l_p \boldsymbol{f}_p \quad \forall p \in P \tag{72}$$

$$\boldsymbol{EP}_p^{PORT} = \boldsymbol{QC}_p^{PORT} EF_p^{PORT} \quad \forall p \in P \tag{73}$$

$$\boldsymbol{EC} = c^{emis} \sum_{p \in P} \left(\boldsymbol{EP}_p^{SEA} + \boldsymbol{EP}_p^{PORT} \right) \tag{74}$$

The objective function (71) of the **GVSP** mathematical model aims to maximize the total profit, which will be generated by the liner shipping company. Constraint sets (72) and (73) estimate the amount of emissions produced at voyage legs and ports of the liner shipping route, respectively. Constraint set (74) computes the total emission cost. Note that constraint sets (72) and (73) of the **GVSP** mathematical model are based on the commonly used methodologies for estimating emissions in sea and at ports. More specifically, the emissions produced in sea are estimated based on the fuel consumption and the associated emission factor (Psaraftis and Kontovas 2013; Kontovas 2014), while the emissions produced at ports are estimated based on the container demand and the associated emission factor (Tran et al. 2017). Constraint sets (72) and (73) are presented in a generalized form but can be adjusted for a specific pollutant type (e.g., CO_2, SO_x, NO_x) by changing the value of emission factor.

The **GVSP** mathematical model accounts for the cost, associated with the emissions that are produced throughout the vessel voyage and service at ports, which can be used to assess the effects of emission/fuel taxation schemes on vessel schedules. However, without loss of generality, additional constraint sets can be introduced within the **GVSP** mathematical model in order to impose restrictions on the total amount of emissions produced at voyage legs of the given liner shipping route. The latter approach has been adopted in a number of previous green vessel scheduling models (Kontovas 2014; Dulebenets et al. 2017; Dulebenets 2018c). Also, the objective of the **GVSP** mathematical model can be changed from the cost minimization to the emission minimization. Specifically, instead of minimizing the total route service cost, which incorporates the total emission cost, the objective of the **GVSP** mathematical model can be altered to minimize the total amount of emissions produced at voyage legs and/or at ports of call. The emission minimization objective has been adopted in a number of previous green vessel scheduling models (Kontovas 2014; Song et al. 2015; Cheaitou and Cariou 2019).

Furthermore, by imposing a particular type of fuel at certain voyage legs (e.g., marine gas oil at the voyages legs, passing through ECAs, and heavy fuel oil at the voyages legs, passing outside ECAs), the **GVSP** mathematical model can be used to assess the effects of fuel switching for the liner shipping routes with ECAs. In the meantime, the **GVSP** mathematical model can be used to analyze various technologies and methods for reducing emissions from vessels (e.g., vessel fleet renewal, vessel re-routing, application of alternative fuels, application of alternative energy sources) if the appropriate data are incorporated within the model (e.g., fuel consumption rates for the new vessel fleet, the information regarding the alternative routes if a re-routing option is considered, cost of alternative fuels). A more detailed review of the collected studies on green liner shipping and presented mathematical models is provided in the following section of the manuscript.

4.5.1 Description of studies

The collected studies under this category were classified into the following sub-categories: (1) emission modeling alternatives in green vessel scheduling; (2) impacts of fuel taxation and emission taxation on vessel scheduling; (3) impacts of slow steaming on vessel scheduling; (4) environmental regulations and vessel scheduling within ECAs; and (5) existing technologies and methods for reducing emissions from vessels.

Emission modeling alternatives in green vessel scheduling Kontovas (2014) highlighted that the vessel sailing speed and payload are the primary factors, which should be considered when estimating the fuel consumption and emissions, produced by vessels. The study suggested a number of methods to model emissions in green vessel scheduling, such as emissions produced as the objective function, emissions produced as a component of the objective function, emission cost as a component of the objective function, and emissions produced as one of the constraint sets. Dulebenets et al. (2017) studied the green vessel scheduling problem, enforcing the constraints on emissions from the main vessel engines at each voyage leg of the considered liner shipping route. The objective of the presented mathematical formulation aimed to minimize the total route service cost. It was observed that the emission constraints could reduce the sailing speeds at voyage legs of the liner shipping route, lowering the total fuel cost. On the contrary, the total vessel operational cost, the total port handling cost, the total late vessel arrival cost, and the total container inventory cost increased from enforcing the emission constraints.

Dulebenets (2018c) incorporated the transit time requirements into the green vessel scheduling problem. A mixed-integer nonlinear optimization model was proposed, aiming to minimize the total route service cost. The problem was linearized and then solved with a dynamic secant approximation procedure. The study revealed that introduction of the transit time requirements and the emission constraints provoked an additional penalty for violation of the transit time requirements for certain cargo types, which further increased the total route service cost. Dulebenets (2018d) considered the CO_2 emissions, produced by vessels both in sea and at ports. The proposed mathematical model aimed to minimize the total route service cost, where the cost of CO_2 emissions in sea and at ports was one of the objective function components. The numerical experiments demonstrated that an increase in the CO_2 tax would significantly change the design of vessel schedules and incur extra route service costs. However, an increase in the CO_2 tax would improve the environmental sustainability of liner shipping operations.

In contrast to typical green vessel scheduling studies that assume fixed revenues for liner shipping companies, Giovannini and Psaraftis (2018) acknowledged the fact that liner shipping companies have a tendency of speeding up vessels when freight rates are high and slowing them down when the market is depressed. The ramifications of the liner shipping company decisions on the amount of CO_2 produced by vessels were also taken into account in the study. The objective of the presented mathematical model maximized the total profit. The computational experiments indicated that fixed frequencies could incur substantial costs (e.g., the additional fuel costs) and result in a loss of revenue. Cheaitou and Cariou (2019) proposed a multi-objective optimization model for vessel scheduling, aiming to maximize the total profit and minimize the CO_2 and SO_x emissions produced. Two demand configurations were modeled in the study, including: (a) elastic; and (b) inelastic. A total of three solution approaches were developed to solve the problem: (1) the weighted sum method; (2) the weighted comprehensive criterion method; and (3) the ε-constraint method. The numerical experiments were conducted for the Trans-Pacific and Europe-Far East markets. It was concluded that the optimal solution for the profit maximization sub-problem differed from the optimal solutions for the sub-problems with emission minimization, especially when the demand was sensitive to the transit time.

Hellsten et al. (2019) focused on the green liner shipping network design problem, aiming to provide liner shipping services and reduce the associated environmental impacts. A number of mathematical formulations were presented in the study, including service formulation, arc formulation, port of call formulation, and consideration of outbound–inbound principles with transit time constraints. The presented models aimed to minimize the total cost. A set of potential solution algorithms (e.g., exact optimization, heuristics, metaheuristics), previously used in the literature, were discussed.

Impacts of fuel taxation and emission taxation on vessel scheduling Corbett et al. (2009) examined the impacts of a fuel tax on a reduction of the vessel sailing speed and CO_2 emissions. It was revealed that a fuel tax of about \$150 per ton of fuel would result in the average speed-related CO_2 reduction of 20–30%. Kosmas and Acciaro (2017) assessed the impacts of a unit tax and an ad valorem tax on fuels, which are used by oceangoing vessels. The unit fuel tax was imposed per ton of fuel, while the ad valorem tax was imposed as a percentage of the fuel price. The study indicated that both taxation schemes would lead to the industry profit decline, and liner shipping companies could ultimately pass the additional costs from implementing new taxation policies to their customers. Halff et al. (2019) studied the impacts of new environmental restrictions on the liner shipping industry. The study indicated that the fuel tax benefits might be one of the effective incentives for liner shipping companies to comply with the IMO regulations.

Lee et al. (2013) aimed to analyze the quantitative effects of maritime CO_2 tax on the global economy with a primary focus on the containerized cargo, transported by vessels. The analysis results demonstrated that fairly low values of the CO_2 tax would not cause substantial economic impacts. However, increasing CO_2 tax would result in the Gross Domestic Product (GDP) losses. In particular, a CO_2 tax of \$90 per ton of CO_2 would cause a 0.02% GDP loss for China. Dai et al. (2018) modeled the vessel operational costs and the CO_2 emissions produced under various geographic network configurations, when the CO_2 tax was imposed at the Asia-Europe liner shipping routes. It was found that increasing CO_2 tax might lead to changes in the liner shipping networks, as liner shipping companies would be willing to alter their routes to minimize the operational costs as well as the CO_2 emission charges. Sheng et al. (2018) underlined the challenges, associated with the bunker emission tax regulations in maritime transportation. The study presented an economic analysis to assess the impact of imposing the bunker emission tax on international trade. It was found that introduction of the global bunker emission tax would decrease the trade volumes and could even result in changing trade patterns. Furthermore, introduction of the global bunker emission tax might accelerate adoption of the energy-saving technologies.

Impacts of slow steaming on vessel scheduling Psaraftis and Kontovas (2010) analyzed the implications of vessel sailing speed reduction on liner shipping operations. The study highlighted that the speed reduction would decrease the CO_2 emissions but might incur additional costs for liner shipping companies. The latter can be justified by the fact that the vessel sailing speed reduction would require more vessels to serve a given liner shipping route, increase the inventory cost of cargo, and might even cause modal shifts. Kontovas and Psaraftis (2011a) indicated that slow steaming was commonly used by liner shipping companies in order to reduce the fuel consumption (hence, decrease the amount of emissions produced). However, slow steaming increases the total vessel sailing time. The study pointed out that a reduction in port handling times might be an effective alternative to compensate for the time losses in sea. Kontovas and Psaraftis (2011b) pointed out that liner shipping companies had been widely using slow steaming during the crisis in shipping due to low demand for transport, fairly low freight rates, and high unit fuel costs. Slow steaming allowed liner shipping companies reducing the fuel consumption and the associated fuel costs, which decreased the total amount of emissions produced as well, thereby, resulting in a win–win situation. The practice of slow steaming and the impacts of slow steaming on vessel schedules were also discussed in detail by Psaraftis and Kontovas (2013) and Psaraftis and Kontovas (2014).

Cariou (2011) indicated that slow steaming decreased the CO_2 emissions by about 11% between 2008 and 2010, against a target of 15% by 2018. The study suggested that slow steaming would remain an efficient mean for reducing the CO_2 emissions if the unit fuel cost would be high and/or certain market-based mechanisms would be introduced (e.g., fuel tax). However, it was pointed out that slow steaming might cause design and safety issues. Lindstad et al. (2011) examined the effects of vessel sailing speed reduction on the CO_2 emissions and marine transportation costs. It was discovered that a reduction of the CO_2 emissions by 19% could be achieved with negative abatement cost, and a reduction of 28% could be achieved with zero abatement cost. It was highlighted that the CO_2 emissions could be decreased to a certain extent by reducing the vessel sailing speed without implementation of new technologies. Cariou and Cheaitou (2012) underlined that the speed limit, considered for implementation by the European Commission for all the vessels entering the European Union ports, is counterproductive. The study indicated that introduction of the speed limit could ultimately generate more CO_2 emissions and incur additional costs for the society. Furthermore, bunker levy was expected to be more promising alternative as compared to introduction of the speed limit.

Chang and Wang (2014) assessed the strategies, which could be used by liner shipping companies for reducing vessel sailing speed in order to minimize the route service costs and the negative environmental impacts. The results from conducted analysis indicated that the optimal speed reduction is a dynamic process, primarily affected by the unit fuel cost and the charter rates. Ferrari et al. (2015) aimed to investigate the implications of slow steaming on liner shipping service patterns. The service patterns between Asia and Europe were considered. It was highlighted that the slow steaming strategy could be effective for the cases with high unit fuel costs. However, the liner shipping company should consider additional factors (e.g., freight rates, size of the vessels deployed, port type) in order to avoid the negative impacts. Lee et al. (2015) discussed the tradeoff between slow steaming and the total transit time. The study proposed a model in order to quantify the relationship between the transit time, delivery reliability, and the total fuel cost. The developed methodology was found to be useful in assessing advantages and drawbacks of slow steaming.

Mansouri et al. (2015) aimed to examine the potential of using multi-objective optimization throughout decision making in order to improve sustainability of maritime shipping. The study highlighted a conflicting nature of the outcomes, which could be caused by slow steaming (i.e., fuel savings vs. transit time increase). Psaraftis and Kontovas (2015) indicated that slow steaming is mainly induced by high unit fuel costs and/or depressed shipping market. The study highlighted that the solutions, yielding the optimal environmental performance of maritime shipping, may not lead to the optimal economic performance. Wong et al. (2015) presented a set of continuous utility-based decision support models for slow steaming. The utility functions were based on the fuel consumption, the CO_2 emissions, and on-time delivery. Applicability of the proposed methodology was demonstrated for the Trans-Pacific service route. De et al. (2016) addressed the vessel routing and scheduling problem, where particular operational measures, such as speed optimization and slow steaming for reducing the CO_2 emissions, were taken into account. A mixed-integer nonlinear programming model was presented, aiming to minimize the total route service cost. A Particle Swarm Optimization-based algorithm was developed to solve the problem. It was found that the proposed methodology could improve the economic and environmental sustainability of liner shipping operations.

Tezdogan et al. (2016) highlighted a wide implementation of slow steaming in liner shipping. However, loss of the vessel sailing speed and added resistance due to waves could result in undesirable delays or course alterations. The study presented a methodology for predicting the vessel motions and estimating the fuel consumption under normal and adverse sea conditions. Wen et al. (2017) focused on the vessel routing and sailing speed optimization problem, capturing time, cost, and environmental objectives. The study discussed potential implications of slow steaming on liner shipping operations. The objective of the proposed mathematical model minimized the total route service cost. The Branch-and-Price algorithm and the Constraint Programming method were adopted to solve the problem. Based on the conducted computational experiments, it was found that the Branch-and-Price algorithm was more promising solution approach. Also, the study presented a set of sensitivity analyses for the unit fuel cost, the unit charter cost, and the unit inventory cost.

Environmental regulations and vessel scheduling within ECAs Acciaro (2014) indicated that the use of liquefied natural gas (LNG) could be considered as a promising alternative for the vessels, passing through ECAs, as it allows meeting the existing IMO regulations. However, retrofitting the existing vessels to be able to use LNG would incur additional costs. The results from conducted real option analysis showed that the future of LNG depends on its price, capital costs, and vessel retrofitting costs. Brynolf et al. (2014) evaluated several alternatives for compliance with the IMO regulations on sulfur and NO_x Tier III within ECAs, including: (1) heavy fuel oil combined with Selective Catalytic Reduction (SCR) and an open loop sea water scrubber; (2) marine gas oil with SCR; and (3) LNG. It was found that all the considered alternatives would substantially decrease the impacts of PM, acidification, photochemical ozone formation, and terrestrial eutrophication. Doudnikoff and Lacoste (2014) aimed to examine the effectiveness of applying the slow steaming strategy within sulfur ECAs. Along with reducing the total fuel cost, slow steaming would require more vessels to provide the agreed service frequency at the ports within ECAs. A cost-minimizing analytical model was proposed in order to investigate the latter tradeoff.

Holmgren et al. (2014) studied the potential of modal shift due to the regulations, which were imposed by IMO within ECAs. The developed agent-based simulation model was applied to the route, connecting Lithuania and the British Midlands. The findings confirmed that the modal shift from sea to road was unlikely. Jiang et al. (2014) analyzed two measures for sulfur reduction: (a) sulfur scrubbers; and (b) marine gas oil. The study concluded that selection of the appropriate measure is significantly dependent on the unit fuel cost. Moreover, installation of scrubbers would be more beneficial for new vessels rather than for retrofits. Schinas and Stefanakos (2014) presented a multi-criteria approach, which was based on the analytic network process, in order to evaluate various technologies for compliance with the IMO regulations. The study demonstrated that the developed multi-criteria approach was able to address a complex nature of decision making, where traditional approaches were generally not efficient.

Since strict limits on the maximum sulfur content in fuel have been forced within ECAs, liner shipping companies are required to use expensive low-sulfur fuel when passing through ECAs. Consequently, increasing unit fuel cost has made an impact on the vessel sailing speed (i.e., liner shipping companies tend to slow down the vessels to reduce consumption of expensive low-sulfur fuel) and further affected the design of vessel schedules. Fagerholt and Psaraftis (2015) evaluated the effects from using expensive low-sulfur fuel (i.e., marine gas oil) within ECAs, since vessels tend to lower sailing speeds due to the use of costlier fuel inside the ECAs. The objective of the study was to maximize the total profit. Based on the conducted analysis, it was found that in case of high unit fuel cost ratios (i.e., marine gas oil vs. heavy fuel oil) vessels could sail shorter distances inside the ECAs and longer distances outside the ECAs. Fagerholt et al. (2015) devised an optimization model, aiming to minimize the total fuel cost, in order to determine sailing paths and speeds of vessels. The model took into consideration fuel switching for the vessels sailing inside ECAs. Xpress-MP was used to solve the problem. The numerical experiments indicated that vessels tended to sail through longer voyage legs in order to avoid ECAs. Furthermore, lower vessel sailing speeds were generally observed within ECAs, as the liner shipping company aimed to decrease the use of expensive low-sulfur fuel.

The International Maritime Organization (IMO) enforced several restrictions to attenuate the negative impacts of maritime transportation on the environment but did not impose any restrictions on the quantity of emissions produced within ECAs. Dulebenets (2016) formulated a mathematical model for the green vessel scheduling problem in order to assess the implications of the IMO regulations and an alternative policy, enforcing the emission restrictions within ECAs along with the IMO regulations. The objective of the model minimized the total route service cost. The computational experiments demonstrated that enforcement of the emission restrictions within ECAs would lower the amount of emissions produced by vessels. However, such restrictions would also cause an increase in the total route service cost. Sys et al. (2016) aimed to examine the effects of the international maritime emission regulations on the competition between ports as well as potential motivations for introducing ECAs. The environmental issues were addressed from the policy, economic, and legislatives perspectives. It was found that liner shipping companies are unlikely to change their routes and ports of call due to the IMO regulations. However, the study suggested that the IMO regulations should be improved in order to avoid potential incompliance and protect competitiveness of complying vessels.

Abadie et al. (2017) focused on an economic assessment of the two common techniques, which are used by liner shipping companies to meet the environmental regulations within ECAs, specifically: (1) use of low-sulfur fuel; and (2) installation of scrubbers. The remaining vessel lifetime was found to be the main factor for opting one alternative over the other. The results showed that installation of scrubbers would be advantageous for the vessels with longer remaining lifetime. Dithmer et al. (2017) focused on the liner shipping routing and scheduling problem, aiming to design vessel schedules and minimize the associated costs. Two objective functions were considered: (a) minimize the total vessel operational cost and the total fuel cost; and (b) minimize the total vessel operational cost, the total fuel cost, and the total emission cost. The numerical experiments were performed for the liner shipping route, passing through ECAs. The study recommended consideration of the total fuel cost and the total emission cost throughout vessel scheduling in order to improve the environmental sustainability of liner shipping operations. Åström et al. (2018) studied advantages and disadvantages from introducing nitrogen ECAs in the Baltic Sea and the North Sea. The conducted analysis indicated that the benefits surpassed the associated costs for the majority of the considered scenarios. However, the nitrogen ECAs were found to be more beneficial for the North Sea as compared to the Baltic Sea.

Chen et al. (2018) assessed the effects of introducing ECAs in the Mediterranean Sea. The findings showed that the introduction of ECAs in the Mediterranean Sea would cause re-routing of vessels. The latter would increase the amount of emissions produced outside ECAs. Smaller vessels were found to be more sensitive to the new ECAs as compared to larger vessels. Sheng et al. (2019) conducted a study, aiming to determine the optimal vessel sailing speed and fleet size for the shipping service, passing through ECAs. The objective function of the presented model minimized the total route service cost. An analytical optimal solution was derived for the problem after a set of relaxations. A number of computational experiments indicated that an increase in the unit fuel cost could lead to reduction of the total emissions produced but might require deployment of additional vessels for service of a given route. Zis and Psaraftis (2019) highlighted that the existing IMO regulations for the vessels, sailing within ECAs, could lead to modal shifts from sea to land-based transport options. A number of operational measures were discussed in order to avoid potential modal shifts, including speed reduction, service frequency changes, use of alternative fuels, improved fleet assignment, and installation of scrubbers. It was underlined that selection of the appropriate measure could make the sea transport more competitive.

Existing technologies and methods for reducing emissions from vessels Eyring et al. (2010) studied the impacts of emissions, produced by oceangoing vessels, on air quality and environment. A variety of technologies were discussed, which could be used for reducing the NO_x emissions, the SO_x emissions, and the PM emissions. Implementation of alternative fuels (e.g., low-sulfur residual fuel, marine distillate oil, bio-oils) was considered as one of the alternatives for decreasing emissions. Moreover, several policy strategies were highlighted, including emission taxes, marketable permits, government subsidies, and others. Psaraftis (2012) reviewed different market-based measures, which were considered by IMO at the moment in order to decrease the greenhouse gas (GHG) emissions from vessels. A total of 10 measures were described, which were primarily based on the establishment of the GHG fund, incentives that are based on the Energy Efficiency Design Index (EEDI), and the establishment of the global emission trading system. Zis et al. (2014) evaluated cold ironing and speed reduction policies, aiming to minimize the emissions, produced by vessels that enter ports of call. It was found that the potential of each policy significantly depended on the unique port and vessel characteristics.

Lam (2015) focused on the design of a sustainable maritime supply chain, considering various customer requirements (e.g., cost, pollution reduction, efficient fuel utilization, health, safety). Implementation of the green design vessels, engines, and machinery were determined to be the most critical design requirements. Lun et al. (2015) studied different environmental governance mechanisms (such as contractual, relational, and organizational mechanisms) and their effects on the environmental performance of liner shipping operations. The mediating roles of the relational and organizational mechanisms for liner shipping companies were discussed as well. In order to improve the environmental sustainability of liner shipping operations through minimization of the fuel consumption, Zis et al. (2015) modeled the emissions of CO_2, SO_2, NO_x, and black carbon (BC) exhausted from marine engines. The study assessed the impacts of slow steaming, fuel regulations, near-port speed reduction schemes, and cold ironing as means to preserve the environment. It was revealed that certain factors, such as vessel specifications, port and country characteristics, unit fuel cost, and journey details, had a notable impact on the quantity of emissions produced.

Deniz and Zincir (2016) performed an economical and environmental assessment of alternative marine fuels, including methanol, LNG, ethanol, and hydrogen. It was found that methanol and ethanol would not be suitable for oceangoing vessels. LNG was identified as the most suitable alternative. The study underlined that more research should be conducted on the use of hydrogen. Rahim et al. (2016) underlined the lack of international instruments for holding liner shipping companies accountable for performance of their vessels as well as emissions produced. The study mentioned that the appropriate stakeholders should address the latter issue by imposing suitable market-based measures. Shi (2016) indicated that the add-on rebate mechanism, built into the global GHG fund, would be the most suitable market-based measure for reducing the GHG emissions from vessels. The market-based measures were not justified for the international shipping industry at the moment but should be implemented in future to decrease the GHG emissions.

Sislian et al. (2016) conducted a comprehensive review of the maritime literature, related to the port sustainability and the liner shipping network design problem. The study listed different types of emissions, which are produced by vessels that enter ports of call. A set of preliminaries were presented for the conceptual framework, aiming to integrate the port sustainability and the liner shipping network design problem with a particular emphasis on the environmental externalities. Zhao et al. (2016) pointed out that an effective power management of the vessel propulsion system could reduce the fuel consumption and associated emissions. It was found that the vessel speed involuntary reduction was significantly influenced by propeller ventilation, especially for extreme sea conditions. Bouman et al. (2017) conducted a comprehensive review of the state-of-the-art technologies for reducing the GHG emissions from vessels. The following categories of technologies and measures were discovered and analyzed: vessel hull design measures, power and propulsion system measures, application of alternative fuels, alternative energy sources, and operations optimization. It was found that the emissions from the maritime sector could be reduced by more than 75% based on deployment of the current technologies and measures by 2050. Moreover, the emissions per freight unit transported could be decreased by a factor, varying from 4 to 6.

Rehmatulla et al. (2017) performed a cross-sectional survey of vessel owners and operators, aiming to evaluate over thirty CO_2 emission reduction alternatives. The following categories of alternatives were analyzed: vessel design measures, hydrodynamic measures, machinery measures, alternative fuels, maintenance strategies, and after-treatment measures. It was found that technologies with smaller energy efficiency gains (e.g., engine tuning, engine de-rating, waste heat recovery) had been used more often in practice as compared to the ones, which were more advantageous in terms of the CO_2 emission reduction (e.g., alternative fuels, renewable energy sources). Hua et al. (2017) compared the life-cycle emissions of heavy fuel and LNG for the vessels, sailing between Mainland China and Taiwan. The analysis results showed that the use of LNG allowed reducing the total GHG and CO_2 emissions but caused an increase in the methane emissions. Obrecht and Knez (2017) discussed an alternative design of containers, which was based on the eco-design principles. The proposed eco-design containers required less material and had lower weight. It was underlined that the optimal container design could drastically reduce the GHG emissions throughout material supply and decrease the weight of vessels. However, the impact of eco-design containers on vessel schedules was not evaluated explicitly.

Sheng et al. (2017) investigated the economic and environmental effects of the unilateral maritime emission regulations against the uniform maritime emission regulations. The study captured competition between regional ports and between liner shipping companies. The results showed that the unilateral regulations could lead to increasing total emissions, while the uniform regulations always reduced the total emissions. Styhre et al. (2017) discussed several measures for reducing the GHG emissions from vessels, entering ports of call, including slow steaming, on-shore power supply, reduced port handling times, and alternative fuels. It was found that the potential of decreasing emissions was directly dependent on how often a given port is visited by vessels. Innes and Monios (2018) conducted a study, aiming to identify the major challenges, associated with implementation of cold ironing at small and medium ports. Based on the case study for the Port of Aberdeen, the need for individual on-shore power supply installation at small berths, long cables, cable reel storage, and the need for onboard technology installation for vessels were found to be the key challenges.

Wan et al. (2018) highlighted the lack of international legal agreements for regulating GHGs, produced by vessels, due to the fact that most of the technical solutions are fairly expensive and the absence of industrial support. The study pointed out a limited potential of the slow steaming strategy and the need for effective market-based approaches in order to address the negative environmental impacts. Balcombe et al. (2019) provided a broad review of different options for reducing the NO_x, SO_x, and GHG emissions from vessels. The suggested options were based on alternative fuels, technologies, and policies. Cariou et al. (2019) studied the major factors, influencing the amount of CO_2 emissions, produced by vessels. The two key factors, which were identified, include the following: (1) increase in fuel efficiency due to the vessel sailing speed reduction and technology changes; and (2) reduction in the total sailing distance for vessels.

4.5.2 Summary of findings

Table 5 presents a summary of findings from the studies that examined the green vessel scheduling problem. Note that certain studies, which were reviewed in Sect. 4.5.1 of the manuscript, discussed and/or evaluated various methods that could be used for reducing the environmental externalities from liner shipping (e.g., vessel hull design measures, power and propulsion system measures, application of alternative fuels, application of alternative energy sources) but did not present any mathematical models for the green vessel scheduling problem, which was defined in Sects. 2 and 4.5 of the manuscript. For example, Zis and Psaraftis (2019) discussed a number of operational measures in order to avoid potential modal shifts from sea to land-based transport options, including speed reduction, service frequency changes, use of alternative fuels, improved fleet assignment, and installation of scrubbers. The modal shifts were modeled using a two-stage nested logit model. However, the study did not present any green vessel scheduling models, which incorporated the considered operational measures for avoiding potential modal shifts. Therefore, the studies, which did not present any green vessel scheduling models, are not provided in Table 5.

As a result of a detailed analysis of the proposed green vessel scheduling models, variable sailing speed was found to be the most common assumption (rather than fixed sailing speed). A total of 68.8% of studies assumed the port times to be fixed, while the remaining 31.2% of studies adopted variable port times. The majority of studies (75.0%) proposed the mathematical models, aiming to minimize the total route service cost. Only 25.0% of the models aimed to maximize the total profit to be generated by the liner shipping company. All the

Table 5 Summary of findings: studies on green vessel scheduling

References	Sailing speed	Port time	Model objective	Objective components	Solution approach	Notes/major considerations
Chang and Wang (2014)	V	F	Maximize the total profit	REV; TOC; TFC; TPC	Analytical method	Sailing speed reduction strategies
Kontovas (2014)	V	F	Minimize the total cost	TOC; TFC; TEC	N/A	Discussion of emission modeling alternatives
Fagerholt and Psaraftis (2015)	V	F	Maximize the total profit	REV; TFC	Analytical method	Use of low-sulfur fuel within ECAs
Fagerholt et al. (2015)	V	F	Minimize the total cost	TFC	Xpress-MP	Use of low-sulfur fuel within ECAs
Zis et al. (2015)	V	F	Minimize the total cost	TFC	Analytical method	Estimation of CO_2, SO_2, NO_x, and BC emissions
De et al. (2016)	V	V	Minimize the total cost	TOC; TFC; TPC; TVC	Metaheuristic	Multiple port arrival TWs; constraints on CO_2
Dulebenets (2016)	V	V	Minimize the total cost	TOC; TFC; TPC; TVC; TIC	Iterative optimization algorithm	Use of low-sulfur fuel within ECAs; constraints on SO_2
Dithmer et al. (2017)	V	F	Minimize the total cost	TOC; TFC; TEC	Exact optimization	Effects of introducing the emission cost
Dulebenets et al. (2017)	V	V	Minimize the total cost	TOC; TFC; TPC; TVC; TIC	CPLEX	Constraints on CO_2, SO_2, and NO_x
Wen et al. (2017)	V	F	Minimize the total cost	TFC; TIC; MSC	Branch-and-price algorithm; constraint programming method	Consideration of time, cost, and environmental objectives
Dulebenets (2018c)	V	V	Minimize the total cost	TOC; TFC; TPC; TVC; TIC; MSC	Iterative optimization algorithm	Use of low-sulfur fuel within ECAs; constraints on CO_2, SO_2, and NO_x; transit time requirements
Dulebenets (2018d)	V	V	Minimize the total cost	TOC; TFC; TPC; TVC; TIC; TEC	CPLEX	CO_2 costs in sea and at ports

Table 5 (continued)

References	Sailing speed	Port time	Model objective	Objective components	Solution approach	Notes/major considerations
Giovannini and Psaraftis (2018)	V	F	Maximize the total profit	REV; TOC; TFC; TPC; TIC; MSC	Analytical method	Flexible port service frequency; CO_2 in sea
Cheaitou and Cariou (2019)	V	F	Maximize the total profit; minimize the total CO_2 emissions; minimize the total SO_x emissions	REV; TOC; TFC; TPC; TEC	The weighted sum method; the weighted comprehensive criterion method; the ε-constraint method	Consideration of elastic (transit time-based) and inelastic demand
Hellstern et al. (2019)	V	F	Minimize the total cost	TOC; TFC; TVC; TIC; TEC; MSC	Exact optimization; heuristics; metaheuristics	Overview of formulations and algorithms for the green liner shipping network design
Sheng et al. (2019)	V	F	Minimize the total cost	TOC; TFC; TIC	Analytical method	Sailing speed and fleet size adjustments when sailing through ECAs

Sailing speed/port time: *V* variable; *F* fixed

Objective components: *REV* total revenue, *TOC* total vessel operational cost, *TFC* total fuel cost, *TPC* total port handling cost, *TVC* total cost for violation of port arrival TWs, *TIC* total container inventory cost, *TEC* total emission cost, *MSC* miscellaneous cost green vessel scheduling studies incorporated the total fuel cost in the presented mathematical models. Moreover, 31.2% of studies adopted analytical methods to solve the proposed mathematical models, 12.5% of studies relied on CPLEX, while 43.8% of studies used iterative optimization algorithms.

4.5.3 Limitations and future research needs

A number of limitations have been identified in the existing studies on green liner shipping. These limitations and future research needs with respect to green liner shipping include the following:

- One of the major challenges in assessing the environmental impacts from oceangoing vessels is the lack of accurate data on vessel emissions (Eyring et al. 2010). The future studies should try to obtain more data from different liner shipping companies and other appropriate stakeholders in order to achieve more accurate results.
- A number of analytical models were presented in the literature, aiming to assess the effects of fuel taxation and emission taxation on vessel schedules. It was found that increasing fuel taxes and emission taxes decrease the vessel sailing speed, fuel consumption, and emissions produced (Corbett et al. 2009; Kosmas and Acciaro 2017). However, other important vessel scheduling aspects were often ignored (e.g., the effects of fuel taxation and emission taxation on port operations and handling time of vessels at ports). The future research should consider a wide range of vessel scheduling aspects that could be affected by fuel taxation and emission taxation, rather than solely focusing on the vessel sailing speed.
- A significant portion of the reviewed studies underlined that the slow steaming strategy is effective in reducing the fuel consumption and the vessel emissions produced (Psaraftis and Kontovas 2010; Kontovas and Psaraftis 2011a, b; Ferrari et al. 2015). However, slow steaming has a number of drawbacks, including the following: increase in the total transit time of containers; increase in the total number of vessels to be deployed for service of the given liner shipping route; potential monetary losses in case of increasing freight rates; and others. The future studies should focus on the development of multi-objective models for a comprehensive analysis of tradeoffs from application of slow steaming.
- As pointed out by Lee and Song (2017), slow steaming was adopted in 2008 with the primary goal to reduce the total fuel cost. However, the unit fuel cost started substantially decreasing since 2015. The future research should evaluate the impact of changing unit fuel cost on the efficiency of different emission reduction strategies.
- Several studies aimed to determine potential impacts from introducing new ECAs (e.g., new ECAs in the Baltic Sea, the North Sea, and the Mediterranean Sea) on liner shipping operations. These studies performed a set of economic analyses; however, no explicit optimization models were proposed in order to

assess the effects of new ECAs on vessel schedules, which would be an important future research direction.

- The future research should focus on the design of vessel schedules for the liner shipping routes with ECAs and assessment of different strategies, which could be used for reducing the additional costs incurred from using low-sulfur fuel within ECAs.
- A large number of various technologies and methods for reducing the emissions from vessels were discussed in the literature, which include, but are not limited to, vessel design measures, application of alternative fuels, alternative energy sources, operations optimization, and market-based measures (Eyring et al. 2010; Bouman et al. 2017; Rehmatulla et al. 2017). The emission reduction strategies, which were found to be the most promising, should be incorporated within the existing vessel scheduling models. The latter will allow assessing the impacts of emission reduction strategies on the design of vessel schedules.
- The future research should focus on a comprehensive evaluation of the emission reduction strategies (e.g., design of alternative vessel engines, deployment of scrubbers, use of alternative fuel types, slow steaming) from different perspectives (i.e., environmental, social, and economic perspectives).
- The future research should put more emphasis on the development of constructive recommendations, which could be used to overcome the existing barriers to implementation of the emission reduction strategies in maritime transportation.
- The existing studies on green vessel scheduling and environmental aspects in vessel scheduling generally do not consider any uncertainties in liner shipping operations. Uncertainties in liner shipping operations may impact the vessel fuel consumption and emissions produced. The future research should focus on modeling uncertainties in liner shipping operations in order to make the analysis of environmental aspects in vessel scheduling more accurate.
- The majority of studies aimed to assess the impact of environmental regulations on vessel scheduling and appropriate stakeholders (i.e., primarily, liner shipping companies and MCT operators). The future research should also consider the impacts on social welfare to determine how the community may benefit from these environmental regulations.
- The majority of green vessel scheduling studies highlighted the negative effects of emissions from vessels on living organisms. However, the proposed models did not provide a sufficient justification for selecting the unit costs, associated with the emissions that are produced by vessels. A comprehensive socio-economic analysis should be performed to examine the effects of different pollutants that are produced by vessels and accurately quantify the associated costs for the major liner shipping routes.

5 Conclusions

Efficient vessel schedules are crucial for both liner shipping and marine container terminal operations. Without proper design of vessel schedules, liner shipping companies may endure substantial monetary losses due to unmet demand, delayed vessel arrivals at ports, additional total fuel cost, increasing cargo transit time, and other factors. The vessel scheduling problem is classified as a tactical-level decision problem, aiming to determine vessel sailing speed at each voyage leg of a port rotation, capture marine container terminal operations (i.e., determination of port arrival time, waiting time, handling time, departure time, potential vessel arrival delays), and allocate a sufficient number of vessels for service of the given liner shipping route. A large number of studies have been conducted to date, aiming to assist liner shipping companies with the design of efficient vessel schedules. This study performed a comprehensive survey of the existing research on vessel scheduling in liner shipping. The collected vessel scheduling studies were classified into five categories, including the following: (1) general vessel scheduling; (2) uncertainty in liner shipping operations; (3) collaborative agreements; (4) vessel schedule recovery; and (5) green liner shipping. A set of representative mathematical models were proposed for the general vessel scheduling problem, the vessel scheduling problem with uncertainties, the collaborative vessel scheduling problem, the vessel schedule recovery problem, and the green vessel scheduling problem.

Each category of studies was systematically reviewed with a focus on the following aspects: (a) vessel sailing speed assumptions; (b) port time assumptions; (c) model objective; (d) objective components; (e) solution approach; and (f) notes/major considerations. As a result of a detailed review of the collected literature, it was found that most of the studies considered variable sailing speeds and port handling times. Various model objectives for the vessel scheduling problem were identified in the existing literature, including minimization of the total route service cost, maximization of the total profit, minimization of the total delay, minimization of the total variation in port arrival times, minimization of the unreliability, minimization of the total CO_2 emissions, minimization of the total fuel cost, and maximization of the total utility. A common objective for the majority of the studies was to minimize the total route service cost, which could comprise of the total vessel operational cost, the total fuel cost, the total port handling cost, the total emission cost, the total container inventory cost, the total late vessel arrival cost, and others. Different solution approaches were employed to solve the developed mathematical models, including heuristics, metaheuristics, and exact solution algorithms. Finally, the existing limitations in the state-of-the-art were highlighted, and future research needs were outlined for each one of the categories of studies.

Findings from this research provide a concise summary of the conducted-to-date studies on vessel scheduling in liner shipping and emphasize the critical gaps in the state-of-the-art, which have to be addressed by the scientific community in future. This study can be expanded in several directions, including the following:

- First, a set of interviews can be conducted with a number of liner shipping companies and marine container terminal operators in order to collect the information regarding the state-of-the-practice with respect to vessel scheduling.
- Second, the existing challenges in the state-of-the-practice should be thoroughly analyzed and determine whether they receive a sufficient attention in the state-of-the-art.

- Third, a set of constructive recommendations should be provided in order to bridge the gap between the state-of-the-art and the state-of-the-practice.

Appendix

This appendix provides a full list of notations that were adopted throughout the manuscript. A description of the sets, decision variables, auxiliary variables, and parameters is provided in Tables 6, 7, 8 and 9, respectively.

Table 6 Description of sets

Set	Set description	Remarks
$P = \{1, \dots, m^1\}$	Set of ports to be visited by vessels for a given liner shipping route (ports)	
$T_p = \left\{1, \dots, m_p^2\right\}, p \in P$	Set of arrival TWs, offered by the MCT operator at port p (TWs)	**CVSP** only
$H_{pt} = \left\{1, \dots, m_{pt}^3\right\}, p \in P, t \in T_p$	Set of handling rates, offered by the MCT operator at port p during TW t (handling rates)	**CVSP** only

CVSP collaborative vessel scheduling problem

Table 7 Description of decision variables

Decision variable	Decision variable description	Remarks
$\boldsymbol{s}_p \in \mathbb{R}^+ \quad \forall p \in P$	Vessel sailing speed at voyage leg p (knots)	
$\tilde{\boldsymbol{s}}_p \in \mathbb{R}^+ \quad \forall p \in P$	Expected vessel sailing speed at voyage leg p (knots)	**UVSP** only
$\overline{\boldsymbol{s}_p} \in \mathbb{R}^+ \quad \forall p \in P$	Recovered vessel sailing speed at voyage leg p (knots)	**VSRP** only
$\boldsymbol{q} \in \mathbb{N}$	Total number of vessels to be deployed for service of the liner shipping route (vessels)	
$\boldsymbol{z}_{pt} \in \mathbb{B} \quad \forall p \in P, t \in T_p$	=1 if TW t is selected at port p (=0 otherwise)	**CVSP** only
$\boldsymbol{x}_{pth} \in \mathbb{B} \quad \forall p \in P, t \in T_p, h \in H_{pt}$	=1 if handling rate h is selected at port p during TW t (=0 otherwise)	**CVSP** only
$\Delta_p^{sea} \in \mathbb{R} \quad \forall p \in P$	Vessel sailing speed adjustment at voyage leg p (knots)	**VSRP** only
$\boldsymbol{x}_p^{skip} \in \mathbb{B} \quad \forall p \in P$	=1 if port p is skipped (=0 otherwise)	**VSRP** only

UVSP vessel scheduling problem with uncertainties in liner shipping operations, *CVSP* collaborative vessel scheduling problem, *VSRP* vessel schedule recovery problem

Table 8 Description of auxiliary variables

Auxiliary variable	Auxiliary variable description	Remarks
$\boldsymbol{\tau}_p^{arr} \in \mathbb{R}^+ \quad \forall p \in P$	Vessel arrival time at port p (hours)	
$\overline{\boldsymbol{\tau}_p^{arr}} \in \mathbb{R}^+ \quad \forall p \in P$	Recovered vessel arrival time at port p (hours)	**VSRP** only
$\boldsymbol{\tau}_p^{wait} \in \mathbb{R}^+ \quad \forall p \in P$	Vessel waiting time at port p (hours)	
$\widetilde{\boldsymbol{\tau}_p^{wait}} \in \mathbb{R}^+ \quad \forall p \in P$	Expected vessel waiting time at port p (hours)	**UVSP** only
$\overline{\boldsymbol{\tau}_p^{wait}} \in \mathbb{R}^+ \quad \forall p \in P$	Recovered vessel waiting time at port p (hours)	**VSRP** only
$\boldsymbol{\tau}_p^{hand} \in \mathbb{R}^+ \quad \forall p \in P$	Vessel handling time at port p (hours)	
$\widetilde{\boldsymbol{\tau}_p^{hand}} \in \mathbb{R}^+ \quad \forall p \in P$	Expected vessel handling time at port p (hours)	**UVSP** only
$\overline{\boldsymbol{\tau}_p^{hand}} \in \mathbb{R}^+ \quad \forall p \in P$	Recovered vessel handling time at port p (hours)	**VSRP** only
$\boldsymbol{\tau}_p^{dep} \in \mathbb{R}^+ \quad \forall p \in P$	Vessel departure time from port p (hours)	
$\overline{\boldsymbol{\tau}_p^{dep}} \in \mathbb{R}^+ \quad \forall p \in P$	Recovered vessel departure time from port p (hours)	**VSRP** only
$\boldsymbol{\tau}_p^{sail} \in \mathbb{R}^+ \quad \forall p \in P$	Vessel sailing time at voyage leg p (hours)	
$\widetilde{\boldsymbol{\tau}_p^{sail}} \in \mathbb{R}^+ \quad \forall p \in P$	Expected vessel sailing time at voyage leg p (hours)	**UVSP** only
$\overline{\boldsymbol{\tau}_p^{sail}} \in \mathbb{R}^+ \quad \forall p \in P$	Recovered vessel sailing time at voyage leg p (hours)	**VSRP** only
$\boldsymbol{\tau}_p^{late} \in \mathbb{R}^+ \quad \forall p \in P$	Late arrival hours port p (hours)	
$\overline{\boldsymbol{\tau}_p^{late}} \in \mathbb{R}^+ \quad \forall p \in P$	Recovered late arrival hours port p (hours)	**VSRP** only
$\overline{\boldsymbol{\tau}^{vtt}} \in \mathbb{R}^+$	Total vessel turnaround time for the recovered vessel schedule (hours)	**VSRP** only
$\boldsymbol{f}_p \in \mathbb{R}^+ \quad \forall p \in P$	Fuel consumption by the main vessel engines at voyage leg p (tons/nmi)	
$\widetilde{\boldsymbol{f}_p} \in \mathbb{R}^+ \quad \forall p \in P$	Expected fuel consumption by the main vessel engines at voyage leg p (tons/nmi)	**UVSP** only
$\overline{\boldsymbol{f}_p} \in \mathbb{R}^+ \quad \forall p \in P$	Recovered fuel consumption by the main vessel engines at voyage leg p (tons/nmi)	**VSRP** only
$\boldsymbol{w}_p \in \mathbb{R}^+ \quad \forall p \in P$	Vessel payload at voyage leg p (tons)	
$\boldsymbol{QC}_p^{PORT} \in \mathbb{R}^+ \quad \forall p \in P$	Container demand at port p (TEUs)	
$\boldsymbol{QC}_p^{SEA} \in \mathbb{R}^+ \quad \forall p \in P$	Number of containers to be transported at voyage leg p (TEUs)	

Table 8 (continued)

Auxiliary variable	Auxiliary variable description	Remarks
$\boldsymbol{EP_p^{PORT}} \in \mathbb{R}^+ \quad \forall p \in P$	Amount of emissions produced at port p (tons)	**GVSP** only
$\boldsymbol{EP_p^{SEA}} \in \mathbb{R}^+ \quad \forall p \in P$	Amount of emissions produced at voyage leg p (tons)	**GVSP** only
$\boldsymbol{PHC} \in \mathbb{R}^+$	Total port handling cost (USD)	
$\overline{\boldsymbol{PHC}} \in \mathbb{R}^+$	Total port handling cost for the recovered vessel schedule (USD)	**VSRP** only
$\boldsymbol{LAC} \in \mathbb{R}^+$	Total late vessel arrival cost (USD)	
$\overline{\boldsymbol{LAC}} \in \mathbb{R}^+$	Total late vessel arrival cost for the recovered vessel schedule (USD)	**VSRP** only
$\boldsymbol{FCC} \in \mathbb{R}^+$	Total fuel cost (USD)	
$\overline{\boldsymbol{FCC}} \in \mathbb{R}^+$	Total fuel cost for the recovered vessel schedule (USD)	**VSRP** only
$\boldsymbol{VOC} \in \mathbb{R}^+$	Total vessel operational cost (USD)	
$\overline{\boldsymbol{VOC}} \in \mathbb{R}^+$	Total vessel operational cost for the recovered vessel schedule (USD)	**VSRP** only
$\boldsymbol{CIC} \in \mathbb{R}^+$	Total container inventory cost (USD)	
$\overline{\boldsymbol{CIC}} \in \mathbb{R}^+$	Total container inventory cost for the recovered vessel schedule (USD)	**VSRP** only
$\boldsymbol{EC} \in \mathbb{R}^+$	Total emission cost (USD)	**GVSP** only
$\boldsymbol{REV} \in \mathbb{R}^+$	Total revenue (USD)	
$\overline{\boldsymbol{REV}} \in \mathbb{R}^+$	Total revenue for the recovered vessel schedule (USD)	**VSRP** only
$\boldsymbol{TP} \in \mathbb{R}^+$	Total profit (USD)	
$\overline{\boldsymbol{TP}} \in \mathbb{R}^+$	Total profit for the recovered vessel schedule (USD)	**VSRP** only

UVSP vessel scheduling problem with uncertainties in liner shipping operations, *VSRP* vessel schedule recovery problem, *GVSP* green vessel scheduling problem

Table 9 Description of parameters

Parameter	Parameter description	Remarks
$\tau_p^{st} \in \mathbb{R}^+ \quad \forall p \in P$	TW start at port p (hours)	
$\tau_{pt}^{st} \in \mathbb{R}^+ \quad \forall p \in P, t \in T_p$	Start of TW t at port p (hours)	**CVSP** only
$\tau_p^{end} \in \mathbb{R}^+ \quad \forall p \in P$	TW end at port p (hours)	
$\tau_{pt}^{end} \in \mathbb{R}^+ \quad \forall p \in P, t \in T_p$	End of TW t at port p (hours)	**CVSP** only
$\tau_p^{arr} \in \mathbb{R}^+ \quad \forall p \in P$	Planned vessel arrival time at port p (hours)	**VSRP** only
$ph_p \in \mathbb{R}^+ \quad \forall p \in P$	Negotiated handling productivity at port p (TEUs/hour)	
$ph_{pth} \in \mathbb{R}^+ \quad \forall p \in P, t \in T_p, h \in H_{pt}$	Handling productivity at port p during TW t under handling rate h (TEU/hour)	**CVSP** only
$\phi \in \mathbb{N}$	Port service frequency (days)	
$q^{max} \in \mathbb{N}$	Maximum number of vessels that can be allocated for service of the given liner shipping route (vessels)	
$q \in \mathbb{N}$	Total number of deployed vessels based on the original vessel schedule (vessels)	**VSRP** only
$l_p \in \mathbb{R}^+ \quad \forall p \in P$	Length of voyage leg p (nmi)	
$k_1, k_2, k_3 \in \mathbb{R}^+$	Fuel consumption function coefficients	
$A \in \mathbb{R}^+$	The “lightship weight” component (tons)	
$s^{max} \in \mathbb{R}^+$	Maximum vessel sailing speed (knots)	
$s^{min} \in \mathbb{R}^+$	Minimum vessel sailing speed (knots)	
$s_p \in \mathbb{R}^+$	Planned vessel sailing speed at voyage leg p (knots)	**VSRP** only
$\widetilde{\delta_p^{port}} \in \mathbb{R}^+ \quad \forall p \in P$	Expected duration of a disruptive event at port p (hours)	**VSRP** only
$\widetilde{\delta_p^{sea}} \in \mathbb{R} \quad \forall p \in P$	Expected vessel sailing speed reduction due to a disruptive event at voyage leg p (knots)	**VSRP** only
$y_p^{port} \in \mathbb{B} \quad \forall p \in P$	=1 if a disruption occurred at port p (=0 otherwise)	**VSRP** only
$y_p^{sea} \in \mathbb{B} \quad \forall p \in P$	=1 if a disruption occurred at voyage leg p (=0 otherwise)	**VSRP** only
$EF_p^{PORT} \in \mathbb{R}^+ \quad \forall p \in P$	Emission factor at port p (tons of emissions/TEU)	**GVSP** only
$EF^{SEA} \in \mathbb{R}^+$	Emission factor in sea (tons of emissions/ton of fuel)	**GVSP** only
$c_p^{hand} \in \mathbb{R}^+ \quad \forall p \in P$	Unit handling cost at port p (USD/TEU)	
$c_{pth}^{hand} \in \mathbb{R}^+ \quad \forall p \in P, t \in T_p, h \in H_{pt}$	Unit handling cost at port p during TW t under handling rate h (USD/TEU)	**CVSP** only

Table 9 (continued)

Parameter	Parameter description	Remarks
$c_p^{late} \in \mathbb{R}^+ \quad \forall p \in P$	Unit late vessel arrival cost at port p (USD/hour)	
$c^{fuel} \in \mathbb{R}^+$	Unit fuel cost (USD/ton)	
$c^{oper} \in \mathbb{R}^+$	Unit vessel operational cost (USD/day)	
$c^{inv} \in \mathbb{R}^+$	Unit container inventory cost (USD/TEU/hour)	
$c_p^{rev} \in \mathbb{R}^+ \quad \forall p \in P$	Unit freight rate (USD/TEU)	
$c_p^{skip} \in \mathbb{R}^+ \quad \forall p \in P$	Total cost of skipping port p (USD)	**VSRP** only
$c^{emis} \in \mathbb{R}^+$	Unit emission cost (USD/ton)	**GVSP** only
$TP^0 \in \mathbb{R}^+$	Total profit based on the original vessel schedule (USD)	**VSRP** only

CVSP collaborative vessel scheduling problem, *VSRP* vessel schedule recovery problem, *GVSP* green vessel scheduling problem

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