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COOPERATIVE LINER SHIPPING NETWORK DESIGN BY MEANS OF A COMBINATORIAL AUCTION

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ABSTRACT

A liner shipping network design problem is considered which includes ship scheduling and cargo routing decisions. The question is how to enable loose cooperation of multiple liner shippers for jointly solving this profit maximizing network design problem. A variable neighborhood search matheuristic is developed to compute a network for each liner shipper. To coordinate the planning process of multiple liner shippers, a combinatorial auction is proposed. To evaluate the mechanism a computational study is performed which shows that cooperation is in many cases possible and beneficial. As the proposed joint planning mechanism requires less exchange of sensitive information compared to a centralized approach, it enables looser forms of cooperation during network design.

Keywords: liner shipping, network design, combinatorial auction, variable neighborhood search

1 INTRODUCTION

Cooperation in the ocean liner shipping industry has always been important to improve efficiency of cargo distribution as well as competitiveness of the cooperating liner shippers. Since a liner shipper operates on fixed schedule, the schedule design is a critical tactical decision problem which is known as the service network design problem. This problem is usually studied from the perspective of a single liner shipper or an alliance of multiple liner shippers which are willing to share private data. However, planning approaches that allow looser forms of cooperation of liner shippers during the planning of a service network are hardly discussed in the literature.

Detailed surveys of the literature on (liner) network design problems are given by Wieberneit (2008), Christiansen et al. (2013), and Tran and Haasis (2013). Liner network design is a complex task, therefore many approaches try to improve the solution of important sub problems. For example, designing an optimal single service route in a liner network is addressed by Tran (2011) and Gelareh et al. (2013). In Wang and Meng (2013) the effects of reversing the port call sequence on transshipment, inventory holding, and slot purchasing costs are studied. Shintani et al. (2007) and Meng and Wang (2011) take into account the need for repositioning empty containers during network design.

Simultaneously designing multiple service routes is considered by Fagerholt (2004). Imai et al. (2009) compare multi port calls versus hub-and-spoke service network structures. Reinhardt and Pisinger (2012) simultaneously take into account network design and fleet assignment and present a sophisticated branch-and-cut approach. Mulder and Dekker (2014) successfully integrated the fleet- and the network-design problem of liner shippers. Agarwal and Ergun (2008) present a comprehensive service network design approach which does not presuppose a specific network structure. Agarwal and Ergun (2010) address problems of collaborative planning between a coalition of liner shippers by integrating mechanisms from cooperative game theory. Andersen et al. (2009) focus on synchronizing multiple service networks operated by different companies.

The majority of the literature studies the liner network design problem as an optimization problem that has to be solved by a single decision maker (liner shipper) with complete information. Even if an alliance of multiple liner shippers is considered, this is still reasonable because the members of such an alliance usually cooperate closely and are willing to exchange sensitive data required for planning. However, if multiple liner shippers 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 shippers, the strict requirements for cooperation would be relaxed and cooperation would be easier to establish.

This is the starting point of the present work. In this paper, a mechanism to facilitate horizontal cooperation between liner shippers is proposed. Such a mechanism might be useful, if shippers organised in alliances want to keep more information private than now. It might also be useful, as it eases cooperation between liner shippers which are very heterogenous, e.g. with respect to the operated fleet, or different main regions of operations, or niche markets.

The study is organized as follows. The underlying liner network optimization problem is presented in Section 2. To solve this model a matheuristic approach based on variable neighborhood search is proposed in Section 3. The coordination mechanisms to exchange excess demand is based on a multi-round combinatorial auction (cf. Section 4). Insights into its performance are given in computational study (cf. Section 5). Section 6 concludes the paper.

2 NETWORK PLANNING PROBLEM OF A LINER SHIPPER

The foundation of the presented approach is the simultaneous ship scheduling and cargo routing problem (SSSCR) as considered by Agarwal and Ergun (2008). In the SSSCR, a liner shipper asks for the design of a liner network that maximizes his profits. *Given are*, among others, a set D of *demand triplets* (DT). A DT is characterized by an origin port, a destination port and a weekday when the demand arises at the origin port. For each DT, the maximum demand in TEU as well as the revenue per TEU are given. Furthermore, a heterogenous ship fleet of the liner shipper is given. The capacity of the ships as well as the ship speed varies.

The goal is to design a maximum profit liner network by servicing a *subset* of the set of DT. The network is defined as a space-time network, see Figure 1. Each port is represented by seven nodes, one node for each day of a week. The nodes are connected by three types of directed edges. A *ground edge* represents an overnight stay of a ship (or cargo) at a port. A *voyage edge* represents the movement of a ship (or cargo). Finally, there are *fictitious edges* for the cargo which are required to model the flow of cargo as a circulation. In particular, the network has to satisfy the following constraints.

- A set of cycles has to be constructed. A cycle is a sequence of nodes in a space-time

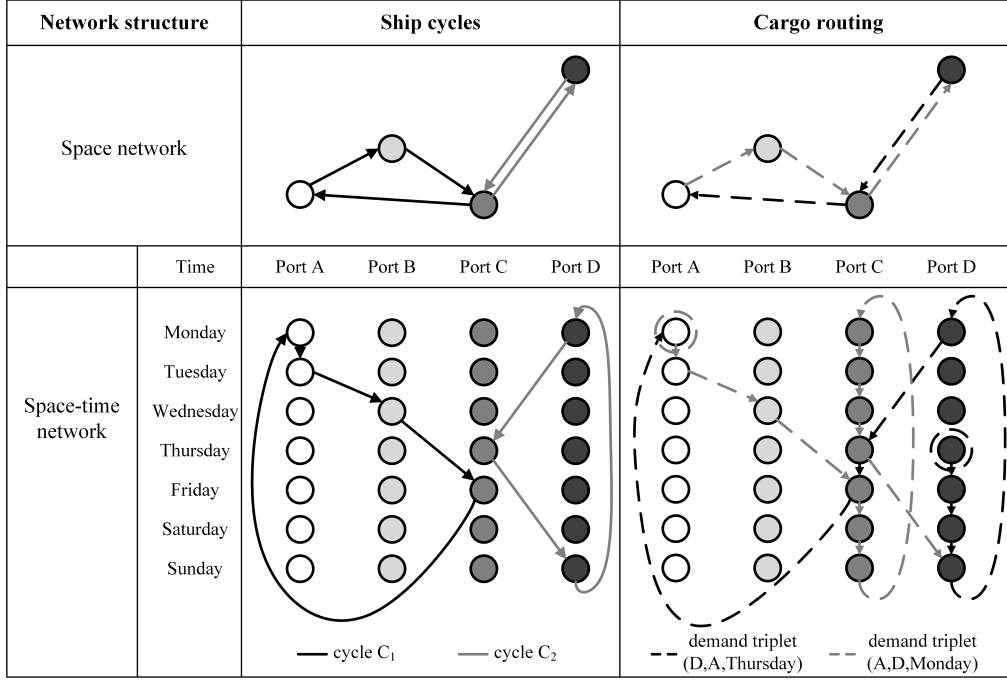


Figure 1: A liner shipping network with two feasible cycles and the associated flow of cargo (cf. Agarwal and Ergun 2008)

network that starts and ends at the same node.

- Each cycle has to be assigned to exactly one ship type. For a pair of a cycle and a ship type, a weekly frequency of port calls is required.
- The set of generated cycles has to comply to the number of available ships.
- The flow of cargo between an origin port and a destination port may use multiple cycles. However, transshipment is considered free of charge.

All in all, the shippers task is to maximize his profit by computing weekly cycles, assigning ships to cycles and search for feasible flows of cargo from origin to destination ports using one ore more cycles. For the complete model, please refer to Agarwal and Ergun (2008).

3 VARIABLE NEIGHBORHOOD SEARCH

The SSSCR is solved by a heuristic based on variable neighborhood search (Hansen et al. 2008). An overview of the variable neighborhood search (VNS) at hand is given by Algorithm 1. VNS is used, because this metaheuristic search concept naturally tries to exploit different structures of search spaces by using multiple neighborhoods. The SSSCR includes aspects of sequencing, selection, assignment, and flow decisions which are nontrivial problems on their own. This decomposition of the SSSCR 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 liner network optimization are Gelareh et al. (2013) or Malliappi et al. (2011) who use VNS for tramp ship scheduling.

The initial step of the VNS is to construct a first feasible solution. For each demand triplet, a ship cycle from the origin port straight to the destination port and back to the origin is constructed in the space-time network. The cycle is assigned to one or more ships from the same ship type, such that the excess capacity of fulfilling the demand completely with the assigned ships is minimal. After all ships or all demands are scheduled, it is tried to increase the cargo flow in the network by solving a multi commodity flow problem (MCF).

The actual VNS consists of three main activities. *First*, a set of *ship cycles* is constructed. Five neighborhood structures are used which focus on the generation of cycles. In Algorithm 1, they are indexed by $j, 1 \leq j \leq 5$. The neighborhood structures try to delete a cycle from the network, add a port to a cycle, delete a port from a cycle, switch two ports inside one cycle, and delay a ship voyage between two ports by one day. If a move interrupts the weekly frequency of a cycle, a simple repair heuristic tries to reassign ships to cycles to re-establish the weekly frequency. *Second*, a cost-minimal routing of cargo through the network is searched for by solving a MCF via a MIP solver. Here, the developed procedure also tries to reduce the size of the MCF instance to be solved by joining multiple demand triplets. By this technique, the number of commodities in the MCF is reduced which eases the solution of the MCF for the MIP solver. *Third*, an assignment of ships to cycles is performed by modelling the problem as a transportation problem. In addition, if the capacity of an edge is exhausted, it is tried to add additional capacity via a capacity optimization process based on the ship assignment stated above. A final remark: 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.

Algorithm 1: Variable Neighborhood Search (VNS)

Input : parameters for ports, ships, and demand triplets, $i_{max}, j_{max}, k_{max}^j$ for $1 \leq j \leq j_{max}$

```

1 bestSolution  $\leftarrow$  constructionHeuristic()
2  $i \leftarrow 1$ 
3 repeat
4    $j \leftarrow 1$ 
5   repeat
6      $k \leftarrow 1$ 
7     while  $f(\text{solution}) < f(\text{bestSolution})$  and  $k < k_{max}^j$  do
8       solution  $\leftarrow$  move(bestSolution,  $j$ )
9       solution  $\leftarrow$  solveMultiCommodityFlow(solution)
10      solution  $\leftarrow$  assignShips(solution)
11      solution  $\leftarrow$  solveMultiCommodityFlow(solution)
12       $k \leftarrow k + 1$ 
13     if  $f(\text{solution}) > f(\text{bestSolution})$  then
14       bestSolution  $\leftarrow$  solution
15        $j \leftarrow 1$ 
16     else
17        $j \leftarrow j + 1$ 
18   until  $j = j_{max}$ 
19    $i \leftarrow i + 1$ 
20 until  $i = i_{max}$ 
Output: bestSolution

```

4 AUCTION BASED EXCHANGE OF DEMAND

In order to construct a network that maximizes the total profit of a liner shipper i for a given set D_i of demand triplets (see Section 2), it is neither required nor wise to actually service all demand triplets in D_i . Those demand triplets that are not serviced in a solution of the SSSCR are denoted as the set R_i of *rejected demand triplets* ($R_i \subseteq D_i$). On the one hand, rejected demand triplets may have a negative impact on i 's customers which is why i should be interested to meet all demands. On the other hand, the rejected demand triplets of one liner shipper may be a good match with the network of another liner shipper. Therefore, we propose a mechanism based on a combinatorial auction to exchange DT's between different liner shippers. The goal of the mechanism is to enable loose cooperation between liner shippers by exchanging rejected DT's and to increase the profit of each liner shipper compared to non-cooperative planning.

The mechanism is operated by a broker which may be a third party or the cooperating liner shippers themselves. The mechanism requires that the participating liner shippers are willing to provide information about all DT's that they want to exchange. Additional data, like the configuration of the network, the fleet, or the demand triplets integrated into their network may remain private.

The coordination mechanism includes six steps, an overview is given by Figure 2. The left side shows the activities of each liner shipper, while the right side shows the activities of the broker. To begin with, each liner shipper i solves the SSSCR (Step 1) for his set D_i of given DT's. The outcome of Step 1 is the network of i which generates a profit of f_i . Furthermore, this network services a set S_i of DT's; consequently, a set R_i of DT's is rejected ($S_i, R_i \subseteq D_i, S_i \cap R_i = \emptyset, S_i \cup R_i = D_i$). Each liner shipper i transfers R_i to the broker. The broker pools these demands, i.e. $M := \bigcup_i R_i$ (Step 2), and announces M to all shippers (Step 3). M is denoted as the set of *market demand triplets*.

Each shipper is now allowed to submit a single bundle bid on any subset of M . A bundle bid of a shipper i is the pair (m_i, p_i) where m_i denotes a subset of M and p_i is the price i is willing to pay in order to fulfill m_i . A bundle bid is an all-or-nothing bid, i.e. the shipper either wins all DT's offered in his bundle or none. This facilitates planning of a balanced network because uncertainty with respect to the DT's to fulfill is reduced.

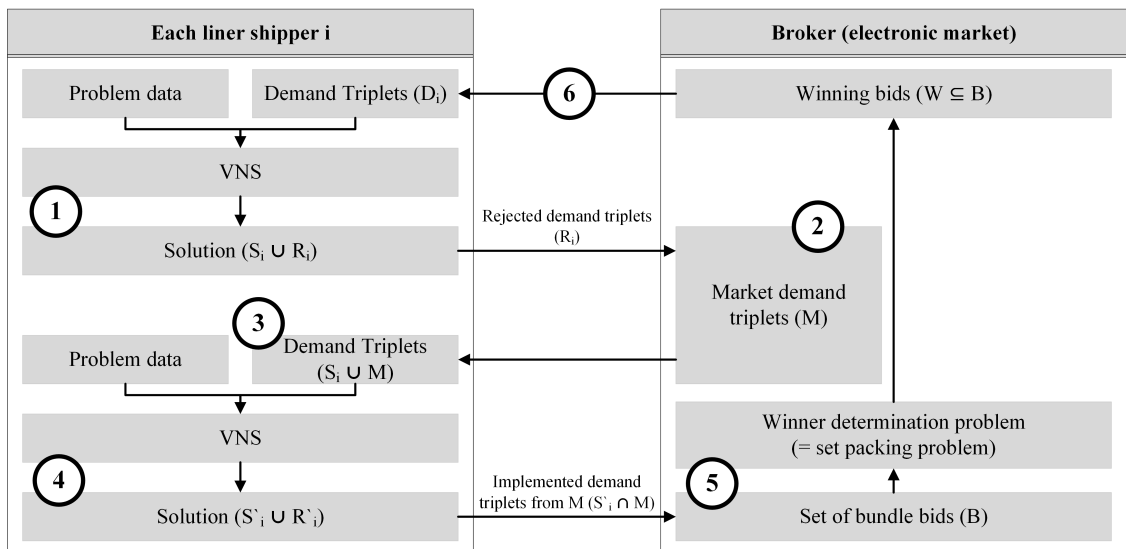


Figure 2: Coordination procedure for demand triplet exchange via a combinatorial auction

In order to calculate a bundle bid, each liner shipper solves the SSSCR again. However, in contrast to Step 1 a different set of DT's is considered in Step 4. Now, the DT's in $S_i \cup M$ are used as input to solve the SSSCR. The updated solution of the SSSCR again gives a profit f'_i and a set S'_i of serviced and a set R'_i of rejected demand triplets ($S'_i, R'_i \subseteq S_i \cup M, S'_i \cap R'_i = \emptyset, S'_i \cup R'_i = S_i \cup M$). The bundle bid includes the set of demand triplets which are added in the updated solution, i.e. $m_i := S' \cap M$. The bid price p_i equals the increase in profits, i.e., $p_i = f'_i - f_i$ which is the profit of the updated network minus the profit of the previous network. Of course, liner shipper i submits a bid only if $p_i > 0$ and $m_i \neq \emptyset$.

In Step 5 the broker decides about the allocation of demand triplets to liner shippers. In the context of combinatorial auctions, this problem is known as the winner determination problem (WDP). For the set B of submitted bids ($B := \{(m_i, p_i) : \forall i\}$), the broker chooses a set W of winning bids ($W \subseteq B$). The broker's goal is to maximize the sum of the prices of the winning bids, such that each demand triplet in M is part of at most one winning bid. Here, the WDP equals the well-known NP-hard set packing problem. Due to the small number of bundle bids it can be quickly solved to optimality with a MIP solver. Finally, the auctioned DT's are assigned to the winning liner shippers (Step 6). The auction process of Step 1 to Step 6 continues until there are no more profitable exchanges of demand triplets.

5 EVALUATION

5.1 Generation of test instances

A set of 54 artificial test instances has been generated which includes parameters with respect to isolated planning as well as cooperative planning. The parameter values are based on real world data inspired by Stopford (2008, p. 540). The chosen values of the parameters are shown in Table 1. In case of a value range, an uniformly distributed number is drawn from the range.

Table 1: Parameter values for ports, ships, and demand triplets.

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					
Ship parameters per ship type (in TEU)	1,200	2,600	4,300	6,500	8,500	11,000
Speed (time for traveling a distance of 1 unit in days)	1	0.95	0.9	0.9	0.85	0.85
Operating costs for a ship in deep sea /day	12,690	23,700	44,160	64,110	69,000	72,000
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
Costs for a ship when staying at a port /day	11,000	14,500	17,500	21,500	30,000	32,500
Number of ships (in total)	30, 60, 90					
Demand parameters	Values or value range [min;max]					
Number of DT's	10, 50, 100					
Amount of containers per demand triplet	[3,000;9000]					
Costs for shipping a TEU of cargo on an edge /day	1					
Profit per container	[50;150]					

Table 1 shows the parameters required for isolated planning, i.e., a single liner shipper solves

his or her SSSCR. Now, it is assumed the ships and the DT's of Table 1 are distributed to *three* liner shippers. Three cooperative scenarios are defined. They differ in the way the ships and DT's are distributed to the three liner shippers.

- In the *balanced scenario*, each liner shippers owns (approximately) a third of the number of ships and a third of the DT's. Thus, the market positioning of the liner shippers is similar.
- In the *proportional scenario*, the fraction of ships and the fraction of DT's assigned to a liner shipper is identical but differs between liner shippers. For example, the first shipper is assigned ten percent of the ships as well as ten percent of the DT's (second shipper 30 percent, third shipper 60 percent). The shippers have different market shares, but the available DT's roughly match the available transport capacity.
- In the *unbalanced scenario*, the available transport capacity (measured in ships) of a liner shipper does not fit the available DT's. It is either too large or too small so that these shippers should clearly benefit from cooperation.

5.2 Discussion of Results

The auction mechanism and the VNS heuristic have been implemented in Java 7. The multi commodity flow problem as a subproblem of the SSSCR, the transportation 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 summarized in Table 2. The 54 test instances are divided into the balanced (b), proportional (p), and unbalanced scenario (u). For each scenario, there are two subgroups: 9 test instances with five ports (P05) and 9 instances with ten ports (P10) for which average results are presented. The parameters of the instances in the five ports and ten ports subgroups vary within the boundaries given in Section 5.1.

Results are reported for a central and a decentral setting. Here, *central* means that a given instance has to be solved by a single decision maker (liner shipper) who owns all planning data. Instances are solved by the construction heuristic only (column C) and by the VNS approach (column VNS). The results of all approaches are given in proportion to the profits of the solutions generated by the central VNS and averaged over the considered instances. The *decentral* setting assumes three decision makers. Column C and Column VNS report results where each decision maker maximizes his profit individually and the profits of each decision maker are added up. The results obtained through coordination of planning activities via the auction-based mechanism are given in column VNS+Exchange. Finally, the rightmost column states for how many instances an exchange of DT's actually occurred. For example, the number 66.6 in line P05u states, that the three liner shippers achieve on average 66.6 percent of the profit that a single liner shipper who owns all ships and all DT's generates; however, through auction-based exchange of DT's the profit may be increased by about ten percent compared to the isolated planning of the three liners which achieves only 60.8 percent of the central profits. Of course, all statements are only valid for the used solution approaches and the used test instances.

First, the performance of the VNS heuristic is compared 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 decentral setting. Looking at the solutions,

Table 2: Aggregated results for six sets of test instances

Set of instances	Central		Decentral			Successful exchanges
	C	VNS	C	VNS	VNS+Exchange	
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

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, the profit for central and decentral planning are compared. Non-coordinated planning of three decision makers leads on an average to networks which are 27 percent less profitable than central planning of a single decision maker. If coordinated planning is considered, the loss compared to central planning is 24 percent; however, if only those instances are considered where an exchange of DT's actually occurs, the profit gap without coordination is 33 percent and decreases to 24 percent. This is reasonable because coordination enables more degrees of freedom during planning and therefore may take advantage from higher capacities, from more DT's to choose from, and in particular there are higher chances that DT's match and provide synergies.

Third, the profits obtained for the balanced, proportional, and unbalanced scenarios are compared (see Figure 3). For the three scenarios, the rank order of the four approaches with respect to the achieved profit is equal. In the unbalanced scenario the potential to increase profits through coordination is highest.

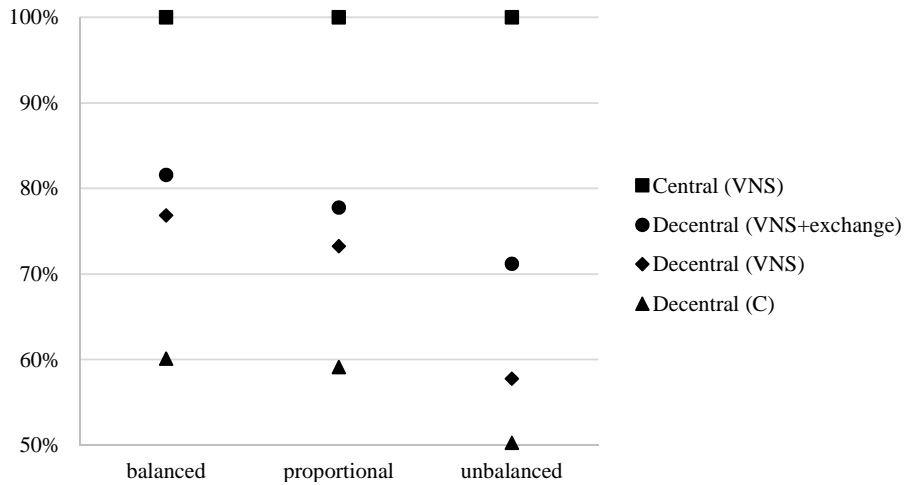


Figure 3: Comparison of difficulty to solve the three scenarios

The unbalanced scenario offers more opportunities to exchange requests. Figure 4 considers the relation of the number of ships of a liner shipper to the number of DT's of this liner shipper, i.e., it abstracts from different ship sizes and different demand sizes. In detail:

- Few ships (or transportation capacity, respectively) and many DT's leads to rejecting many DT's which may be announced to the market. Therefore, the cardinality of the set of market DT's is higher than in the other scenarios. However, those shippers are not able to bid on market DT's.
- Many ships compared to few DT's means that almost no requests are rejected by this liner shipper. However, these liner shippers are able to integrated more market DT's in their network.
- In the proportional and the balanced scenario these effects do only emerge to a much lesser extent. As only those DT's are announced to the market that do not increase the profit of a liner shipper, capacity considerations are very important. This might change, if other criteria are applied in order to define which DT's to announce to the market.

These reasons also explain, why an actual exchange of requests takes place in only a fraction of the studied test instances (see Table 2, rightmost column).

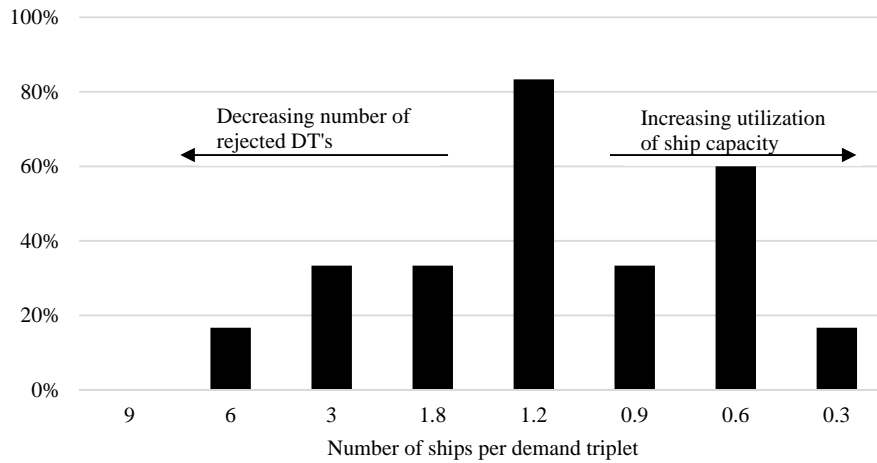


Figure 4: Successful exchange of DT's with respect to the the number of ships in relation to the number of DT's of a liner shipper.

6 CONCLUSION

An approach for enabling cooperation of liner shippers during the design of liner shipping networks was presented. It is based on the model of the simultaneous ship scheduling and cargo routing problem (SSSCR, Agarwal and Ergun 2008). To solve the SSSCR, a matheuristic based on variable neighborhood search (VNS) was developed. Joint planning is enabled by a combinatorial auction approach. The computational experiments on a set of 56 test instances suggest that collaboration of liner shippers significantly increases solution quality compared to individual planning. 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 shippers is. Future extensions of the approach should deal with improving the performance of VNS by developing a larger set of neighborhood operators which are even stronger tailored to the various structures of the problem. Fine-grained rules for deciding which demand triplets to offer in the market could also improve the outcome of the auction.

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