OR Spectrum (2010) 32:809–830
DOI 10.1007/s00291-010-0211-6

REGULAR ARTICLE

# A collaborative planning approach for intermodal freight transportation

**Carolin Puettmann · Hartmut Stadtler**

Published online: 16 April 2010


**Abstract** Very few research efforts have been spent on the coordination of plans and operations of independent service providers in an intermodal transportation chain. The impact of the lack of collaboration and coordination is pointed out in a setting considering overseas transports. It shows that due to information asymmetry and double marginalisation, costs considerably exceed the cost minimum of the whole transportation chain. In order to reduce these inefficiencies, a coordination scheme is elaborated which is able to identify significant improvements and which allows the service providers involved to keep their private planning domain with no disclosure of critical data. Due to the time lag in maritime transportation, uncertainties about future requests exist that could make the improvements achieved from coordination invalid. Hence, the effect of the stochastic demand on the coordinated plans is analysed.

**Keywords** Collaborative planning · Intermodal transportation · Stochastic demand · Overseas transportation

## 1 Introduction

Intermodal freight transportation is defined as transportation of goods in one and the same loading unit or vehicle using successively at least two modes of transportation (OECD 2007). Although intermodal transportation results in more complex operations than direct shipments, it has become a significant and still growing sector of the

C. Puettmann (✉) · H. Stadtler
Institute for Logistics and Transportation, University of Hamburg,
Von-Melle-Park 5, 20146 Hamburg, Germany
e-mail: carolin.puettmann@uni-hamburg.de

H. Stadtler
e-mail: hartmut.stadtler@uni-hamburg.de

transportation industry. One reason is that the increase in global sea trade results in a need for drayage transportation. On the other hand, the growing volume of road traffic also enforces the need for using alternative transportation modes. About 90% in unaccompanied intermodal traffic is carried by containers (Reim 2007). Thus, container transportation is a major component of intermodal transportation and is investigated in this paper.

The different tasks along an intermodal transportation chain are typically executed by organisationally independent service providers that can be distinguished in drayage, terminal, network and intermodal operators (Macharis and Bontekoning 2004). Drayage operators are responsible for carrying the freight between shippers or receivers and a terminal. At the terminal the modal shift takes place managed by terminal operators. Network operators take care of the infrastructure planning and long-haul transportation between terminals, whereas intermodal operators conduct route selection for shipments through the whole intermodal network.

The literature review in Sect. 2 reveals that there is a lack of research on specific collaborative planning approaches for intermodal transportation chains of individual operators. Hence, as collaborative planning may reduce operational costs considerably, this paper presents a coordination scheme for an intermodal transportation chain with three parties: an intermodal operator and two carriers; one is responsible for the drayage in the shipper's region and the other in the region of the receiver. In Sect. 3, the intermodal setting is described in greater detail. The parties' decisions are formulated by mathematical planning models, and the need for coordination is pointed out. In Sect. 4, a coordination scheme is elaborated, which is based on an iterative exchange of proposals. The course of the scheme is generally outlined before the models for proposal generation are introduced. When the coordination scheme is applied, there might be a stochastic demand in the region of destination due to time-consuming long-haul transportation. Hence, a methodology is presented to estimate the effect of the stochastic demand on the coordination results. The performance of the coordination scheme is analysed and discussed via numerical tests in Sect. 5. The paper is concluded with a summary and an outlook.

## 2 Literature review

Bektaş and Crainic (2008), Crainic and Kim (2007), Macharis and Bontekoning (2004), and Bontekoning et al. (2004) review the application of operations research models and methods in the field of intermodal transportation. Macharis and Bontekoning (2004) distinguish the planning tasks among the four groups of service providers and conclude that research focuses mostly on single transportation modes without integrating more than one decision maker. But the many decision makers in the transportation chain need to work in collaboration to ensure that the system runs smoothly and with minimum costs. Hence, the authors claim that more cooperative decision-making support tools are required. Also Crainic and Kim (2007) reveal the lack of coordinated plans and operations of independent carriers.

In more recent transportation literature, approaches for inter-organisational coordination have been developed. But typically they concentrate on collaboration among service providers of the same transportation mode and stage. The involved carriers are competitors and, hence, do not belong to one supply chain. Examples for such a horizontal collaboration are given by Ergun et al. (2007) and Dahl and Derigs (2009), who analyse collaboration in truck transportation. Agarwal and Ergun (2007) study transportation networks that operate as an alliance among carriers in liner shipping and suggest a mechanism to form sustainable alliances. The design of a service network that is covered by different fleets, and additionally the synchronisation with existing connected services is modelled by Andersen et al. (2009). But these approaches assume a central decision-making entity. Thus, they cannot be applied when the service providers want to keep their planning domain and are reluctant to disclose private data. Especially the exchange of capacity or cost data is critical because the other parties could take advantage of it during negotiations.

Moreover, auction-based approaches are proposed to arrange an exchange of orders within horizontal transport cooperations (see e.g. Krajewska and Kopfer 2006; Berger and Bierwirth 2007). Their application requires only a limited data exchange while the carriers keep their individual planning domain.

In the broader field of supply chain management several collaborative planning approaches have been developed that focus for example on proposal generation based on mathematical programming models. Collaborative planning is understood here as "a joint decision making process for aligning plans of individual supply chain members with the aim of achieving coordination in light of information asymmetry" (Stadtler 2009). For example, Schneeweiss and Zimmer (2004) propose a scheme based on hierarchical anticipation. Fink (2006) assumes a mediator that generates feasible proposals that are accepted or rejected by the parties. Ertogral and Wu (2000) and Walther et al. (2008) develop coordination schemes based on dual decomposition.

Dudek and Stadtler (2005, 2007) propose a negotiation scheme that relies on the iterative exchange of proposals together with their corresponding cost effects. This basic idea is further elaborated by Albrecht and Stadtler (2008), who also prove convergence of their coordination scheme and design an incentive-compatible mechanism. The advantages are that no private information is disclosed (only cost effects), even self-interested parties have an incentive for truth-telling and no third party is needed.

In this paper, a collaborative planning approach for intermodal transportation is provided, which investigates for the first time the coordination and collaboration among more than one type of service provider in a transportation chain. In doing so, all parties maintain their private planning domain and do not exchange critical data.

## 3 Decentralised planning in intermodal transportation

An inter-organisational planning situation in intermodal transportation is described in this section. By this setting, drawbacks of a typically decentralised planning approach are discussed. However, these can be reduced via collaborative planning.

A global transportation network consisting of various customer locations and a seaport terminal in each of two remote regions A and B is investigated. The regions are connected via long-haul transportation among the two terminals. Consequently, intermodal planning tasks have to be performed in order to carry freight between customers who are located in different regions.

### 3.1 Description of the setting

An intermodal operator (IMO) receives transportation requests (or equivalently used: orders) for containers that have to be carried from a shipper in region A to a receiver in region B meeting given time windows. Hence, the containers are transported from their shipper to the terminal in region A first. From there, they are forwarded to terminal B using another mode of transportation, just as on the third stage of the chain, where the containers are carried from terminal B to the receiver of the goods. In this context, a time window specifies a set of consecutive periods in which all three transportation tasks must be performed.

For long-haul, the IMO enlists the service of an ocean liner operating according to given time tables. Overseas transportation typically takes several weeks; hence, there is a considerable time lag $\tau$ between the departure and arrival of an order at the terminals. The regarded containers leave their shippers in region A in a period $t \in T^A$ and arrive at their receiver in region B in a period $t \in T^B$. For drayage, transportation by trucks is assumed. These can carry only one container at a time, i.e. there are full truckload transports within the regions. Since the IMO does not operate an own fleet, motor carriers commit time capacity quotas to him by medium-term contracts. Within each region, the IMO collaborates exclusively with one carrier, who in turn can employ subcontractors to satisfy peak demand. The motor carriers in both regions are denoted by carrier A and carrier B.

Subsequently, the drayage and intermodal operators are considered for coordination. Additionally, they use an existing liner service for long-haul transportation.

### 3.2 Initial planning process

In the initial, uncoordinated situation, the planning of the transportation requests takes place decentralised and, more precisely, successively due to the organisationally independent partners. First, the IMO selects long-haul lines for each transportation request and books drayage transportation at the carriers A and B accordingly. He utilises the quota of the carriers' time capacity, which is granted to him per period by contract. This is the maximum amount to which the carriers have to fulfil the tasks of the IMO at a predefined price per distance unit. For excess capacity, a higher price is charged.

Based on the line presetting of the IMO, the carriers plan tours within their region to fulfil all orders in time. In doing so, they make plans for their total amount of orders, i.e. the carriers also serve other external customers besides the IMO. In order to be able to meet all given time restrictions, the carriers have the possibility to outsource transportation requests to subcontractors. The outsourcing capacity is not limited but of course more costly and, hence, unfavoured compared to using their own fleet.

In addition to the transportation requests from region A to region B, i.e. $j \in AB$, the IMO might also receive requests in the opposite direction, i.e. $i \in BA$. However, only the coordination of the IMO orders $j \in AB$ is explicitly investigated. The reason is that due to the time lag $\tau$ between departure and arrival of long-haul transportation, planning of the IMO orders going from region A to B and the planning vice versa become independent from each other (cf. Fig. 1). The IMO orders $j \in AB$ and

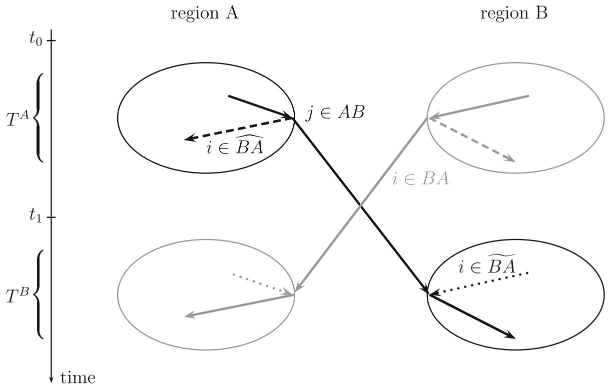


**Fig. 1** Illustration of flows

$i \in BA$ which leave their shippers in the upcoming planning phase $T^A$ neither can be combined by the carriers for a tour nor utilise the IMO's quotas of the same period. Exemplarily, the analysis focuses on orders $j \in AB$ going from region A to B.

Of course, there are also orders in the opposite direction, i.e. from region B to A, which are of major importance for the carriers to build efficient tours. But in region A, the relevant arriving orders during time interval $T^A$, $i \in \widehat{BA}$, are already on their way when the coordination scheme is applied before the beginning of $T^A$ at $t_0$ and, hence, cannot be rescheduled. Their arrival periods at terminal A have been determined in a previous planning phase and cannot be changed. In region B, only forecasts exist for the backward flows $i \in \widetilde{BA}$ at $t_0$ due to the time lag. Hence, there is a stochastic demand. It is assumed that all orders $i \in \widetilde{BA}$ definitely occur and only their final execution period is uncertain. The execution periods can be described by discrete random variables, i.e. the probability that order $i$ has to be hauled in period $t$ is given for all orders $i \in \widetilde{BA}$ and all periods $t \in T^B$. Thus, carrier B will not schedule his tours until $t_1$ when all his orders $i \in \widetilde{BA}$ are finally realised.

### 3.3 Mathematical planning models

The planning tasks of the IMO and the carriers are formally described by mathematical models. The first one is an extended multi-commodity network flow model. It is applied by the IMO, who decides for each order $j \in AB$ which long-haul line $l \in L$ to take as well as the periods $t \in T^A$ and $t \in T^B$ in which carrier A and B, respectively, should haul the container.

Sets

| | |
|---|---|
| $AB$ | set of IMO orders from region A to region B, $j \in AB$ |
| $L$ | set of long-haul lines, $l \in L$ |
| $T^A$ | set of periods which are relevant for carrier A, $t \in T^A$ |
| $T^B$ | set of periods which are relevant for carrier B, $t \in T^B$ |

| | |
|---|---|
| $TL_l$ | set containing the departure periods of line $l \in L$ at terminal A, $t \in TL_l$ |
| Data | |
| $c^{A^+}$ ($c^{B^+}$) | cost for one unit of additional capacity in region A (or B) |
| $c_l^{AB}$ | costs for using line $l$ operating from terminal A to B (inclusive transshipment costs) |
| $h^A$ ($h^B$) | storage cost at terminal A (or B) per period |
| $I_{j0}^A$ | initial inventory at terminal A, =0 for all orders $j \in AB$ |
| $I_{j,\lvert T^A\rvert+\tau-1}^B$ | inventory at terminal B before the relevant planning period of carrier B starts, =0 for all orders $j \in AB$ |
| $t_l^{AB}$ | time needed (in periods) to travel from terminal A to B using line $l$ |
| $tc_j^A$ ($tc_j^B$) | quota consumption at carrier A (or B) for order $j$ |
| $tq^A$ ($tq^B$) | the IMO's quota for carrier A (or B) per period |
| $tw_j^{AB}$ | (complete) time window for order $j \in AB$ |
| Variables | |
| $Add_t^A$ ($Add_t^B$) | additional capacity needed in region A (or B) in period $t$ |
| $I_{jt}^A$ ($I_{jt}^B$) | inventory of $j \in AB$ at terminal A (or B) in period $t$ |
| $X_{jt}^A$ ($X_{jt}^B$) | =1, if capacity of carrier A (or B) is booked for order $j$ in $t$, 0 otherwise |
| $X_{jlt}^{AB}$ | =1, if $j \in AB$ is transported by line $l$ departing in period $t$, 0 otherwise |

$$(\text{INIT}^{\text{IMO}}) \quad \min \mathrm{c}^{\text{IMO}}(X) = \sum_{j\in AB}\sum_{l\in L}\sum_{t\in TL_l} c_l^{AB}\cdot X_{jlt}^{AB} + c^{A^+}\sum_{t\in T^A} Add_t^A + c^{B^+}\sum_{t\in T^B} Add_t^B + h^A\sum_{t\in T^A}\sum_{j\in AB} I_{jt}^A + h^B\sum_{t\in T^B}\sum_{j\in AB} I_{jt}^B \tag{1}$$

s. t.

$$\sum_{t\in tw_j^{AB}\cap T^A} X_{jt}^A = 1 \quad \forall j \in AB \tag{2}$$

$$\sum_{t\in tw_j^{AB}\cap T^B} X_{jt}^B = 1 \quad \forall j \in AB \tag{3}$$

$$\sum_{j\in AB} tc_j^A\cdot X_{jt}^A \le tq^A + Add_t^A \quad \forall t \in T^A \tag{4}$$

$$\sum_{j\in AB} tc_j^B\cdot X_{jt}^B \le tq^B + Add_t^B \quad \forall t \in T^B \tag{5}$$

$$I_{jt}^A = I_{j,t-1}^A + X_{jt}^A - \sum_{l\in L\mid t\in TL_l} X_{jlt}^{AB} \quad \forall j \in AB, t \in T^A \tag{6}$$

$$I^B_{jt} = I^B_{j,t-1} + \sum_{l \in L | t - t^{AB}_l \in TL_l} X^{AB}_{j,l,t-t^{AB}_l} - X^B_{jt} \quad \forall j \in AB, t \in T^B \tag{7}$$

$$I^A_{j|T^A|} = 0,\ I^B_{j|T^B|} = 0 \quad \forall j \in AB \tag{8}$$

$$\sum_{l \in L} \sum_{t \in TL_l} X^{AB}_{jlt} = 1 \quad \forall j \in AB \tag{9}$$

$$Add^A_t \geq 0 \quad \forall t \in T^A, \quad Add^B_t \geq 0 \quad \forall t \in T^B \tag{10}$$

$$X^A_{jt} \in \{0, 1\}\ \forall j \in AB, t \in T^A, \quad X^B_{jt} \in \{0, 1\}\ \forall j \in AB, t \in T^B \tag{11}$$

$$X^{AB}_{jlt} \in \{0, 1\} \quad \forall j \in AB, l \in L, t \in TL_l \tag{12}$$

$$I^A_{jt} \geq 0\ \forall j \in AB, t \in T^A, \quad I^B_{jt} \geq 0\ \forall j \in AB, t \in T^B \tag{13}$$

The IMO's objective is to minimise the costs that are incurred by using long-haul lines (including transshipment costs), the use of additional capacity when the quotas are exceeded and for storage at the terminals A and B. Constraints (2) and (3) ensure that each order $j \in AB$ is fulfilled in both regions within its given time window. Moreover, quota restrictions and resulting additional capacities are included by (4) and (5). The subsequent restrictions (6) to (7) represent inventory balance equations at the terminals A and B. Constraints (8) set the inventory at the end of the planning horizon equal to zero and ensure that each order is scheduled only once per region. W.l.o.g., it is assumed that drayage transportation does not exceed one period and that transportation can start as soon as a container arrives at the terminal. Equations (9) make sure that each order takes exactly one long-haul line. In all periods $t \notin TL_l$, a departure of line $l$ is not permitted. The ranges of the variables are defined by (10) to (13).

The carriers try to efficiently combine pickup and delivery orders into tours in their respective region, i.e. into tours with a low fraction of empty travelling. Their planning model is described using the example of carrier A, the model for carrier B is structured accordingly.

Sets

| | |
|---|---|
| $AB_0$ | set of IMO orders $j \in AB$ plus a dummy customer 0 that is located at the terminal, $j \in AB_0$ |
| $\widehat{BA}_{(0)}$ | set of carrier orders going from terminal A to a customer in region A (including dummy customer 0 at the terminal location), $i \in \widehat{BA}$ |

Data

| | |
|---|---|
| $c^A_{ij}$ | costs for a tour combining orders $i \in \widehat{BA}$ and $j \in AB$ in region A |
| $cap^A$ | time capacity of carrier A |
| $sc^A_k$ | carrier A's costs for outsourcing order $k$ |
| $tc^A_{ij}$ | time needed for a tour combining orders $i \in \widehat{BA}$ and $j \in AB$ in region A |
| $tw^{A,AB}_j$ | time window for order $j \in AB$ in region A, $tw^{A,AB}_j \subseteq tw^{AB}_j$ |
| $tw^{A,BA}_i$ | time window for order $i \in \widehat{BA}$ |

Variables

$X_{ijt}^{A}$ = 1, if orders $i$ and $j$ are combined in period $t$ for a tour in region A, 0 otherwise

$X_{kt}^{scA}$ = 1, if order $k$ is sourced out by carrier A in period $t$, 0 otherwise

$$(\text{EVAL}^{\text{A}}) \qquad \min \text{c}^{\text{A}}(X) = \sum_{i\in\widehat{BA}_0}\sum_{j\in AB_0}\sum_{t\in T^A} c_{ij}^{A}\cdot X_{ijt}^{A} + \sum_{t\in T^A}\sum_{k\in AB\cup\widehat{BA}} sc_k^{A}\cdot X_{kt}^{scA} \tag{14}$$

$$\text{s. t.} \qquad \sum_{t\in tw_i^{A,BA}}\left(\sum_{j\in AB_0} X_{ijt}^{A} + X_{it}^{scA}\right) = 1 \quad \forall i\in\widehat{BA} \tag{15}$$

$$\sum_{t\in tw_j^{A,AB}}\left(\sum_{i\in\widehat{BA}_0} X_{ijt}^{A} + X_{jt}^{scA}\right) = 1 \quad \forall j\in AB \tag{16}$$

$$\sum_{i\in\widehat{BA}_0}\sum_{j\in AB_0} tc_{ij}^{A}\cdot X_{ijt}^{A} \le cap^{A} \quad \forall t\in T^A \tag{17}$$

$$X_{ijt}^{A}\in\{0,1\} \quad \forall i\in\widehat{BA}_0, j\in AB_0, t\in T^A \tag{18}$$

$$X_{kt}^{scA}\in\{0,1\} \quad \forall k\in AB\cup\widehat{BA}, t\in T^A \tag{19}$$

In the objective function (14) of the carrier's model, the costs for haulage with own trucks and for outsourcing orders are minimised. Constraints (15) to (16) ensure that the target time windows are met, which are given by the external customers and the IMO's (initial) plan. For example, if solving (INIT$^{\text{IMO}}$) yields $X_{jt^{target}}^{A} = 1$ for order $j$, then

$$tw_j^{A,AB} = \left\{t\in tw_j^{AB} | t\le t^{target}\right\}. \tag{20}$$

The variables $X_{ijt}^{A}$ denote that orders $i\in\widehat{BA}_0$ and $j\in AB_0$ are combined in period $t$ for a tour in region A. The combination with the dummy customer 0 states a pure pickup or a pure delivery tour. The carrier's time capacities are considered in (17). Constraints (18) and (19) define the ranges of the variables.

The above presented carrier problem is NP-hard, since it includes the generalised assignment problem as a special case, which is known to be NP-hard (cf. Fisher et al. 1986).

### 3.4 Need for coordination

The successive planning approach, which is described in the preceding paragraphs, determines a plan that is feasible for the whole transportation chain. But it generally does not lead to a (near) optimal performance. This inefficiency can be traced back to information asymmetry and double marginalisation (cf. Spengler 1950).

Information asymmetry prevails since the IMO does not know the carriers' capacities, costs and their total amount of orders. This information is also not available for the carrier in the remote region. Moreover, the rates for long-haul transportation might not be public because typically, special rates are offered to the IMO.

Since each party regulates its own objectives, the problem of double marginalisation arises, too. The IMO determines the line presetting, i.e. the pickup and delivery periods at the terminals, based on his local costs, without taking the carriers' planning into consideration. He is motivated to utilise the capacities fairly regularly only by the periodic capacity commitment. However, he is not affected by a high fraction of empty travelling or outsourcing in the regions as prices are negotiated on a medium-term basis. Hence, both carriers have to optimise their local plans based on the IMO's individual optimal targets.

More precisely, the main reasons for suboptimal plans are that the IMO chooses more expensive long-haul lines compared to a supply chain optimal solution because of the quota restrictions, and that efficient carrier tours are not possible due to the line presetting of the IMO. The level of the suboptimalities, which also indicates the savings potential, is documented by the results of numerical tests which are given in Sect. 5 (especially Table 3).

Despite the drawbacks of decentralised planning with private information, it is a main prerequisite for inter-organisational coordination among legally independent parties. Hence, a collaborative planning approach, which is applied to reduce the transportation chain costs, should still rely on this assumption.

## 4 Coordination of the intermodal transportation chain

In order to achieve coordination, i.e. an improvement of the initial, uncoordinated situation, a coordination scheme for transportation service providers collaborating in an intermodal transportation chain is presented in Sect. 4.1. The scheme is applied at $t_0$ when the IMO receives the transportation requests which start during the time interval $T^A$ from a customer in region A. At that point in time, carrier A's requests are already known but due to the time lag only forecasts exist for some orders of carrier B. Hence, it is assumed that carrier B plans at $t_0$ based on the expected execution period $t^*$ per uncertain request $i \in \widetilde{BA}$, i.e. $t^*$ is taken for real in the coordination process. However, it is possible that the orders have to be hauled earlier or later than expected. Consequently, carrier B checks whether a rescheduling might be beneficial when the final execution periods of the uncertain orders $i \in \widetilde{BA}$ become certain at $t_1$ (cf. Fig. 2).

Obviously, the savings that are identified by the scheme at $t_0$ are not definite in case of stochastic demand. Therefore, a methodology is derived in Sect. 4.2 to determine the expected costs of carrier B and, hence, to estimate the expected benefits from collaboration.

### 4.1 Coordination scheme

In order to align their plans towards a supply chain optimal solution, the decentralised partners iteratively exchange proposals and their cost effects compared to the initial

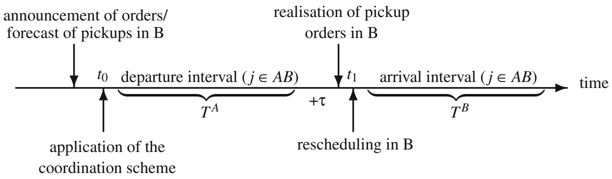


**Fig. 2** Time bar of events and actions

solution (cf. Dudek and Stadtler 2005, 2007; Albrecht and Stadtler 2008). The proposals state the transshipment periods per request at the terminals. They are specified by binary variables $X_{jt}$ which become one if order $j$ arrives at or leaves a terminal in period $t$. In the subsequent models for proposal generation given in Sect. 4.1.2, these variables specify the transshipment periods at terminal A (B) if a model is applied by carrier A (B). For the IMO, the values of $X_{jt}$ also indicate the transshipment periods at terminal A. Additionally, the specific lines chosen for each order have to be recorded and taken into account. Thus, it is possible to determine the arrival times in region B and to compare an IMO proposal with the previous ones.

Subsequently, a general outline of the coordination process is given before the details of proposal generation are explained.

### 4.1.1 General outline

Negotiations start based on the initial, uncoordinated transportation proposal of the IMO and on the carriers' evaluations. Then carrier A generates a counter proposal and passes the new proposal and the corresponding cost effect compared to his initial costs ($\Delta$cost) to the IMO (see step 1 in Fig. 3). After the IMO has evaluated the new carrier proposal by determining his best possible plan given the target dates of carrier A, the arrival dates at terminal B which result from his evaluation are transmitted to carrier B (step 2). Carrier B in turn evaluates that proposal and reports the corresponding cost effect back to the IMO (step 3). Now the IMO derives a counter proposal (step 4) that is evaluated by both carriers, who also disclose their cost effects (step 5). Then one iteration is finished and the IMO determines, based on the cost effects of both carriers and his own costs, whether a schedule has been found resulting in lower transportation chain costs than all previous proposals.

In order to evaluate an IMO proposal, e.g. carrier A applies model (EVAL$^{\mathrm{A}}$) using the values of $X^A_{jt}$ which result from the IMO's model for proposal generation. With these values the target time windows are determined according to formula (20). The IMO evaluates a proposal of carrier A based on a model which is very similar to (INIT$^{\mathrm{IMO}}$). The only differences are that the quotas are not anymore included and that $X^A_{jt}$ is no longer a variable but a target equal to carrier A's proposal $X_{jt}$. Carrier B's evaluation of carrier A's proposal is then based on the values of $X^B_{jt}$ which result from the IMO's evaluation.

In the next iteration, carrier A and B change their roles, i.e. carrier A only evaluates two proposals while carrier B also generates a new one. Consequently, the IMO

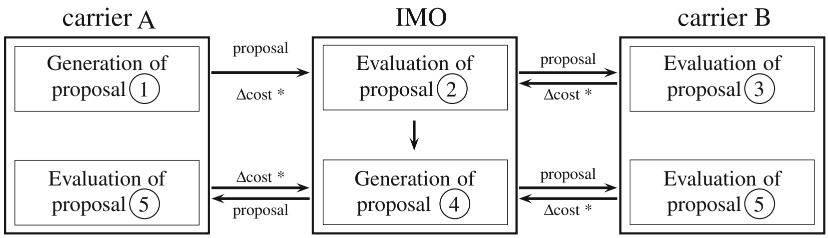


**Fig. 3** Course of one iteration and information exchange

generates a new proposal in each iteration and the carriers alternate. The iterations stop after a predefined number of iterations.

The course of one iteration, in which carrier A and the IMO generate one proposal each, is illustrated in Fig. 3. In Sect. 4.1.2, it turns out that additional, non-critical information has to be exchanged, i.e. priorities. However, their exchange does not alter the procedure. The priorities are not included in the description here since their meaning has not been explained yet. The '*' in Fig. 3 denotes the additional data.

Summarising, only the carriers have to disclose their cost effects compared to their initial costs with each new proposal. The IMO reveals the liner time tables (but no costs) as well as the complete time windows per request. This information is needed by the carriers to be able to generate plans that are feasible for the whole transportation chain.

The coordination scheme is able to identify transportation plans which improve the performance of the whole transportation chain. However, it might not provide all partners with an incentive to participate in the collaboration because there is no guarantee that each party is better off than before. Therefore, the payment of compensations and the allocation of the surplus have to be considered, too. These issues are of great importance for an application in practice but also that all parties have an incentive to follow the rules of the scheme (i.e. for the carriers to disclose their cost effects truthfully). Especially if the latter cannot be assured, the scheme can be embedded in a strategy-proof coordination mechanism like the one developed by Albrecht and Stadtler (2008). It is based on a lump sum, which is received by the carriers in case of a successful coordination process. A prerequisite for its application is a unilateral information exchange.

In order to keep the number of iterations of the coordination scheme manageable, it is of special importance how the proposals are derived. This is explained in the following subsection.

### *4.1.2 Proposal generation*

Three different models and corresponding modifications are applied for purposeful proposal generation. They all have to ensure that the generated plans are feasible for the whole transportation chain. Hence, general network constraints ($NC^p$) are included in each model of party $p$. For the IMO, these constraints ($NC^{IMO}$) are equivalent to the constraints of model ($INIT^{IMO}$) excluding the quota restrictions (4) and (5).

Consequently, the costs of the IMO no longer contain costs for exceeding the quota restrictions. They are subsequently denoted by $c^{\mathrm{IMO}'}$.

Set ($\mathrm{NC}^{\mathrm{A}}$) of carrier A comprises the constraints given in ($\mathrm{EVAL}^{\mathrm{A}}$) complemented by inventory balance equations for both terminals, long-haul constraints and time window restrictions in region B (cf. ($\mathrm{NC}^{\mathrm{IMO}}$)).

Additionally, both sets of constraints ensure that the new proposal $X_{jt}$ is linked to the transport restrictions. For example, set ($\mathrm{NC}^{\mathrm{A}}$) includes constraints

$$\sum_{i \in \widehat{BA}_0} X_{ijt}^{A} = X_{jt} \quad \forall j \in AB, t \in T^{A}.$$

*Model (CS1)* The first model for proposal generation (CS1) is specifically for application in truckload transportation and only applied by the IMO in step 4 (see Fig. 3). Its fundamental idea is that the IMO tries to anticipate the carriers' planning. Therefore, the carriers state *priorities* that are additionally transferred to the IMO. These priorities give the IMO a hint in which period(s) a carrier favours to haul an order. An indicator for this is the fraction of empty travelling in the planned tours of previous proposals. If a request $j$ can be combined in period $t$ with another request resulting in an efficient tour for carrier A or B, the value of $prio_{jt}^{A}$ or $prio_{jt}^{B}$, respectively, becomes one. A tour of, e.g. carrier A is called efficient if

$$\frac{et_{ij}^{A}}{d_{ij}^{A}} \leq \delta,$$

with $et_{ij}^{A}$ and $d_{ij}^{A}$ denoting the distance in the tour combining orders $i$ and $j$ that is travelled empty and in total, respectively. In numerical tests, $\delta = 0.2$ turned out to be most appropriate. In case that one of the orders is the dummy customer 0, a fraction of empty travelling of 0.5 results.

With these priorities, the carriers try to influence the IMO's planning: If no priority of one carrier for an order is met by the IMO, penalty costs are added to his objective function value.

The information about the priorities is not critical, and neither is its exchange.

At the beginning of the coordination process, all entries of the carriers' priority matrices, $prio^{A}$ and $prio^{B}$, are zero. During iterations, $prio_{jt}^{A}$ or $prio_{jt}^{B}$ is updated by the respective carrier to a value of one if in the current proposal order $j \in AB$ is combined efficiently in period $t$ by carrier A or B, respectively. Hence, it is also possible that a carrier sets multiple priorities per request.

The following model formalises the decisions of the IMO:

Data

| | |
|---|---|
| $nb^{A}$ ($nb^{B}$) | number of orders for which priorities are given by carrier A (or B) |
| $pot^{A}$ ($pot^{B}$) | savings potential of carrier A (or B) |
| $prio_{jt}^{A}$ ($prio_{jt}^{B}$) | =1, if carrier A (or B) sets a priority for hauling $j$ in $t$, 0 otherwise |

Variables

$D_j^A$ ($D_j^B$) =1, if no priority of carrier A (or B) for order $j$ is met, 0 otherwise

$$(\text{CS1}^{\text{IMO}}) \qquad \min c^{\text{IMO'}}(X) + \frac{pot^A}{nb^A} \sum_{j \in AB} D_j^A + \frac{pot^B}{nb^B} \sum_{j \in AB} D_j^B \tag{21}$$

$$\text{s. t.} \qquad \sum_{t \in T^A | prio_{jt}^A = 1} X_{jt}^A \geq 1 - D_j^A \quad \forall j \in AB | \sum_{t \in T^A} prio_{jt}^A \geq 1 \tag{22}$$

$$\sum_{t \in T^B | prio_{jt}^B = 1} X_{jt}^B \geq 1 - D_j^B \quad \forall j \in AB | \sum_{t \in T^B} prio_{jt}^B \geq 1 \tag{23}$$

$$D_j^A \geq 0, \; D_j^B \geq 0 \quad \forall j \in AB \tag{24}$$

$(\text{NC}^{\text{IMO}})$.

In constraints (22) and (23), $D_j^A$ and $D_j^B$ automatically assume a value of one if no priority value of carrier A and B, respectively, for request $j$ is met, given there exists at least one for $j$. In that case, penalty costs arise in the objective function. Consequently, the new proposal will meet the carriers' priorities unless the IMO's benefit from a deviation exceeds the penalties. The level of the penalty costs depends on the savings potential of each carrier, which is derived from the costs of the individually best and overall feasible solution, $c_{best}^A$ and $c_{best}^B$. This solution is obtained by applying a model which aims to minimise, e.g. carrier A's costs given the set of constraints ($\text{NC}^{\text{A}}$). The difference between these costs and the initial costs in the uncoordinated case, $c_{init}^A$ and $c_{init}^B$, yields the potential savings, e.g. for carrier A

$$pot^A = c_{init}^A - c_{best}^A.$$

This information is announced by both carriers at the beginning of iterations. The denominators of the penalty terms, $nb^A$ and $nb^B$, count the number of requests for which priorities are given for the respective carrier. Thus, the potential savings are evenly allocated to the prioritised orders to approximate roughly the carriers' cost increase with each prioritised order for which no priority is met. The alteration of the denominators during iterations activates the generation of new proposals.

*Model (CS2)* The second basic model (CS2) is again only applied by the IMO for proposal generation in step 4 (cf. Fig. 3) due to the unilateral exchange of cost effects. It is used when the solution of (CS1) does not result in a new proposal compared to the previous ones.

By solving (CS2), a recombination of previous proposals is built such that each request $j$ is hauled as determined in at least one previous proposal $e$. A similar idea of convex combinations is also applied by Albrecht and Stadtler (2008) for proposals comprising continuous data but is here transferred to binary values.

Sets

$E$ index set of previously exchanged proposals, $e \in E$

Data

$\Delta c^e$ cost effect of both carriers with proposal $e$ compared to the initial solution
$x^e_{jt}$ =1, if in previous proposal $e \in E$ order $j$ is scheduled in $t$, 0 otherwise

Variables

$\mu_{ej}$ =1, if order $j$ is scheduled according to proposal $e$, 0 otherwise

$$(\text{CS2}^{\text{IMO}}) \qquad \min c^{\text{IMO'}}(X) + \sum_{e \in E} \Delta c^e \frac{\sum_{j \in AB} \mu_{ej}}{|AB|} \tag{25}$$

$$\text{s. t.} \qquad \sum_{e \in E} x^e_{jt} \mu_{ej} = X_{jt} \quad \forall j \in AB, \forall t \in T^A \tag{26}$$

$$\sum_{e \in E} \mu_{ej} = 1 \quad \forall j \in AB \tag{27}$$

$$\mu_{ej} \in \{0, 1\} \quad \forall e \in E, \forall j \in AB \tag{28}$$

$$(\text{NC}^{\text{IMO}})$$

In the objective function, weighted cost effects of previous proposals $x^e$ are included in addition to the real transportation costs. Their influence depends on the number of requests that are hauled according to proposal $x^e$. Constraints (26) combine previous proposals into a new one, whereas all orders have to follow exactly one previous proposal (27). The variables $\mu_{ej}$ are restricted to binary values in (28).

In case no new proposal can be found by solving (CS2), the model is applied again but modified by allowing deviations from the recombination at the expense of penalty costs. The penalty costs per unit are given by the maximum savings potential of both carriers, i.e. $pot^A + pot^B$, divided by the number of negotiated requests.

*Model (CS3)* The third model for proposal generation (CS3) is applied by all parties $p$, i.e. by the IMO in step 4 in case that (CS1) and (CS2) do not yield a new proposal and by the carriers in step 1 (cf. Fig. 3). It is based on the ideas of Albrecht and Stadtler (2008) but further adapted and modified. The aim is to find completely new proposals that also yield a considerable cost savings.

Sets

$T^p$ set of periods relevant for party $p$, $t \in T^p$

Data

$c^e$ costs of party $p$ that result from previous proposal $e \in E$
$c^{st}$ costs of party $p$ that result from the starting proposal
$m_{jt}$ upper bound for $K_{jt}$
$x^{st}_{jt}$ =1, if in the starting proposal order $j$ is scheduled in $t$, 0 otherwise

Variables

$K_{jt}$ endogenously determined unit prices for deviations from $x_{jt}^{st}$

$$\text{(CS3}^{\text{p}}\text{)} \qquad \min c^{\text{p}}(X) + \sum_{j \in AB} \sum_{t \in T^p} K_{jt} \cdot \left( X_{jt} - x_{jt}^{st} \right) \tag{29}$$

$$\text{s. t.} \qquad \sum_{j \in AB} \sum_{t \in T^p} K_{jt} \left( x_{jt}^{e} - x_{jt}^{st} \right) > c^{st} - c^{e} \quad \forall e \in E \tag{30}$$

$$0 \le K_{jt} \le m_{jt} \quad \forall j \in AB, \forall t \in T^p \tag{31}$$

$$\text{(NC}^{\text{p}}\text{)}$$

The objective function does not only consider transportation costs, but it also regards new control costs: Deviations of the new proposal $X_{jt}$ from a starting solution $x_{jt}^{st}$, which is randomly chosen from the set of previous proposals, are penalised or rewarded by an endogenously determined price $K_{jt}$ per unit. The penalty prices are set via constraints (30). Given the index set of already exchanged proposals $E$, the constraints stipulate that if a proposal $x^e$ is repeated, a penalty term is added to the objective function that is higher than the cost effect that results from this proposal compared to the starting solution ($c^{st} - c^e$). Thus, a proposal repetition cannot lead to a reduction of the objective function value and is therefore avoided.

The ranges of the prices are limited by $m_{jt}$ and zero via (31). The upper bounds are large numbers that exceed the potential cost increase from shifting request $j$. They are derived based on the outsourcing costs and the potential liner cost increase of the carriers and the IMO, respectively.

Due to the non-linear objective function, (CS3ᵖ) cannot be solved straightforwardly by a standard solver. Thus, the objective function is approximated by a piecewise linear function (see, e.g. Williams 2003).

Moreover, four modifications are introduced which can be applied alternatively in order to increase the probability to find a new proposal but also to reduce model size.

First, only positive deviations from $x^{st}$ are considered in the objective function of (CS3ᵖ) as well as in constraints (30). E.g. for the latter, solely $x_{jt}^{e} - x_{jt}^{st} > 0$ are employed to determine the penalty costs. Hence, they are assigned for shifts to the same target period as in a previous proposal only.

Second, the extent of the shifts is included in model (CS3ᵖ) by using cumulative deviations $D_{jt}^{+}$ and $D_{jt}^{-}$, which also indicate the direction of the shifts. E.g. for deviations of proposal $X_{jt}$ from $x_{jt}^{st}$ they can be determined by

$$X_{jt} + D_{jt}^{+} + D_{j,t-1}^{-} = x_{jt}^{st} + D_{j,t-1}^{+} + D_{jt}^{-} \quad \forall j \in AB, \forall t \in T$$

with $D_{j0}^{+} = D_{j0}^{-} = 0 \; \forall j \in AB$.

Third, these deviations are also aggregated over time. Thus, the exact target period of a shift is less important. And finally, additional penalty costs analog to the ones in (CS2) are included for deviations from $x^{st}$.

Summarising, carrier A and B only apply model (CS3) and its modifications for proposal generation. Thereby, they start with (CS3) including all four modifications and try it with randomly selected starting proposals $x^{st}$ until a new proposal is identified.

If this does not succeed, the fourth modification is skipped and the resulting model is again tried with varying starting solutions, and so on. The IMO applies all three models and their modifications in the given sequence until a new proposal is found. See Puettmann (2010) for a detailed description.

### 4.2 Cost evaluation under stochastic demand

In order to evaluate whether coordination is expected to be beneficial in case of stochastic demand, the expected costs of the transportation chain

$$E(c^{\mathrm{TC}}) = c^{\mathrm{IMO'}} + c^{\mathrm{A}} + E(c^{\mathrm{B}})$$

are compared in the initial and coordinated setting. Hence, the expected costs of transportation and storage in region B, $E(c^{\mathrm{B}})$, have to be determined.

The methodology to derive them is as follows: A simple heuristic to calculate the carrier's transportation plan is presented first. Based on this heuristic, a scenario tree is constructed with each path representing a transportation plan in case of any realisation of the uncertain orders. It is assumed that the execution periods of the uncertain pickup orders in region B ($i \in \widetilde{BA}$) are described by discrete random variables. Thus, combinations of their potential values build scenarios for which the costs of the resulting transportation plan as well as the probability can be determined. The heuristic is needed to reduce the size of the scenario tree as well as the computational effort.

*PDC-Heuristic* The idea of the heuristic that builds a transportation plan out of **p**ickup and **d**elivery **c**ombinations is that all feasible tours, i.e. $(i, j, t)$-combinations including outsourcing, are arranged in a list $\mathcal{L}$ according to their preference value that is specified by

$$pref(i, j, t) = \frac{ce_{ij}^{B} + h^{B} \cdot \left(t - t_j^{min}\right)}{c_{ij}^{B}}.$$

The numerator is made up by the decision relevant costs for empty travelling in a tour that combines order $i$ and $j$, $ce_{ij}^{B}$, plus storage costs. $t_j^{min}$ states the period in which the delivery order $j$ is available at the terminal. Its difference to the hauling period $t$ is multiplied with the unit storage cost $h^{B}$ per period. The denominator states the overall transportation costs of the tour.

The list is processed strictly in the determined order starting with the best combination that has the lowest preference value. In the iterations, all entries which contain no transportation request that is already assigned and do not exceed capacities are appended to the transportation plan.

Due to the straightforward processing of the tour entries in $\mathcal{L}$, the heuristic can be used to build a scenario tree with branches that already represent all potential transportation plans. Hence, the size of the tree is reduced compared to all potential realisations. Of course the application of this heuristic handling stochastic data is limited to rather small instances or instances with not too many uncertain orders. Otherwise, the time needed for computation explodes due to the exponentially increasing number of paths.

But it is appropriate to document the general effect of the uncertainty on the outcome of the coordination scheme.

Typically, the stages of a scenario tree represent the revelation of information or decisions at different points in time (see e.g. Gülpinar et al. 2004; Dupačov et al. 2000). In the subsequent procedure, the construct is employed somewhat differently. The stages represent the entries of $\mathcal{L}$ that are processed sequentially. Thus, not only are scenarios but also simultaneously the (near optimal) transportation plans for all possible scenarios together with their probability, derived.

*Construction of scenario tree* First, $\mathcal{L}$ is extended so that it contains all tours that are potentially feasible. If an uncertain order $i$ could occur in several periods, combinations in all of these periods are included in $\mathcal{L}$ at a position that corresponds to their preference value.

In order to build the scenario tree, $\mathcal{L}$ is run through just like in the case of deterministic data. The decisions which tours to add to the transportation plan are made following the principles of the PDC-heuristic. But if the next tour entry involves an uncertain order, the decision whether it can be included in the transportation plan or not depends on the realisation of the uncertain data. If rejection and acceptance of the next tour entry $(i, j, t)$ are possible due to the preceding path, the node is split and an additional path is established. The branches indicate a scenario split: In one branch it is assumed that request $i$ occurs in $t$. Hence, it is included in the plan. For the second branch the reverse holds. Thus, each node has one or two successor nodes dependent on the realisations of the preceding path.

To derive the probability of each generated potential transportation plan, i.e. path $s$, conditional probabilities are consulted. With $|\mathcal{L}|$ representing the number of list entries and $r_k^s$ the realisation of the $k$th entry of $\mathcal{L}$ in the potential plan $s$, the probability of $s$ is given by

$$P(s) = P(r_1^s) \cdot \prod_{k=2}^{|\mathcal{L}|} P\left(r_k^s | r_1^s \dots r_{k-1}^s\right).$$

For example, suppose that the first two entries of $\mathcal{L}$ are given by (1, 1, 2) and (1, 2, 3) and that the pickup order 1 is uncertain, i.e. with a probability of 80% it occurs in period 2, but it is also possible that the order is available one period earlier or later. A deviation in both directions is equally likely. The first two stages of the corresponding scenario tree are depicted in Fig. 4 in which rejected tours are marked by a bar. The first branches on stage 1 indicate that it is uncertain whether the pickup order 1 occurs in period 2. Dependent on the assumption made on this stage, it is determined whether the second entry of $\mathcal{L}$ has to be branched, too. Figure 4 also displays the probabilities of each branch. By multiplying them along a path, its probability is determined.

The expected transportation costs can be derived straightforwardly from the probability and the costs of each path. See Puettmann (2010) for a formal description of the procedure.

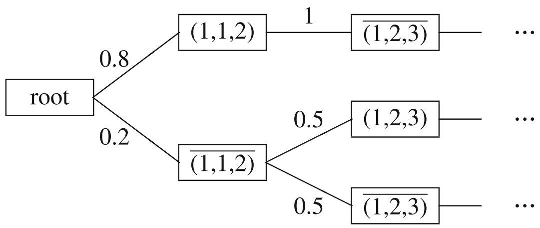


**Fig. 4** Example of a scenario tree (stage 1 and 2)

**Table 1** Size of the test sets

| Test set | Number of locations | Carrier orders | IMO orders | Capacity A, B [TU/period] |
|---|---|---|---|---|
| S | 12 | 48 | 24 | 16 |
| M | 25 | 100 | 50 | 32 |
| L | 40 | 160 | 80 | 48 |

## 5 Numerical tests

Next, the main attributes of the test data are described before the numerical results are presented and analysed.

*Test instances* The transportation requests are generated based on a number of potential customer locations in both regions. These locations are uniformly determined at random (as all random numbers used in the subsequent) within two $340 \times 340$ distance unit (DU) square regions A and B, and the terminal in the centre. An order $j \in AB$ is created by randomly selecting a pickup location in A and a delivery location in B. For the orders $i \in \widehat{BA} \cup \widetilde{BA}$, just one location is chosen in the respective region, because one end of the transportation lane is always the terminal.

In the test cases, the number of IMO orders is set equal to the number of pure carrier orders, which are not negotiated in the scheme. Besides, half of the orders go from region A to B and the rest in the opposite direction. Therefore, it is assumed that the carriers serve other customers besides the IMO and that all these additional orders go in the opposite direction. The reason is that the ratio of coordinated and uncoordinated orders should be balanced as well as the one of the number of pickup and delivery requests. Hence, the effect of coordination can be demonstrated best.

In the cost calculations, a hauling cost of 1 monetary unit (MU) per DU is used for drayage transportation. The carriers' costs for outsourcing an order are set equal to the carriers' costs for a tour without any combination plus $\epsilon \ll 1$ MU. This ensures that self-fulfillment is always preferred, but it does not yield exaggerated outsourcing costs. The travel times as well as the carriers' capacities are measured in time units (TU) and are based on the assumption of an average truck speed of 60 DU/TU. The test sets and the basic attributes concerning their instance size small (S), medium (M), and large (L) are resumed in Table 1.

The relevant planning periods of carrier A and B are split into $T^A$ and $T^B$, respectively, which consist of ten periods each and are separated by the time lag $\tau$. Hence, all

**Table 2** Data of the liner service (long-haul)

| Lines | Departure times [period] | | | | | | | | | | Duration [periods] $+\tau$ | $\Delta$-costs [MU] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | |
| 1 | × | | × | | × | | × | | × | | 10 | +135 |
| 2 | | × | | × | | × | | × | | × | 11 | 0 |
| 3 | × | × | | × | × | | × | × | | × | 11 | +45 |

$j \in AB$ start in $t \in T^A$ and arrive at the receiver in $t \in T^B$. Their time windows are selected with a random flexibility between two and six periods. For $i \in \widetilde{BA} \cup \widehat{BA}$, one period is chosen randomly for execution. For the uncertain orders $i \in \widetilde{BA}$ in region B, it represents the expected period $t^*$. However, the order can also be available one period earlier or later with the probability

$$P(t^* - 1) = P(t^* + 1) = \frac{1 - P(t^*)}{2}.$$

In case $t^*$ is the first or the last period of $T^B$, the probability of the periods that are not in the planning horizon of region B are added to $t^* + 1$ or $t^* - 1$.

In the computational tests, several levels of uncertainty are analysed. First, the number of uncertain orders is increased from 25 to 50 and 75% of them having random execution periods. Additionally, the probability that a request is executed in the predicted period $t^*$ is set to the values of 80, 50 and $33.\overline{3}$%.

For long-haul transportation, three lines are chosen varying in duration, price and frequency. Thereby, the frequency is chosen relatively high so that (with a high probability) at least two possible long-haul lines are available for each transportation request. Otherwise, a coordination would not make sense because no alternative schedules are possible.

The departure times of the lines are given in Table 2 as well as their duration and the corresponding cost differences among them.

Moreover, the IMO's quota at a carrier per period is set equal to 60% of the maximum travel distance that would be needed to fulfil all IMO orders without any pickup and delivery combination, equally divided by the number of periods. Additional capacity for the IMO is available at an extra charge of 30%, and storage costs at the terminals are set to 20 MU. In the cost calculations we constrain to decision-relevant costs and analyse 100 instances per test set.

*Test results* For the numerical evaluation, the collaboration process as well as the procedure to derive the expected costs have been implemented in Java (jdk 1.6.0) using Xpress-MP (version 2008A parallel 64-bit) to solve the optimisation models. The tests were run on eight threads of an Intel SMP with a clock speed of 2.33 GHz and 8 GB RAM.

The benchmarks used to assess the performance of the coordination scheme are based on the overall transportation chain costs $c^{\mathrm{TC}*}$ derived from a central planning

**Table 3** Performance of the coordination scheme given $P(t^*) = 1$

| Set | AGU (%) | AGS (%) | AGC (%) | Average time (s) |
|---|---|---|---|---|
| S | 17.9 | 4.3 | 74.3 | 222 |
| M | 18.9 | 6.2 | 67.0 | 115 |
| L | 20.2 | 7.0 | 65.0 | 217 |

model, assuming that there is only one decision maker for the whole transportation chain with complete information. Consequently, the best achievable solution is provided in case of deterministic data.

The average of 1 minus the transportation chain costs of the uncoordinated plan relative to $c^{\mathrm{TC}^*}$ over all instances states the average gap of the uncoordinated solution (AGU). For comparison, the average gap of the coordinated solution (AGS) is consulted, which is based on the costs of the coordinated plan after 10 iterations of the scheme.

The results in Table 3 show that the average initial gap compared to the central solution is about 18–20%. After applying the scheme, this gap could be reduced significantly. For example, for the S-sized instances, on average nearly 75% of the initial gap could be closed (cf. AGC).

In case of uncertainties, we cannot derive the costs of the central solution for benchmark. Hence, the gap between the expected coordinated and initial costs is consulted, i.e., the expected average cost increase over all instances $k \in TI$ is specified by

$$\mathrm{E(ACI)} = \frac{1}{|TI|} \sum_{k \in TI} \frac{E(c_k^{\mathrm{TC\,init}}) - E(c_k^{\mathrm{TC\,coord}})}{E(c_k^{\mathrm{TC\,coord}})}.$$

Table 4 presents the results for S- and M-sized instances. For test set M, only the instances with 25% and 50% uncertain orders have been solved and analysed due to the high computational effort; however, for the latter only 30 instances.

The values of the key figures show that the coordinated plans yield on average significant improvements in spite of the stochastic demand. The values of the E(ACI), which relate the expected costs of the coordinated plans with the expected costs of the initial plans, are only slightly lower than the values of the ACI that are based on deterministic data, i.e. $P(t^*) = 1$. This indicates that the major share of the savings is still achieved on average. However, with an increasing percentage of uncertain orders, the values of the E(ACI) slightly decrease. Moreover, the key figures indicate that for set M, the performance is also only slightly worse than for set S, suggesting that the expected coordination results are also good for larger instances.

The assumption that the carriers' plans are determined by the PDC-heuristic hardly affects the results. In case of deterministic data, the results are only on average about 2.5 and 3.5% higher for the S- and M-sized instances, respectively, than the optimal solution.

**Table 4** Evaluation of coordination results under stochastic demand

| Set | ACI (%) | % uncertain | $P(t^*)$ (%) | E(ACI) (%) |
|---|---|---|---|---|
| S | 13.0 | 25 | 80 | 12.8 |
| | | | 50 | 12.0 |
| | | | $33.\overline{3}$ | 11.6 |
| | | 50 | 80 | 12.4 |
| | | | 50 | 11.4 |
| | | | $33.\overline{3}$ | 10.9 |
| | | 75 | 80 | 12.0 |
| | | | 50 | 10.4 |
| | | | $33.\overline{3}$ | 9.8 |
| M | 12.0 | 25 | 80 | 11.5 |
| | | | 50 | 11.1 |
| | | | $33.\overline{3}$ | 10.9 |
| | | 50 | 80 | 11.1 |
| | | | 50 | 10.7 |
| | | | $33.\overline{3}$ | 10.3 |

## 6 Summary and outlook

In this paper, a quantitative collaborative planning approach is presented which studies the coordination of independent service providers operating on three different stages of an intermodal transportation chain. A collaboration setting of overseas transportation is specified, and the need for coordination is pointed out. Hence, a coordination scheme is elaborated which leads to significant reductions in overall transportation costs, while all parties maintain their planning domain and exchange only non-critical data.

Due to the time lag between the departure and arrival of the orders at the sea ports, several kinds of uncertainty can arise in the region of destination. We investigate the case that orders are forecasted, but for example, considering delay in long-haul transportation would require no adaptations of the procedure. A methodology based on a scenario tree generation is presented to quantify the expected gain from coordination. The numerical tests indicate that significant improvements can still be expected.

The carriers' planning models are NP-hard. Hence, the implementation of a metaheuristic or a simple heuristic like the PDC-heuristic seems advisable to solve larger problem instances. However, the collaborative planning scheme presented here can be used without alterations.

Future research should investigate which adaptations or extensions are necessary when the collaborative planning approach is applied to real world problems.

## References

Agarwal R, Ergun Ö (2007) Network design and allocation mechanisms for carrier alliances in liner shipping. Working paper, Georgia Institute of Technology, Atlanta

Albrecht M, Stadtler H (2008) Decentralized coordination by exchange of primal information. Research papers on operations and supply chain management (1), University of Hamburg, Hamburg

Andersen J, Crainic TG, Christiansen M (2009) Service network design with management and coordination of multiple fleets. Eur J Oper Res 193(2):377–389

Bektaş T, Crainic TG (2008) Brief overview of intermodal transportation. In: Taylor GD (ed) Logistics engineering handbook. Taylor & Francis Group, Boca Raton, chap 28, pp 1–16

Berger S, Bierwirth C (2007) The collaborative carrier vehicle routing problem for capacitated traveling salesman tours. In: Koschke R, Herzog O, Rödiger KH, Ronthaler M (eds) Informatik 2007-Informatik trifft Logistik, vol 1. Gesellschaft für Informatik (GI), Bonn, pp 75–78

Bontekoning YM, Macharis C, Trip JJ (2004) Is a new applied transportation research field emerging? A review of intermodal rail-truck freight transport literature. Transp Res Part A Policy Pract 38(1):1–34

Crainic TG, Kim KH (2007) Intermodal transportation. In: Barnhart C, Laporte G (eds) Handbooks in operations research and management science: transportation, vol 14. North-Holland, Amsterdam, chap 8, pp 467–537

Dahl S, Derigs U (2009) Planning in express carrier networks: A simulation study. In: Fleischmann B, Borgwardt KH, Klein R, Tuma A (eds) Operations research proceedings 2008. Springer, Berlin, pp 259–264

Dudek G, Stadtler H (2005) Negotiation-based collaborative planning between supply chain partners. Eur J Oper Res 163(3):668–687

Dudek G, Stadtler H (2007) Negotiation-based collaborative planning in divergent two-tier supply chains. Int J Prod Res 45(2):465–484

Dupačov J, Consigli G, Wallace SW (2000) Scenarios for multistage stochastic programs. Ann Oper Res 100(1–4):25–53

Ergun Ö, Kuyzu G, Savelsbergh M (2007) Reducing truckload transportation costs through collaboration. Transp Sci 41(2):206–221

Ertogral K, Wu SD (2000) Auction-theoretic coordination of production planning in the supply chain. IIE Trans 32(10):931–940

Fink A (2006) Coordinating autonomous decision making units by automated negotiations. In: Chaib-draa B, Müller J (eds) Multiagent-based supply chain management. Springer, Berlin, pp 351–372

Fisher ML, Jaikumar R, van Wassenhove LN (1986) A multiplier adjustment method for the generalized assignment problem. Manage Sci 32(9):1095–1103

Gülpinar N, Rustem B, Settergren R (2004) Simulation and optimization approaches to scenario tree generation. J Econ Dyn Control 28(7):1291–1315

Krajewska MA, Kopfer H (2006) Collaborating freight forwarding enterprises. OR Spectr 28(3):301–317

Macharis C, Bontekoning YM (2004) Opportunities for OR in intermodal freight transport research: a review. Eur J Oper Res 153(2):400–416

OECD (2007) OECD Glossary of statistical terms. Tech. rep., Organisation for Economic Co-operation and Development, Paris

Puettmann C (2010) Collaborative planning in intermodal freight transportation. PhD thesis, University of Hamburg (forthcoming)

Reim U (2007) Kombinierter Verkehr 2005-Wachstum der Containertransporte in allen Verkehrsbereichen. Wirtschaft und Statistik, Statistisches Bundesamt, Wiesbaden 2:169–179

Schneeweiss C, Zimmer K (2004) Hierachical coordination mechanisms within the supply chain. Eur J Oper Res 153(3):687–703

Spengler J (1950) Vertical integration and antitrust policy. J Polit Econ 58(4):347–352

Stadtler H (2009) A framework for collaborative planning and state-of-the-art. OR Spectr 31(1):5–30

Walther G, Schmid E, Spengler TS (2008) Negotiation-based coordination in product recovery networks. Int J Prod Econ 111(2):334–350

Williams HP (2003) Model building in mathematical programming, 4th edn. Wiley, Chichester