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Cooperative liner shipping network design by means of a combinatorial auction

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Cooperative liner shipping network design by means of a combinatorial auction

Tobias Buer · Rasmus Haass

Abstract Cooperation in the ocean liner shipping industry has always been important to improve liner shipping networks (LSN's). As tight cooperations like alliances are challenged by antitrust laws, looser forms of cooperation among liner carriers might become a reasonable way to increase efficiency of LSN's. Our goal is to facilitate a loose form of cooperation among liner carriers. Therefore, we introduce a coordination mechanism for designing a collaborative LSN based on a multi round combinatorial auction. Via the auction, carriers exchange *demand triplets*, i.e. orders which describe the transport of containers between ports. A standard network design problem which includes ship scheduling and cargo routing decisions is used as isolated network design problem of an individual carrier. A carrier has to solve this isolated problem repeatedly during the auction so that the carrier is able to decide which demand triplets to sell, on which demand triplets to bid, and what prices to charge. To solve these problems we propose a variable neighborhood search based matheuristic. The matheuristic addresses the isolated planning problem in four phases (construct ship cycles, modify cycles, determine container flow, and reallocate ships to cycles). Our computational experiments on a set of 56 synthetic test instances suggest that the introduced combinatorial auction increases profits on average compared to isolated planning significantly by four percent. The more diverse the original assignment of demand triplets and ships to carriers is, the higher the potential for collaboration; for 18 diverse instances, the profits increase on average by ten percent.

Keywords liner shipping · network design · combinatorial auction · bundle bidding · collaborative planning · variable neighborhood search

1 Introduction

Liner shipping is the backbone of world trade and therefore contributes to raise the standard of living of many people. Liner carriers offer seaborne transport based on

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their shipping networks. A *liner shipping network* (LSN) is similar to a bus schedule: stops are visited in a fixed and a priori known sequence independently of the precise demand at the stops. LSN's of larger carriers consist of multiple routes. A route defines the sequence of ports which are visited by ships of the liner carrier (often in a weekly frequency and with repetitions). Although carriers adjust transport capacity offered on a route constantly, the routes themselves are usually quite stable over multiple months or years. LSN design is therefore a critical tactical decision problem for liner carriers in particular and in general for an efficient and effective world-wide cargo distribution.

Cooperation in the ocean liner shipping industry has always been important to improve LSN's. That is, to increase the efficiency and service level of cargo distribution as well as the competitiveness of the cooperating liner carriers. Cooperations in liner shipping have often been tight. Liner conferences were used by carriers to coordinate their routes and agree on prices. Liner conferences disappeared due to stricter competition laws in the USA and Europe. Since the 1990's, strategic liner alliances have become popular. The number of members in an alliance is small. Members of an alliance agree on the design of global routes (e.g. Asia-Europe) which are jointly serviced by the members' ships. In addition, they jointly organize sales and marketing, and they agree on profit and cost sharing contracts. Alliance agreements are again a tight form of cooperation. From cooperations in an alliance, liner carriers expect economies of scale by a higher utilisation of ships and economies and scope by complementary network routes and shipper orders. However, the unlockable potential of bigger alliance and tighter forms of cooperation is limited for legal reasons. Liner alliances are subject to stricter antitrust laws in the USA, Europe, and China. As an example, the "P3 Network" – an alliance initiative of the three carriers Maersk, Mediterranean Shipping Company, and CMA CGM to form the world's biggest alliance in terms of ships and carrying capacity – has been rejected by China in 2014 for antitrust reasons. This clearly shows restrictions on alliance formation and the need to find alternative ways to improve shipping networks.

As tight cooperations are challenged by antitrust laws, *looser* forms of cooperation among liner carriers seem a reasonable way to increase efficiency of LSN's. In that case, however, traditional *central planning* methods for LSN design will no longer be applicable. Central planning assumes a single decision maker who has complete information and full decision authority. This is justifiable for an alliance: although the liner carriers of an alliance are self-interested and independent companies, they cooperate tightly and share private information which is required to be a member of the alliance. When we consider looser forms of cooperation, competition among liner carriers increases. It is therefore necessary to assume private information: estimated shipper orders, utilization of ships, or costs, for example, are sensitive business data. Privacy has to be preserved as much as possible during joint planning. In such a scenario *collaborative planning* (Stadtler 2009) should be preferred to central planning. Collaborative planning mechanisms are based, e.g. on voting mechanisms (see Buer et al 2013, for a lot-sizing example) or on combinatorial auction mechanisms (see Krajewska and Kopfer 2006, for a vehicle routing example). Combinatorial auctions allow all-or-nothing bundle bids which are useful to express preferences for complementary items. Mechanism which contribute to preserve private information

for cooperative LSN design of liner carriers are rare. Recent survey papers on designing liner shipping networks are provided by Tran and Haasis (2015) and Christiansen et al (2013). Although central planning approaches on network design are sophisticated and numerous, there are little reports about collaborative planning for LSN design.

This is the starting point of the present work. Our goal is to facilitate horizontal cooperation among liner carriers by proposing a coordination mechanism. The idea is to support liner carriers at jointly planning their liner shipping networks. Joint planning is enabled by a combinatorial auction. When a liner carrier is not able to integrate a shipper order in a profitable way into its network, the carrier can sell the order via the auction. The carrier can also try to buy orders from other carriers. Multiple orders are auctioned at the same time; liner carriers bid on self-compiled bundles of orders. Bundle bidding proves beneficial because it allows liner carriers to better account for the manifold interdependent decisions in network design. Computational experiments demonstrate the profit raising potential of the auction.

This article is organized as follows. The literature on cooperative network design in liner shipping is reviewed in Section 2. Section 3 describes the used network design model. To solve this model for the isolated case (i.e., only one liner carrier plans) a matheuristic approach based on variable neighborhood search is introduced in Section 4. Using this method, a liner carrier decides which orders to sell, which orders to buy, and how much to bid. The multi round combinatorial auction protocol to coordinate decisions among liner carriers is proposed and integrated into network design in Section 5. Insights into its profit raising potential are investigated by means of a computational study (cf. Section 6). Section 7 concludes the paper.

2 Literature on cooperative approaches of liner carriers for network design

The liner shipping business as well as the network design problem are explained from an operations research perspective by Brouer et al (2014). Recent surveys on designing liner shipping networks are given by Tran and Haasis (2015) and Christiansen et al (2013). Reports about cooperative approaches of liner carriers for network design are negligible. Now, we first refer to papers that deal with the network design problem from the perspective of an individual liner carrier. Afterwards, we mention papers that deal with or integrate cooperative approaches into liner shipping.

Liner shipping network (LSN) design is a difficult task. Consequently many papers try to improve solution approaches for important sub problems. For example, an optimal single route in a liner network is planned by Gelareh et al (2013). A single route is also studied by Tran et al (2016); here, effects of integrating the route into the design of the hinterland network are examined. The literature discusses approaches for designing multiple routes simultaneously. Multi route models usually do not limit the route structure (like, e.g. hub-and-spoke structures) and they allow for transshipments between routes. One of the early approaches has been proposed by Fagerholt (1999). A comprehensive model for LSN design is introduced by Agarwal and Ergun (2008). They present a model which does not presuppose a specific network structure. Based on a space-time graph they design networks that guarantee a weekly service

frequency. Wang and Meng (2013) focus on the effects of reversing the port call sequence on transshipment, inventory holding, and slot purchasing costs of networks. Reinhardt and Pisinger (2012) simultaneously take into account network design and fleet assignment and solve it via an algorithm based on branch-and-cut. Mulder and Dekker (2014) study a network design problem and integrate it with a fleet design problem of a liner carrier.

Slight forms of cooperation among liner carriers are introduced into the LSN design domain by researchers who solve slot purchasing and empty container repositioning problems. Lei et al (2008), Álvarez (2009) and Wang (2013) integrate the option to purchase slots on ships owned by other liner carriers. This is a first collaborative element in LSN design, because it enables the transport of cargo by competing carriers. However, actual planning is central and assumes symmetric information. Another challenge that is tackled by means of cooperative elements are supply and demand of empty containers. The trade imbalances among regions require the repositioning of empty containers. This is taken into account by Shintani et al (2007) as well as Meng and Wang (2011) for their network design approaches. Advantages of jointly solving this problem by multiple carriers are studied by Sterzik et al (2012). Their focus is on truck-based transport and not on liner shipping, however. Only recently, Zheng et al (2015b) have presented a coordination mechanism to exchange empty containers among liner carriers.

Agarwal and Ergun (2010) address the problem of jointly planning a LSN of multiple liner carriers who cooperate in an alliance. The planning mechanism itself is centralized and assumes complete information. However, the mechanism computes side payments using the core concept from cooperative game theory. As a result it takes the self-interest of the carriers into account and enables the planning of a cooperative network. Zheng et al (2015a) use a similar LSN design model like Agarwal and Ergun (2010). In addition, they consider transshipment costs and the time a ship stays at a port depends on the amount of handled containers. On the other hand, Zheng et al (2015a) limit the route design decisions, because they assume a fixed set of candidate ship routes from which a subset has to be selected. The proposed mechanism allocates capacities from the alliance network to liner carriers which are members of an alliance. Carriers are compensated for sharing capacities. Compensation is calculated by means of a capacity exchange cost model. Both Agarwal and Ergun (2010) and Zheng et al (2015a) enable cooperation among liner carriers based on sharing slot capacities. That is, a liner carrier designs his own network and uses his own ships but reserves slot capacities for competing carriers. Finally, Chun et al (InPress) present a generic approach for exchanging resources in alliances and sharing profits. In the context of liner shipping alliances, it is for example applicable to sharing slot capacities.

To sum up, the majority of the literature studies LSN design problems as optimization problems that are solved by a single decision maker (liner carrier). What is more, in the context of alliances complete information and a central decision maker are assumed. Of course, even for multiple liner carriers this might be quite reasonable because the members of an alliance usually cooperate closely and are therefore willing to exchange sensitive data. Furthermore, coordination of LSN design is usually enabled via capacity sharing; that is, slot purchasing from other liner carriers.

So far, collaborative approaches for LNS design imply a tight cooperation among liner carriers. However, tight cooperations are not always possible or desired. For example, antitrust laws prevent to some extent bigger and bigger alliances. Also, collaborating on the planning level in order to generate more effective LSN's could and should be possible without setting up an alliance and the premise to share private information. For these situations, looser forms of cooperation could be appropriate. Here, loose means, without expensive organisational overhead of forming an alliance. However, if multiple liner carriers want to cooperate on a more loosely basis, they strive to keep their sensitive information private. If a lesser amount of private information has to be disclosed to enable cooperation of multiple liner carriers, the strict requirements for cooperation would be relaxed and cooperation would be easier to establish. The contribution of this paper is a coordination mechanism for collaborative LNS design. The mechanism enables a looser form of collaboration. It is based on the combinatorial auction protocol. In contrast to all approaches of the literature, coordination is not achieved though capacity sharing but through the exchange of shipper orders.

3 Liner shipping network design problems for isolated and collaborative cases

To solve the collaborative service network design problem, each carrier has to be in the position to solve its personal network design problem at first. Section 3.1 takes the perspective of a single liner carrier and introduces the isolated network design problem. Section 3.2 shifts the point of view to the collaborative situation. Multiple liner carriers cooperate to improve their service networks compared to the isolated case. We argue that central planning is often not possible or desired. That is why an alternative coordination mechanism that enables collaborative planning among a coalition of self-interested liner carriers is required.

3.1 Isolated network design problem of a liner carrier

The isolated network design problem (referred to as INDP) of a liner carrier is presented. We decided to base our approach on the *simultaneous ship scheduling and cargo routing problem* (SSSCR) as introduced by Agarwal and Ergun (2008). The SSSCR is a well-established representative model of the INDP. It includes many important real-world characteristics like a weekly service frequency, a heterogenous ship fleet or large degrees of freedom in the structures of the liner services. Therefore, it is a fine candidate for an initial study of our auction protocol. Because our proposed auction protocol depends only on the exchange of requests via bundle bidding many other network design problems – see literature review – could be used just as well.

To describe the SSSCR the notation shown in Table 1 is used. We are given a set Θ of *demand triplets*. A demand triplet $\theta \in \Theta$ is a triple $\theta := (p^o, p^d, w)$ which is characterized by an origin port p^o , a destination port p^d , and a day of the week w when the cargo supply is available at p^o . For each θ , the maximum demand $d(\theta)$ in TEU as well as the revenue per TEU $r(\theta)$ are given. Furthermore, the liner carrier

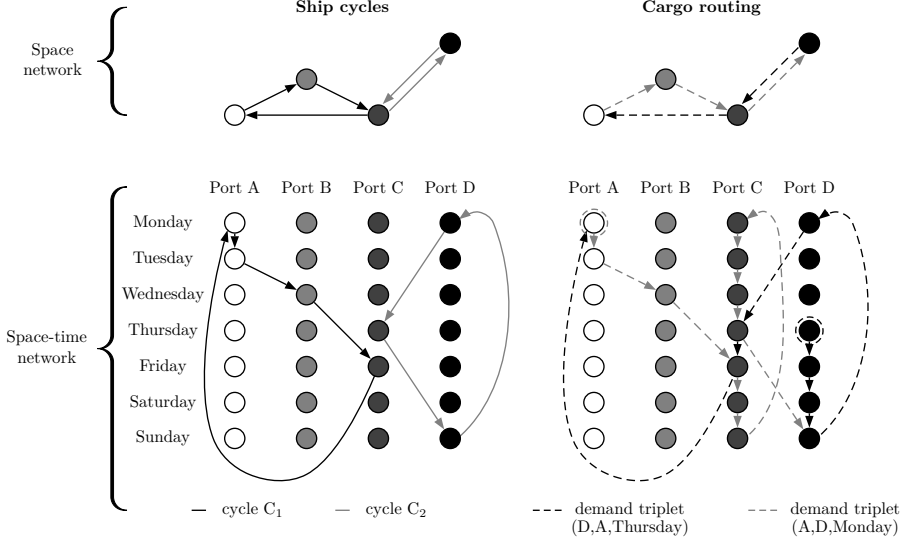


Fig. 1 A liner shipping network with two feasible cycles and the associated flow of cargo.

deploys a heterogenous ship fleet on his network. Let T be the set of ship types. There are \bar{n}_t ships of type $t \in T$; each with a carrying capacity in TEU of c_t . The speed of each ship type differs but is constant during a trip.

The carrier's goal is to design a maximum profit LSN by servicing a *subset* of the demand triplets Θ . To enable a weekly service the ports and the days of the week are represented as a space-time network $G = (V, E)$; see Fig. 1 and the description of Agarwal and Ergun (2008, p. 179). Each node $v \in V$ represents a port p at a day w of the week. The set of edges E is made up of a set of ground edges E_g and a set of voyage edges E_v . E_g and E_v are disjoint. Let $v := (p_i, w_m)$ be the node in V that represents port p_i on day w_m . A *voyage edge* $e \in E_v$ starts in node (p_i, w_m) and ends in node (p_j, w_n) with $p_i \neq p_j$ and $w_m \neq w_n$. The length $l_{e,t}$ of voyage edge $e \in E_v$ is measured in days; it depends on the speed of the used ship type $t \in T$. A voyage edge represents the movement of a ship (or cargo) between different ports. In contrast, a *ground edge* $e \in E_g$ represents an overnight stay of a ship (or cargo) at a port which is why its length is one day (i.e., $l_{e,t} = 1$). Consequently, a ground edge starts in node (p_i, w_m) and ends in node (p_i, w_{m+1}) . Like Agarwal and Ergun (2008), we also used *fictitious edges* to model cargo flows as circulations; they are only required in Section 4.3.

Cost parameters for operating a service network are given. Ship related costs are: for each ship type, the cost of calling a port, the cost for waiting at a port per day, and the costs per day at sea. Cargo related costs are: costs for storing a TEU of cargo at a port and costs for transporting a TEU of cargo on a voyage edge depending on the used ship type.

Table 1 Notation of parameters and decision variables

Demand parameters	
Θ	set of given demand triplets
θ	a demand triplet $\theta \in \Theta$ with $\theta := (p^o, p^d, w)$
$p^o(\theta), p^d(\theta)$	port of origin and port of destination of demand triplet θ
$d(\theta)$	maximum cargo demand (in TEU) of demand triplet θ
$w(\theta)$	day of the week at which $d(\theta)$ arises at $p^o(\theta)$
$r(\theta)$	revenue per TEU of θ
Ship fleet parameters	
T	set of ship types
c_t	capacity in TEU of a ship of type $t \in T$
\bar{n}_t	number of available ships of type t
$n_t(C)$	minimum number of ships of type t to sail cycle C within a weekly frequency
$n_t(\theta)$	minimum number of required ships of type t to service the cargo volume of θ
Space-time network parameters	
V	set of nodes of the space-time network
$v(p, w)$	the node of the space-time network referring to port p at weekday w , $v(p, w) \in V$
$l_{e,t}$	travel time on edge e required by a ship of type $t \in T$
Cycle decisions	
Γ	set of cycles, to be generated by a carrier
C	a cycle $C \in \Gamma$ is a sequence (v_1, \dots, v_n) of adjacent nodes in V without repetitions other than first node and the last node, i.e., $v_1 = v_n$.
$\gamma := (C, n_t)$	a <i>cycle tuple</i> on which cycle C is operated by n_t ships of type $t \in T$; γ is feasible, if $n_t \leq n_t(C)$ and infeasible otherwise
(γ, Δ)	the subset Δ of demand triplets ($\Delta \subseteq \Theta$) that is serviced using γ

Based on this space-time network, the carrier's task in the SSSCR is to construct a set of cycles Γ and determine the flow of cargo from all origin ports to all destination ports which maximizes the carrier's profit and satisfies the following constraints:

- A cycle $C \in \Gamma$ is a sequence of adjacent nodes in the space-time network that starts and ends at the same node.
- Each cycle $C \in \Gamma$ is assigned a number of ships n_t of type $t \in T$; this cycle-tuple (C, n_t) has to enable a weekly frequency of port calls. Cycles are serviced by a single ship type only.
- The number of ships assigned to cycles may not exceed the number of available ships \bar{n}_t (per type $t \in T$, respectively).
- The flow of cargo between an origin port and a destination port may use multiple cycles. However, transshipment between cycles is considered free of charge.

All in all, a carrier maximizes its profit by computing weekly cycles, assigning ships to cycles and searching for feasible flows of cargo from origin to destination ports using one or more cycles. The isolated network design problem was solved via variable neighborhood search, see Section 4. Before we describe this approach, we first introduce the collaborative network design problem in the next section.

3.2 Collaborative network design problem of a coalition of liner carriers

The point of view is switched from the isolated planning problem to the collaborative network planning problem (CNPD). Multiple liner carriers form a coalition. They cooperate in order to improve their isolated networks, i.e., plan a network that generates a higher profit. A nearby solution approach would be *central planning*. Central planning means, that the coalition of carriers plans like a single entity. The carriers of the coalition reveal all data required for planning, i.e., all parameters of the SSSCR described in Section 3.1. A central planner solves the SSSCR, but the solved instance is bigger. Central planning also requires that the carriers of the coalition subordinate their decision authority to the decisions of the central planner.

Central planning is however often not possible or desired. Often the planning situation is *collaborative*. The carriers are economical and legally independent of each other. They are self-interested and want to maximize their personal profit, not the profit of the coalition. Although the carriers are willing to cooperate, they compete with each other. Competition might affect only some business activities, e.g. certain customers, freight, or geographical regions. It is therefore almost always possible to cooperate. However, because they compete to a certain degree with each other, they do not want to reveal private information. Private information could be, e.g. costs, free shipping capacities, or shipper/customer orders.

Coordination of the planning might occur on different levels. One approach could be the sharing of capacities. A carrier books capacities on the ship of another carrier and uses this capacity for transporting its freight. Another approach might be the exchange of orders (i.e. demand triplets) among carriers. A carrier plans its network assuming to fulfill the demand triplets of its customers as well as demand triplets of foreign customers. Anyway, economies of scope play an important role for the design of service networks and have to be considered by a collaborative planning mechanism.

Finally, through collaboration a surplus is expected. That is, the sum of the carriers' profits with collaborative planning is higher than the sum of the carriers' profits without collaborative planning. How to distribute this surplus among the carriers is not studied in this paper. We limit ourselves to the task to generate a surplus under the given requirements. After all, if a surplus is possible, cooperating in a coalition is reasonable. The surplus might be divided equally among the carriers. More sophisticated approaches might use methods from cooperative game theory to distribute the surplus.

We present in Section 5 a combinatorial auction protocol to solve the collaborative network design problem (CNDP) of a coalition of carriers. This coordination mechanism enables cooperation through the exchange of demand triplets, considers economies of scope through bundle bidding, and uses private information sparingly. Basically, it enables a loose form of cooperation among carriers as it only requires the exchange of information about selected subsets of demand triplets. However, before we can solve the collaborative case we present a solution approach for the isolated case in the next section.

4 A variable neighborhood search for the isolated network design problem

The SSSCR was solved by a heuristic based on variable neighborhood search (Hansen et al 2008). VNS was used, because this metaheuristic tries to escape from local optima by using different neighborhoods. With different neighborhoods, it should be easier to solve different subproblems in the SSSCR. Subproblems of the SSSCR are sequencing, selection, assignment, and flow decisions which are nontrivial problems on their own. This decomposition of the SSSCR into subproblems is also used by Agarwal and Ergun (2008). They propose three solution approaches, which are based on a greedy heuristic, column generation, and Benders decomposition. Examples for using VNS in the context of LSN optimization are Gelareh et al (2013) or Malliappi et al (2011) who use VNS for tramp ship scheduling.

4.1 Construction heuristic

Usually, multiple cycles are used to service cargo of multiple demand triplets. The main idea of the construction heuristic is to generate an initial feasible solution at which one cycle C services only one demand triplet (i.e. (C, Δ) with $\Delta \subseteq \Theta$ and $|\Delta| = 1$). Such a cycle is referred to as *single-triplet cycle*. For each demand triplet $\theta \in \Theta$, the heuristic constructs a cycle C that includes $p^o(\theta)$ and $p^d(\theta)$. Next, a number $n_t(C)$ of ships of type $t \in T$ is calculated for cycle C such that the weekly frequency of C is guaranteed and the idle capacity of the ships is small. The heuristic terminates once each demand triplet has been considered.

The most important construction steps are characterized in more detail. Consider the demand triplets $\theta \in \Theta$ in random order and perform the following steps:

Step 1 Determine a ship type $t \in T$ for θ by considering idle capacity.

$$t \leftarrow \arg_{t \in T} \min\{d(\theta) \bmod c_t\} \quad (1)$$

Assuming a sufficient number of ships is available, the cargo volume $d(\theta)$ is modulo divided by the ship capacity c_t to determine the idle capacity when ships of type t are used to service θ .

Step 2 Due to capacity reasons, the transport of cargo by a ship type t requires at least $n_t(\theta) := \lceil \frac{d(\theta)}{c_t} \rceil$ ships. If there are enough ships (i.e., $n_t(\theta) \leq \bar{n}_t$), then go to Step 3. Otherwise, go to Step 1 but do no longer consider t as an available ship type for θ .

Step 3 Generate a cycle C for θ that starts in node $v(p^o(\theta), w(\theta))$. Sail immediately to port $p^d(\theta)$ and return to port $p^o(\theta)$.

Let $E(C)$ denote the set of edges of cycle C . The number $n_t(C)$ of required ships on cycle C that ensures a weekly frequency is

$$n_t(C) := \left\lceil \frac{\sum_{e \in E(C)} l_{e,t}}{7} \right\rceil. \quad (2)$$

If enough ships are available (i.e., $n_t(C) \leq \bar{n}_t$), then n_t ships are assigned to C with $n_t := \max\{n_t(C), n_t(\theta)\}$. The number of ships left for planning are

reduced $\bar{n}_t := \bar{n}_t - n_t$. Otherwise and if there are non-examined ship types left, got to Step 1. Terminate, if all ship types have been examined.

The generated single-triplet cycles with the assigned ships are an initial feasible solution of the SSSCR. Because the number of ships is limited, some demand triplets may be left unassigned to a cycle.

4.2 Modify cycles via neighborhood search

The set of cycles Γ is modified via one of five neighborhood moves, in the following order:

1. *Remove cycle*: Deletes a cycle C from Γ . This increases the number of available ships which may be assigned to other cycles.
2. *Insert port*: Determines a most valuable destination port and inserts it into a matching cycle. First, the destination port p^d which is shared by the majority of those demand triplets that are *not yet* fulfilled is selected. From the unfulfilled demand triplets with p^d as destination the most frequent origin port p^o is chosen. Second, a cycle $C \in \Gamma$ is selected that contains p^o but not p^d . The move tries to insert p^d into C .
3. *Random removal of a port*: Selects a cycle randomly and randomly deletes a port from this cycle.
4. *Swap ports*: Selects a cycle randomly and interchanges the position of two ports in the cycle.
5. *Postpone departure*: Randomly selects a $C \in \Gamma$ and chooses the voyage edge e in C with the lowest capacity utilization. At the origin port of e , the berthing time of a ship is increased by an additional day and the remaining voyage is postponed accordingly.

Minor modifications with respect to the position of a port (which is represented by seven nodes) in a cycle may alter the used voyage edges in this cycle significantly. If a move violates the weekly frequency of a cycle, a repair heuristic tries to reassign ships to cycles in order to re-establish the weekly frequency.

The repair heuristic modifies an infeasible cycle-tuple $\gamma^{\text{inf}} = (C, n_t)$. If a weekly frequency is not possible, a cycle-tuple is characterized as infeasible. In case the number of available ships of type t is large enough, n_t is increased sufficiently to enable a weekly frequency on C . The repair heuristic terminates. Otherwise, a ship reassignment procedure starts: Let $\Gamma(t)$ be the set of cycles that use ship type t , $t \in T$. For each cycle-tuple (C, n_t) with $C \in \Gamma(t)$, the number of *excess* ships is calculated. That is, the number of ships that can be removed from (C, n_t) without violating its weekly frequency. Subsequently, all cycles are ranked according to their importance to the network. Importance is defined as revenue contribution. Revenue is generated by cargo flows which may use multiple cycles. Vice versa, a single cycle enables different cargo flows. Hence, measuring actual revenue contribution of a cycle to a network is difficult. We use $\rho(C)$ as defined in (3) to measure the importance of a cycle C . Let $m(C)$ denote the maximum number of containers shipped on an edge in C . Let $\Delta(C) \subseteq \Theta$ denote the set of demand triplets which are serviced using cycle C .

Let $\Gamma(\theta) \subseteq \Gamma$ denote the set of cycles that enables the cargo flow of demand triplet θ . $\rho(C)$ is defined as:

$$\rho(C) := m(C) \cdot \sum_{\theta \in \Delta(C)} \frac{r(\theta)}{d(\theta)} \cdot \frac{1}{|\Gamma(\theta)|}. \quad (3)$$

All cycles $C \in \Gamma$ are ranked by $\rho(C)$. The excess ships of the cycle with minimum $\rho(C)$ are reassigned to γ^{inf} . If a weekly service at γ^{inf} is still impossible, the excess ships of the cycle with the second lowest rating are reassigned to γ^{inf} and so on. If it is not possible to regain feasibility by following this procedure, the neighborhood move that lead to infeasibility of γ^{inf} is cancelled.

4.3 Determine cargo flow

By means of the construction heuristic and the cycle generation procedures a shipping network emerges. The shipping network is made up of the a set of cycles Γ and the set of ground edges E_g which allow waiting at a port. The capacity of the shipping network is given by the ship type and the number ships assigned to a cycle $C \in \Gamma$, respectively. In fact, a set of demand triplets $\Delta \subseteq \Theta$ has been selected during the construction process. However, Δ was just used a kind of proxy information for the heuristics so that the potential cycles are limited and suitable. From this follows, that we have to decide on two things: Which cargo available in Θ should we service? How should we actually route the cargo through this shipping network? In answering these questions, the well-known multi commodity network flow problem played an essential role.

Conversion into multi commodity flow network. The shipping network $G = (V, E)$ is defined by the ground edges E_g and the set of cycles Γ generated previously. We convert G into a multi commodity flow (MCF) network denoted as $G^M = (V^M, E^M)$. An edge $(i, j) \in E^M$ is weighted by costs c_{ij} and an upper flow bound u_{ij} . The cargo of a demand triplet $\theta \in \Theta$ represents a commodity. The conversion works in the following way:

- For each node $i \in V$ there is corresponding node $i \in V^M$ in the MCF network. Each ground edge in E_g and each edge used by a cycle in Γ are represented by a corresponding MCF network edge in E^M . The upper flow bound u_{ij} is set to the transport capacity of the ship type used on edge $(i, j) \in E^M$. All costs are modelled as costs on edges c_{ij} . Node related costs like calling a port are considered on additional (artificial) edges (see also Agarwal and Ergun 2008, p. 180). Costs on voyage edges are given by the used ship type and the length of the edge.
- If a node $i \in V$ is part of $n \geq 2$ cycles, then $n - 1$ transition nodes and $2n - 2$ transition edges are added to V^M and to E^M , respectively. For example: Let $C_1, C_2 \in \Gamma$ be two cycles with edge (i_1, j) in C_1 and edge (i_2, j) in C_2 . An additional transition node j' is introduced. One of the original edges remains, say (i_1, j) and two transition edges (i_2, j') and (j', j) replace (i_2, j) in E^M . The costs of the transition edges are $c_{i_2, j'} := c_{i_2, j}$ and $c_{j', j} := 0$. The upper flow bounds are $u_{i_2, j'} := u_{i_2, j}$ and $u_{j', j} := \infty$.

- For each demand triplet θ (i.e., a commodity) a source node i is introduced to V^M . The supply of i is set to $d(\theta)$. A *source edge* (i, v) links the source node i to the node v which represents the origin port of θ at day $w(\theta)$. The cost of the source edge is set to $c_{i,v} := -r(\theta)/d(\theta)$. This represents the negative revenue per TEU of demand of θ . The upper flow bounds are set to the maximum demand of θ , i.e., $u_{i,v} := d(\theta)$.
- For each $v \in V$ a sink node is introduced to V^M . The demand of i is set to $-d(\theta)$. A *sink edge* (v, j) links the original node v to a sink node j with $c_{v,j} := 0$ and $u_{v,j} := \infty$.
- The flow balance constraint is relaxed compared to the classical MCF problem: the demand of a sink node must not be exceeded and therefore it is not necessary to satisfy the demand of a source node.

Solving a MCF problem on G^M we obtain the profit maximal cargo flows given the shipping network G . Due to the definition of costs on the source edges in G^M we minimize the total flow costs of the MCF and obtain a flow network which is profit maximal. This includes the decision which demand triplets and which quantity of cargo to service. The size of the MCF networks allowed solving the instances by means of the mixed integer programming (MIP) solver CPLEX 12 from IBM. This basic idea to determine the cargo flows, which has been used before in a comparable way by Agarwal and Ergun (2008) may be improved by a demand triplet aggregation procedure that is described next.

Demand aggregation and separation. Instead of considering each demand triplet $\theta \in \Theta$ as a unique commodity, we now consider those demand triplets with the same destination ports as one commodity. In doing so, we are able to reduce the number of commodities and as a result the required computational effort.

Let $P(\Theta)$ denote a partition of the set of demand triplets Θ . This partition is defined such that all demand triplets in an element of $P(\Theta)$ have the same destination port. That is, $\theta^1(p^d) = \theta^2(p^d)$ for all $\theta^1, \theta^2 \in \Theta_k$ with $\Theta_k \in P(\Theta)$ and $\theta^1(p^d) \neq \theta^2(p^d)$ for $\theta^1 \in \Theta_k$ and $\theta^2 \in \Theta_l$ with $\Theta_k, \Theta_l \in P(\Theta)$ and $\Theta_k \neq \Theta_l$. Now, the shipping network conversion to a MCF network is done based on $\Theta_k \in P(\Theta)$ instead of $\theta \in \Theta$ which may reduce the number of commodities significantly.

To reverse the process a separation procedure is required. Commodity flow is converted into demand triplet flow. In G^M , for each demand triplet a path from its source node to its sink node is identified. The path and the cargo flow as given by the source edge are assigned to θ . This is repeated until all commodity flows are assigned to demand triplets.

4.4 Reallocation of ships to cycles

The allocation of a number of ships (of the same type) to the computed cycles is to be improved by a reallocation procedure, see Algorithm 1. The procedure selects cycles which are used to full capacity and increases the capacity by temporarily assigning another ship to these cycles. A cycle is used to full capacity, when the container flow on at least one edge exhausts the transport capacity of the used ship type.

Under these requirements, integer programming is used to solve a *ship-to-cycle allocation problem* (SCA). The task of the SCA is to decide, which cycle $C \in \Gamma$ should be assigned to which ship type $t \in T$ and to which number of ships n_t . The SCA seeks the assignment with maximum profit. Again, the revenue contribution of a cycle was estimated by the substitute measure $\rho(C)$, see (3). The objective function of the SCA is:

$$\max \sum_{t \in T} \sum_{C \in \Gamma} \rho(C) \cdot c_t \cdot x_{t,C} - c_{t,C} \cdot n_t(C) \cdot x_{t,C} \quad (4)$$

The decision variable is $x_{t,C} \in \mathbb{N}$. It is used as coefficient in the product $n_t(C) \cdot x_{t,C}$ which indicates how many ships of type $t \in T$ are used to service cycle $c \in C$. Herein, at least $n_t(C)$ ships of type t are required to offer a weekly service on cycle C , see (2). The other parameters are: $\rho(C)$ is a proxy measure for the revenue per TEU contributed by cycle C , see (3). The transport capacity in TEU of ship type t is given by c_t . Let $c_{t,C}$ be the total cost of one ship of type $t \in T$ servicing cycle $C \in \Gamma$.

An allocation of ships to cycles is feasible, if the following conditions hold:

- At most one ship type is assigned to each cycle.
- The number of ships of type t allocated to all cycles is less or equal to the total number of available ships of type t .
- If ship type t is assigned to cycle C , make sure that an integer multiple of $n_t(C)$ ships are assigned to C .
- For each cycle $C \in \Gamma$ and ship type $t \in T$: Ensure that the transport capacity (i.e., $c_t \cdot x_{t,C}$) allocated to C does not exceed the maximum number of containers $m(C)$ on any edge in cycle C .

The SCA is integrated into a *ship reallocation procedure*, see Algorithm 1. Herein, the SCA is repeatedly solved via integer programming. After a number of ships is assigned to each cycle the unused cycles are removed from the solution. On the emerging network, the optimal container flow is calculate via the procedure presented in Section 4.3. If the cargo flow based on the new ship allocation leads to a superior solution of the SSSCR, the capacity of bottleneck edges is again increased and the steps are repeated. Otherwise, the reallocation phase terminates.

A final remark on the presented VNS: The evaluation of most moves is computationally costly. In addition to a first fit acceptance strategy, the maximum number of iterations of the three main loops in the VNS is therefore restricted.

5 A combinatorial auction for the collaborative service network design problem

The matheuristic solution approach introduced in the previous section allows a liner carrier to solve its isolated network design problem. In order to improve the efficiency of networks further on, another approach is making use of the resources of other liner carriers. In such a collaborative scenario liner carriers remain independent and self-interested companies. There are no tight and binding agreements like in an alliance. It is fair to assume the carriers are open-minded towards collaborating and make some concessions. Nevertheless, collaborating is a means to an end and as a result each

Algorithm 1: Ship Reallocation Procedure

```

Input : problem instance, bestSolution
repeat
  forall  $C \in \Gamma$  with  $m_C = t_C$  do
     $m_C := m_C + c_t$ 
    newSolution  $\leftarrow$  solveShipToCycleAllocationProblem
    delete cycles from newSolution which are unassigned to a ship type
    newSolution  $\leftarrow$  solveMultiCommodityFlow(newSolution)
    if  $f(\text{newSolution}) > f(\text{bestSolution})$  then
      bestSolution  $\leftarrow$  newSolution
      improvement  $\leftarrow$  true
    else improvement  $\leftarrow$  false
until improvement = true
Output: bestSolution

```

carrier hopes for additional profits. In operational research terms, a carrier wants to optimize its own or *local* objective function and not the *global* objective function of the coalition. In line with this, carriers aim to protect their private information. Although they collaborate, they usually do not intend to share information about, e.g., customers, sales, costs, or utilisation of capacity because they fear disadvantages in the future from disclosing this information. In operational research terms, most of the parameters and constraints of a model like the SSSCR are private information which should remain – as far as possible – private. Due to asymmetric information and local objective functions, it is not feasible to simply solve the SSSCR using the aggregated local planning data of all collaborating carriers. This conclusion is based on and supported by Stadler (2009). That is, in the scenario at hand central planning is unreal and a method for collaborative planning is required. A way to enable collaborative planning among self-interested liner carriers are auctions.

For solving the collaborative network design problem we propose a multi round combinatorial auction protocol. The auctioneer may be a neutral party like a broker or a piece of software which works transparent (i.e. open source) for the involved parties. Each carrier acts as a bidder. In a combinatorial auction, multiple items are auctioned at the same time. A combinatorial auction supports bundle bidding (de Vries and Vohra 2003). A bundle bid is a bid on any subset of the tendered items. A bundle bid is an all-or-nothing bid, i.e. a carrier either is awarded all items in its bundle bid or none at all. Bundle bidding avoids the exposure problem (Pekeč and Rothkopf 2003). The exposure problem is present, when a bidder bids rational but pays more for a set of items than the value of the items. For example, when a bidder bids on a set of items assuming strong synergies among them but is awarded a subset of these items that offers less synergies, the bidder might have overpaid. The bid price is higher than the bid value. The exposure problem may arise when there are economies of scope between the items and the items are auctioned (more or less) independently of one another, e.g. in a simultaneous multi-item auction or one by one in sequential single-item auctions. As strong interdependencies among the demand triplets exist that affect network configuration and local costs of the carriers, the collaborative planning

mechanism is enabled by a combinatorial auction where the carriers bid on bundles of demand triplets.

The proposed auction protocol is a multi round combinatorial auction. The interface between the auctioneer and the bidders (i.e. the liner carriers) is defined by the activities of the auctioneer. In particular, the ones which define information exchange via bundle bids. In order to participate in the auction, the carriers have to reveal those demand triplets that they want to sale and a bid price for a set of required demand triplets. Additional data, like the configuration of the network, the fleet, or the demand triplets integrated into their network may remain private. For the carriers' sales and bidding decisions methods are implemented which are equal for each carrier. Of course, each real-world carrier would be free to use its own models and methods for sales and bidding decisions, as long as they are compatible with the interface which relies on bundle bidding.

The coordination mechanism includes six steps, an overview is given by Figure 2. The left side shows the activities of each liner carrier, while the right side shows the activities of the auctioneer. To begin with, each liner carrier $l \in L$ decides which demand triplets to offer for sale. The auctioneer joins these in Step 2 and tenders them in Step 3. Carriers bid on a subset of the tendered demand triplets (Step 4). In Step 5 the auctioneer solves a winner determination problem in order to select the winning bids. By this reallocation of demand triplets to liner carriers the first round of the auction is complete and another one starts. We now give more details on the specific decisions.

Carrier's sales decision (Step 1). The decision which demand triplets a carrier l should offer for sale is l 's private matter. Each carrier $l \in L$ is free to decide individually. Here, this decision is implemented in the same way for all carriers as follows: Liner carrier l first maximizes its profits by solving the SSSCR considering its given set of demand triplets Θ_l . Those demand triplets that are not serviced in l 's profit-maximal network are offered for sale by carrier l ; this set of demand triplets is denoted as $\Theta_l^s, \Theta_l^s \subseteq \Theta_l$.

Auctioneer's announces tendering (Step 2 and Step 3). Each carrier $l \in L$ announces its demand triplets offered for sale Θ_l^s to the auctioneer. At this point, this information is no longer private and becomes public. The auctioneer joins the demand triplets, i.e. $\Theta_M := \bigcup_{l \in L} \Theta_l^s$ (Step 2). Θ_M is denoted as the set of *market demand triplets*. In Step 3, the auctioneer tenders Θ_M .

Carrier's bid decision (Step 4). The main feature of a combinatorial auction is the use of bundle bidding in order to account for synergies among items. A bundle bid is an all-or-nothing bid on a *subset* of the tendered demand triplets. Here, a bundle bid b consists of three elements: a bid price $p(b) \in \mathbb{N}$, the bidder $l(b) \in L$ which is a liner carrier, and a set of desired demand triplets $\Theta(b) \subseteq \Theta_M$. That means: If carrier $l(b)$ wins bid b then the carrier is willing to pay the price $p(b)$ for servicing the demand triplets of $\Theta(b)$. The set of all bundle bids is referred to as B .

Deciding on which subset of demand triplets to bid is computationally challenging, because it involves solving the SSSCR. In the proposed auction protocol, each

carrier $l \in L$ is allowed to submit a single bundle bid only. We keep things straight and implement the bid decision in the same way for all carriers: The first round of the auction is round $i = 1$. We distinguish two sets of demand triplets. The set of demand triplets carrier l wants to keep $\Theta_l^{k,i}$ and the set of market demand triplets Θ_M^i . The initial values before the start of the round $i = 1$ are $\Theta_l^{k,0} := \Theta_l$ and $\Theta_M^0 := \emptyset$. In order to decide how to bid, a carrier solves the SSSCR by means of the matheuristic of Section 4 for the set of demand triplets $\Theta_M^i \cup \Theta_l^{k,i}$ which are the market demand triplets of the current round and the set of demand triplets the carrier decided to keep in the current round. Note, the set of demand triplets includes the set of demand triplets the carrier wanted to sell $\Theta_l^{s,i-1}$ in the previous round.

After solving the SSSCR for $\Theta_M^i \cup \Theta_l^{k,i}$, the bid price and the desired demand triplets are extracted from the updated shipping network. The carrier bids on the set of demand triplets $\Theta(b)$ that have been added to the network in round i compared to the network in round $i - 1$. As bid price the *marginal profit* is used, i.e., the profit generated by the network in round i minus the profit of the network in round $i - 1$. The profit of a bidder in round i is always greater or equal to the profit in round $i - 1$.

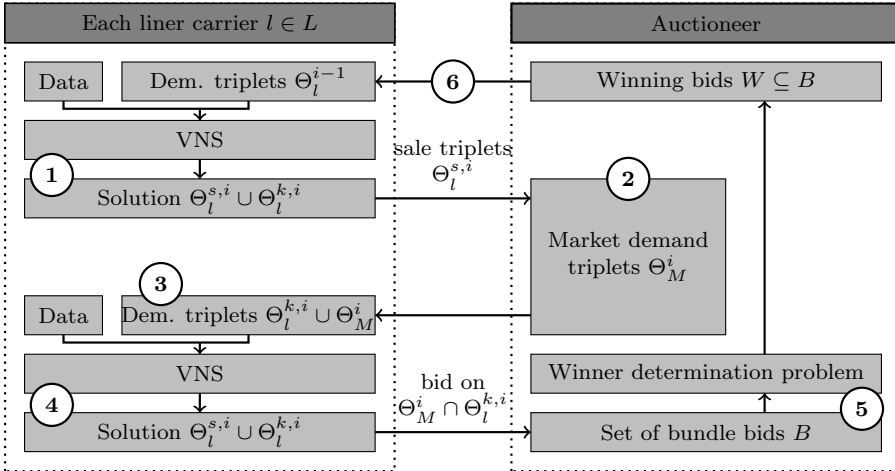


Fig. 2 Coordination procedure for demand triplet exchange via a combinatorial auction

Auctioneer's winner determination decision (Step 5). In Step 5 the auctioneer allocates the demand triplets to the liner carriers. Deciding which bids are awarded is easy for most single-item auction protocols. However, for combinatorial auctions this problem is difficult because the bundle bids overlap with respect to the included items which leads to interdependencies among the bids. In the context of a combinatorial auction, the problem of selecting the winning bids is known as the winner determination problem (WDP). It is often modeled based on a set covering, set partitioning or a set packing problem (de Vries and Vohra 2003). While single-objective models usually minimize total costs or maximize total revenues are customary, there are

multi objective WDP which incorporate, e.g. qualitative decision criteria (Buer and Pankratz 2010). Here, the WDP is formulated as the well-known NP-hard set packing problem, see formula (5) and (6). The task of the WDP is to select a set $W, W \subseteq B$, of winning bids with maximum revenue such that each of the tendered demand triplets in Θ_M is part of *at most* one winning bid $b, b \in W$. Parameter $a_{\theta,b} = 1$ provided that demand triplet $\theta \in \Theta$ is part of bundle bid $b \in B$, otherwise $a_{\theta,b} = 0$:

$$\max \sum_{b \in W} p(b) \quad (5)$$

$$s.t. \sum_{b \in W} a_{\theta,b} \leq 1 \quad \forall \theta \in \Theta \quad (6)$$

As each liner carrier submits at most one bundle bid, the number of bundle bids is usually small. That is why the WDP can be solved quickly with a MIP-solver.

Finally, in Step 6 the demand triplets $\Theta(b), b \in W$, are assigned to their winning liner carriers. The next round $i + 1$ of the auction starts. At the beginning of round $i + 1$ the set of demand triplets of carrier l is composed by: l 's initial set of demand triplets at the beginning of the previous round i *plus* the won demand triplets in round i *minus* the sold demand triplets in round i . Note, due to the formulation of the WDP it is possible that some of the demand triplets offered for sale in Θ_l^s are not sold. These unsold demand triplets are available again to l in round $i + 1$.

Profit sharing. The total profit achieved through collaboration is the profit of the WDP as given in (5) added up over all rounds. A profit sharing scheme is not implemented in this auction protocol. However, there are straight forward schemes like distributing the total profit gained through collaboration equally to all members of the coalition.

Stopping rule of the multi round auction. The auction process of Step 1 to Step 6 continues until there are no more profitable exchanges of demand triplets. The auction terminates once (a) no demand triplets are offered for sale or (b) the bid decision of all carriers is negative, i.e. no carrier is able to increase its profits by integrating market demand triplets.

6 Computational evaluation of the combinatorial auction

We perform a computational study based on synthetic instances of the collaborative network design problem. The goal is to demonstrate the working of the auction mechanism and study the potential of increasing profits through collaborative network design. The generation the test instances is described in Section 6.1. The results are presented and discussed in Section 6.2.

6.1 Generation of test instances

A set of 54 synthetic instances of the collaborative SSSCR has been randomly generated. They differ with respect to parameters related to ports, demand triplets, ship

fleet and initial distribution of demand triplets to liner carriers. Table 2 shows the chosen parameter values and value ranges, respectively. In case of a value range, an uniformly distributed number is drawn from the range. The parameter values are inspired by real world data presented in Stopford (2008, p. 540). We like to mention the comprehensive suite of the instances introduced by Brouer et al (2014). Although we did not use them, they contain valuable data and other modelling approaches in particular interesting for isolated liner shipping network design.

Table 2 Parameter values of test instances for ports, demand triplets, and ships.

Port parameters	Values or value range [min;max]					
Number of ports	5, 10					
Distance between two ports (in units)	[1;10]					
Daily costs for storing a TEU at a port	13.5					
Demand parameters	Values or value range [min;max]					
No. of demand triplets $ \Theta $	10, 50, 100					
No. of containers per demand triplet	[3,000;9000]					
Costs for shipping a TEU per day	1					
Profit per container	[50;150]					
Ship parameters per ship type	1	2	3	4	5	6
Cargo capacity in TEU	1,200	2,600	4,300	6,500	8,500	11,000
Travel time in days per distance unit	1	0.95	0.90	0.90	0.85	0.85
Daily costs for a ship at sea	12,690	23,700	44,160	64,110	69,000	72,000
Daily costs of a ship berthing at a port	11,000	14,500	17,500	21,500	30,000	32,500
Minimum costs for a ship calling a port	16,500	21,750	26,250	32,250	45,000	48,750
Maximum costs for a ship calling a port	27,500	36,250	43,750	53,750	75,000	81,250
Total number of ships	30, 60, 90					

Table 2 shows the parameters required for isolated planning, i.e., a single liner carrier solves its SSSCR. Now, it is assumed the ships and the demand triplets of Table 2 are distributed to *three* liner carriers. Three cooperative scenarios are defined. They differ in the way the ships and demand triplets are allocated to the three liner carriers.

- In the *balanced scenario*, each liner carriers owns (approximately) a third of the number of ships and a third of the demand triplets. Thus, the market positioning of the liner carriers is similar.
- In the *proportional scenario*, the fraction of ships and the fraction of demand triplets assigned to a liner carrier is identical but differs between liner carriers. For example, the first carrier is assigned ten percent of the ships as well as ten percent of the demand triplets (second carrier 30 percent, third carrier 60 percent). The carriers have different market shares, but the available demand triplets roughly match the available transport capacity.

- In the *unbalanced scenario*, the available transport capacity (measured in ships) of a liner carrier does not fit the available demand triplets. It is either too large or too small so that these carriers should clearly benefit from cooperation.

By means of these three allocation scenarios we like to study effects when liner carriers of different company size or equipment configuration collaborate.

6.2 Results and discussion

Tight forms of cooperation among liner carriers are challenged by anti trust laws. A looser form of cooperation may well be a way forward. Not only for big alliances but also for smaller liner carriers. However, there is little research on collaborative planning in the liner industry. To enable a looser form of cooperation during network design, we introduced a collaborative planning mechanism based on a combinatorial auction. The auction is characterized by bundle bidding; private information of liner carriers is only revealed sparsely. We study potential benefits of collaborating in general and using the auction protocol in particular by computational experiments. Generally speaking, the results show that collaboration of liner carriers offers a significant potential to increase profits. While the potential for similar carriers is rather small (approximately 2 percent), the potential to increase profits through collaborative planning is much higher for unequal carriers (approximately 10 percent).

The auction mechanism and the VNS matheuristic have been implemented in Java 7. The multi commodity flow problem as a subproblem of the SSSCR, the ship-to-cycle allocation problem, as well as the WDP were solved to optimality by the commercial MIP-solver CPLEX 12.5. The computational tests have been performed on a personal computer with an Intel Core i7-3770 CPU with 3.4 GHz and 16 GB of working memory. Multiple test instances were solved in parallel on the computer.

The results are detailed in Table 3. The 54 test instances are divided into six groups: On the one hand, they are grouped by the number of ports, i.e. instances with five ports (indicated by “P05”) and instances with ten ports (“P10”). On the other hand, the balanced (“b”), proportional (“p”), and unbalanced scenarios (“u”) are distinguished. Each group consists of 9 test instances. The presented results in Table 3 are averaged over all instances of a group. Results are reported for a central and a decentralized setting. The central setting is used to get some reference value. Central means that a given instance was solved under the assumption that a single liner carrier owns all resources and knows all planning data of the instance. In the *central case*, instances were solved using the construction heuristic only (column C, see Section 4.1) or the complete VNS matheuristic (column VNS). As expected, the central planning VNS provided the best results because it did not have to deal with private information and multiple decision makers. The averaged profit obtained through central planning via VNS was defined as 100 percent in Table 3; results of all other approaches are given proportionally. In the *decentral case* three liner carriers design their networks. Column C and Column VNS report results where each carrier solves its isolated network design problem. There is no exchange of resources; the isolated profits of the three carriers are only added up. Results for the collaborative mechanism are given in the column “VNS+Auction”. Finally, the rightmost column

states for how many instances an exchange of demand triplets actually occurred. For example, the number 66.6 in line P05u states that the three liner carriers achieve on average 66.6 percent of the profit that a hypothetical liner carrier who owns all ships and all demand triplets generates; however, through auction-based exchange of demand triplets the profit may be increased by about ten percent (or 5.8 points) compared to isolated planning of the three carriers which achieves only 60.8 percent of the central profits. Naturally, all statements are only valid for the used solution approaches and the used test instances.

Table 3 Aggregated results for six sets of test instances

Set of instances	Central		Decentral			Successful exchanges
	C	VNS	C	VNS	VNS+Auction	
P05b	77.2	100.0	65.0	79.8	81.5	3 of 9
P10b	85.8	100.0	64.3	80.3	82.2	4 of 9
P05p	69.9	100.0	59.7	76.9	77.8	1 of 9
P10p	83.5	100.0	65.8	77.0	78.1	3 of 9
P05u	83.3	100.0	52.2	60.8	66.6	5 of 9
P10u	84.6	100.0	50.7	63.3	69.4	3 of 9
balanced (P05b, P10b)	81.5	100.0	64.7	80.1	81.8	7 of 18
proportional (P05p, P10p)	76.7	100.0	62.8	76.9	77.9	4 of 18
unbalanced (P05u, P10u)	84.0	100.0	51.4	62.1	68.0	8 of 18
total	80.7	100.0	59.6	73.0	75.9	19 of 54

First, we compare the VNS matheuristic to the construction heuristic. VNS generates solutions whose profits are approximately 23 percent higher than those of the construction heuristic, both for the central and for the decentralized setting. Looking at the solutions, VNS generates networks with a lower number of cycles which are characterized by a higher cycle length and more ports compared to the solutions generated by the construction heuristic.

Second, collaborative planning (Table 3, column “VNS+Auction”) increases the profit by almost 4 percent compared to the non-collaborative case (75.9% vs 73.0%). This is a high increase, considering the long-term effect of networks for the business model of a liner carrier. Furthermore, it is achieved just by changing the way of planning. Although we do not make cost calculations for the required auction software, the investment costs should be small by comparison with, for example, the costs of operating vessels. From the lower third part of Table 3 we observe, that the potential for collaborative planning depends on the initial resources and the similarity of the carriers. In the unbalanced scenario the potential to increase profits through coordination is with roughly 10 percent clearly the highest.

Third, these effects of the balanced, proportional, and unbalanced scenarios on profits are compared by Figure 3. For the three scenarios, the rank order of the four approaches with respect to the achieved profit is equal. The figure shows the substan-

tial profit increase through collaborative planning in the unbalanced scenario compared to both the balanced and proportional scenario.

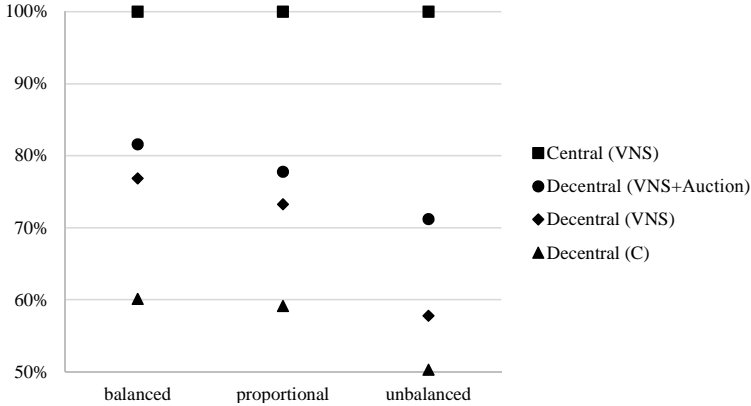


Fig. 3 Comparison of the average gains of the planning approaches for three scenarios

Considering the rightmost column of Table 3, we expected to see varying numbers of instances where collaborating is actually possible. The numbers in the column confirm our expectation. Admittedly, as a whole we expected a higher number of instances where exchanges of demand triplets actually happen. There are several instances where no demand triplets are exchanged through the auction mechanism. The reasons are not completely clear. On the one hand, it might be possible that an exchange of demand triplets is simply not beneficial given an instance. On the other hand, it may be hard for the algorithms to identify suitable demand triplets for exchange. In this case, the carrier's sales decision or the bid decision as described in Section 5 should be replaced by more powerful methods in the future. Keeping in mind that there are several instances where no collaboration actually happens, the profit increase for those instances with actual collaboration as reported by Table 3 is significantly higher.

In either case, the unbalanced scenario offers more opportunities to exchange requests. Figure 4 considers the relation of the number of ships of a carrier to the number of demand triplets of this carrier, i.e., it abstracts from different ship sizes and different demand sizes. The figure is interpreted as follows:

- Few ships (or transportation capacity, respectively) and many demand triplets leads to offering many demand triplets for sale at the market. Therefore, the cardinality of the set of market demand triplets Θ_M is higher than in the other scenarios. However, those carriers are not able to bid on market demand triplets due to capacity bottlenecks.
- When a carrier has many ships compared to few demand triplets it means that this carrier offers almost no requests for sale. However, such a carrier is able to integrate more market demand triplets into its network.

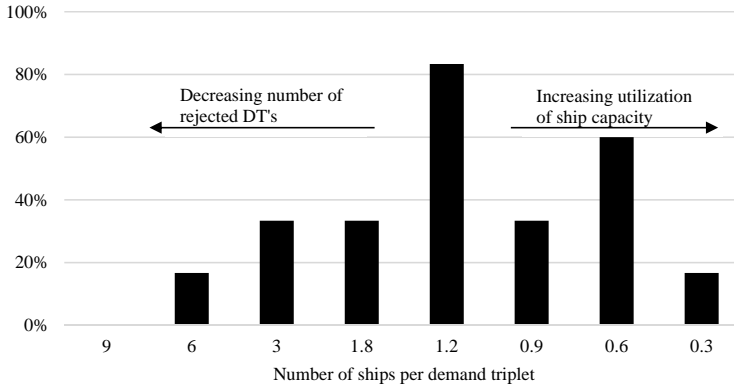


Fig. 4 Successful exchange of demand triplets (DT's) with respect to the the number of ships in relation to the number of demand triplets of an liner carrier.

- In the proportional and the balanced scenario these effects emerge to a much lesser extent. As only those demand triplets are announced to the market that do not increase the profit of a carrier, capacity considerations appear to be very important. This might change when other criteria are applied for the carrier's sales decision (see Section 5) in order to define which demand triplets to announce to the market.

These characteristics also explain, why an actual exchange of requests takes place in only a fraction of the studied test instances (see Table 3, rightmost column).

Fourth, the profit for central and decentralized planning are compared. Non-coordinated planning of three liner carriers leads on an average to networks which are 27 percent less profitable than central planning of a (hypothetical) single carrier. This demonstrates the exceptional potential of resource sharing and coordinating activities. Collaborative planning ("VNS+Auction") leads to a gap of 24.1 percent compared to (hypothetical) central planning. Evaluating this gap is difficult. It is unknown to what extent the gap of 24.1 percent between central planning and collaborative planning ("VNS+Auction") can be reduced. Apart from the fact that we solve the problem approximately by a heuristic, central planning can be considered as a relaxation of collaborative planning because there are no asymmetric information and no conflicting goals of carriers. Like the optimality gap for a linear relaxation of an integer optimization problem it is unclear, how large the central planning gap actually is.

The results support the idea that the introduced combinatorial auctions protocol enables a loose form of cooperation which is advantageous for liner carriers. Although collaboration has not been possible for some instances, the averaged profit over all instances is increased by a considerable amount of four percent. This implies that mechanism which enable increase flexibility during planning and enable looser forms of cooperation for liner carriers – based on combinatorial auctions or other planning or organisational manners – are a fruitful research field.

7 Conclusion

The problem of liner shipping network design of a coalition of self-interested liner carriers was studied. We expect the relevance of this problem will continue to increase. On the one hand, there is high competitive pressure in the liner shipping business which may be released through cooperation. On the other hand, liner carriers are subject to stricter antitrust laws in the USA, Europe, and China which will make cooperation by means of global alliances more difficult. This requires looser forms of cooperation among carriers to increase efficiency of liner shipping networks; applying central planning based methods will be inappropriate. However, little research on collaborative network design has been done (Christiansen et al 2013). For this reason, we have developed a multi round combinatorial auction protocol. The auction supports the collaborative design of liner shipping networks. The items of the auction are the shipper orders (“demand triplets”). Bundle bidding on a set of demand triplets is allowed which is effective because it solves the exposure problem of carriers in an easy way. Bundle bidding allows carriers to calculate networks and bid prices taking into account the strong interdependencies among network structures, demand triplets, and costs. At the same time, the exchange of sensitive information is limited to the information revealed by bidding. All other information, e.g. actual weekly services among ports, offered and used transport capacity, other demand triplets, or operational costs can remain private.

We assumed the liner carriers plan their isolated networks following the *simultaneous ship scheduling and cargo routing problem* (SSSCR) introduced by Agarwal and Ergun (2008). Among other things, the SSSCR takes into account a weekly service frequency, a heterogenous ship fleet, and large degrees of freedom in the structures of the services; all of these features are relevant real-world characteristics. The SSSCR has to be solved repeatedly by the carriers that participate in the auction because the carriers have to decide which demand triplets to sale and on which set of demand triplets to submit a bundle bid. We have introduced a variable neighborhood search (VNS) matheuristic which supports the carriers in these tasks and solves the isolated SSSCR. The VNS starts by constructing ship cycles that service single demand triplets, respectively. During an iterative process, (a) the cycles are improved by means of several neighborhood moves; (b) the cargo flow over these cycles is computed by performing network transformations and solving the multi commodity flow problem; and (c) the ship-to-cycle allocation problem is solved via a MIP-solver.

Our computational experiments on a set of 56 synthetic test instances suggest that the introduced auction protocol enables collaborative planning and increases solution quality compared to isolated planning significantly by, on average, four percent. The increase in solution quality as well as the number of exchanged demand triplets is the higher, the more diverse the original assignment of demand triplets and ships to liner carriers is. On the instance group which is most diverse with respect to these characteristics, a remarkable profit increase of up to ten percent has been observed. We also have found out that there are quite a number of instances where no demand triplets are exchanged. On the one hand, excluding these instances from the set of 56 instances will improve the (averaged) performance of the proposed combinatorial auction. On the other hand, this indicates fruitful directions for future research. It might be pos-

sible to improve the performance of the auction by using more fine-grained rules in order to decide which demand triplets to sale or on which set of demand triplets to place a bundle bid. In doing so, it should also be investigated if it is promising to allow for more than one bundle bid per carrier. Small changes in the planning data can have big effects on the (cost) structure of the network. Therefore, implementing these extensions in a reasonable way is not to be underestimated because they require an appropriate interconnection with the solution approach of the network planning problem in order to keep the computational effort manageable.

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