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Operationalizing Auction-Based Strategic Carriers' Selection in Distribution Networks

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Abstract. This paper proposes a general framework for carriers' selection that includes both strategic and operational phases. The strategic phase uses a combinatorial auction mechanism in which a set of carriers compete by submitting package bids on the shipper's requests. Winning bidders are determined based on an aggregated data to minimize the shipper transportation costs. At the operational phase, more detailed information is available. Shipments are periodically assigned to carriers in order to minimize inventory, backorder and transportation costs while considering a number of restrictions implied by the strategic phase. Mathematical models for optimal carriers' selection at the strategic and operational phases are presented. An intensive experimental study is conducted to analyze the impact of different restrictions on operational costs and on the recourse that should be used by the shipper to operationalize its strategic decisions. We also investigate the relevance of the two-phase framework compared to a carriers' selection strategy where no strategic phase is performed.

Keywords: Carriers' selection, TL operations, combinatorial auctions, operational costs, shipments assignment.

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1. INTRODUCTION

According to the 25th Annual Third-Party Logistics Study (Langley and Infosys, 2020), "shippers and their third-party logistics providers (3PL) continue to experience benefits from their relationships". The study also shows that shippers and their 3PL "are moving closer to a strategic relationship than a transactional one". For the next five years, shippers predicted that strategic relationships with their 3PLs would increase to 45% (from the current 28%). Domestic and international transportation are reported as the most prevalent activities outsourced by shippers (Langley and Infosys, 2020).

A company that decides to outsource its transportation operations to external carriers has to make important decisions regarding the selection process. For example, should it favour long-term contracts relationship (1 to 3 years) and benefit from low rates and close relationships? In this case, a strategic phase becomes mandatory to select core carriers and standing contracts with binding clauses are to be respected. Or, isn't the company rather better to go for the spot market without engaging in such long-term relationships? In spot markets, transport rates are generally higher but long-term contracts are no more needed. If the company decides to go for the strategic selection, how should it manage the contracts clauses at the operational phase when assigning shipments to the carriers selected at the strategic phase?

Our paper aims to give insights on how to handle these issues in different operational contexts. Besides, companies that decide to engage with strategic carriers on a long-time period are guaranteed that some carriers are available to satisfy their shipment requests at the operational phase with relatively low transportation costs compared to the sport market. This strategic selection is thus mainly governed by transportation costs. However, at the operational phase, additional costs such as inventory and backorder costs should be considered. Moreover, at the strategic phase the shipper requests derive from a forecasting process resulting in aggregated and uncertain information. In other words, there is no guarantee neither for the carrier nor for the shipper that the strategic shipments will materialize during operations at the forecasted demand. Hence, if the forecasting system used by the shipper is unreliable, the strategic phase might be more detrimental than beneficial.

Our paper addresses these issues by considering a distribution problem where a company (the shipper) decides to outsource its full truckload (TL) transportation operations from its warehouses to its distribution centers (DCs) for the upcoming n-years planning horizon. We propose a general framework for carriers' selection that includes both the strategic and the operational phases in case strategic procurement prevails. The strategic selection uses an auction-based mechanism inspired by the work of Caplice and Sheffi (2006). A set of contract clauses from this strategic step are then handled at the operational phase to assign shipping contracts that effectively materialize to winning carriers (called strategic carriers).

A multi-period mathematical model is proposed for which constraints derived from the strategic phase are handled. The proposed model minimizes, in addition to transportation costs, inventory and backorder costs. While the proposed mathematical formulation uses standard concepts of production and logistics planning, it incorporates additional constraints to tackle the restrictions yielded by the strategic stage. The proposed model is an extension of existing models and, to the best of our knowledge, is the first to integrate information from the auction-based strategic selection phase.

Beyond proposing a mathematical model that can be solved to optimality by commercial solvers, our main objective is also to study the relevance of the strategic stage and evaluate its impact on the total distribution costs under different operational contexts obtained through varying the strategic contracts' clauses, the shipper replenishment strategy and the carriers' capacity. To do this, we conduct an exhaustive experimental study and compare two scenarios: a scenario in which a strategic phase is performed and a scenario where no strategic selection is done.

Another important objective of our experiments is to point out the different recourses that can be used by the shipper to tackle the engagements made with strategic carriers at the strategic phase and manage the variability of a number of operational parameters such as backorder costs, spot transportation costs and demand variability. Based on our results, we point out a number of insights and recommendations for the shippers questioning the relevance and the economic merits of the strategic phase for externals carriers' selection. To the best of our knowledge, there is no published paper that tackled the above issues in TL transportations services outsourcing.

The reminder of the paper is organized as follows. Section 2 presents a literature review on carriers' selection problems. Section 3 formally defines the problem addressed. Section 4 describes the proposed two-phase framework. Section 5 reports detailed results of the experimental study. Section 6 gives insights and recommendation for shippers based on a deep analysis of the obtained results. Section 7 concludes the paper and discusses future research avenues.

2. LITERATURE REVIEW

In a highly competitive market, shippers need to control their costs while providing high services quality for their clients. Thus, the procurement of efficient and competitive transportation services become central for shippers (Meixell and Norbis,2008).

Premeaux (2002) defines six main criteria used by shippers to select external carriers: information access, consistent carrier performance, solid customer relationships, flexible rates, service quality and the availability of certain desired services such as effective responses in emergency or unexpected situations. Voss et al. (2006) and Liao and Rittscher (2007) reported that the reliability of delivery and transfer prices are the first two criteria considered by shippers when selecting carriers. Mesa-Arango and Ukkusuri (2014) developed a mixed logit model in order to test the selection attributes and help shippers quantifying the willingness to pay. Davis-Sramek et al. (2018) study the effects of a carrier's economic, environmental and social sustainability performance on a shipper's truckload carrier selection decision. The results of their empirical study reveal that while all three dimensions of sustainable supply chain management positively influence carriers' selection, the economic dimension plays the biggest role.

Generally, transportation services can be procured either on a spot market (one-time procurement) or through long-term contracts with a set of core carriers (referred to in the following as the strategic carriers). In the last decades, several problems have been widely considered by researchers to study the procurement process at the strategic phase. A systematic review of the literature in the general context of full truckload transportation service procurement can be found in Basu et al. (2015). Our literature review focuses on papers that tackle strategic transportation services procurement trough auction mechanisms.

The use of the so-called combinatorial auctions for the procurement of TL transportation services considerably increased in the last decades. In an auction context, the shipper submits its requests to a set of pre-selected carriers invited to participate based on pre-specified criteria. A shipper request is defined by the shipments that must be ensured between an origin and a destination location (also called a lane) over a specified panning horizon. Carriers compete by submitting bids on the shipper's requests. They may either bid on each lane individually (the so-called simple bids) or on a package of lanes (the so-called package or combinatorial bids). Combinatorial auctions enable package bidding so that a carrier is ensured to be allocated all the lanes covered by its bid if it wins. When constructing such bids, the carriers aim at maximizing their profits and/or minimizing their empty moves. After receiving all the carriers' bids, the shipper solves the so-called Winner Determination Problem (WDP) to determine winning carriers with the objective to minimize its transportation costs.

Various modelling approaches have been proposed to study and solve the WDP in combinatorial auctions for transportation services procurement. Caplice and Sheffi (2003) provided several optimization models for assigning lanes to carriers without and with permitting package bids. They also discussed extensions of the WDP by including business side constraints. In Guo et al. (2006), the objective was to solve a WDP while incorporating shipper non-financial objectives and carrier transit point costs. Yadati et al. (2007) considered a WDP in which the carriers provide a quantity-discount function of prices. Xu and Huang (2014) propose a one-sided Vickrey-Clarke-Groves (O-VCG) combinatorial auction for the distributed transportation procurement problem. The O-VCG auction minimizes the total transportation cost and induces truthful bidding from carriers. Later, Mansouri and Hassini (2019) considered both the WDP and the bid pricing problem and established the convergence of the so-called iterative flexible auctions. They demonstrate that flexible auctions generate lower market prices, require less computational effort to reach optimality and converge faster than static auctions. Rekik and Mellouli (2012) proposed a general model for the WDP that aims at managing the trade-off between bid ask-prices and carriers' reputation. The reputation is modeled as unexpected hidden costs that the shipper may incur during operations when dealing with the winning carriers.

Short-term procurement through transportation spot markets was also addressed by various researchers. Mes et al. (2009) focused on revenue maximizing strategies for shippers in the spot market. They conducted a simulation study in order to analyze the performance of the dynamic threshold policy adopted by the shipper in a spot market setting. Berger and Bierwirth (2010) developed a framework for collaboration among carriers in a competitive market setting while maximizing the total profit of the collaborative carriers' network. Wang et al. (2014) addressed the way that the operational planning of freight forwarders in road haulage should be performed considering subcontracting and collaborative requests exchange. Ziebuhr and Kopfer (2014) proposed an approach based on an adaptive large neighborhood search combined with a column generation procedure to solve the integrated operational transportation planning problem with different kinds of compulsory requests. Lindsey and Mahmassani (2017) developed a behaviourally based conceptual framework that uses third party logistics broker data to improve the search for capacity on the spot market and reduce costs. Scott (2018) analyzes the behavior of different participants in online spot auctions and proves that the effective use of the spot market allows carriers to price their assets more competitively and increase profitability. The results obtained suggest that an online marketplace linking shippers directly with the thousands of asset-based carriers could add considerable value to the for-hire trucking industry.

Few studies have addressed the integration of strategic and operational planning in freight transportation. In this context, Feki et al. (2016) proposed an adaptive carriers' selection strategy under demand and carriers' availability uncertainty. Within a long-short term framework, their study emphasis on the allocation of freight shipments in a short-term continuous time.

Hassan et al. (2020) addressed the problem of freight demand forecasting. This issue appears to be important to help managing, planning, operating and optimizing the use of resources. The authors propose a demand forecasting methodology that supports freight operation planning over short to long term horizons and show its effectiveness through a case study. Recently, Wang et al. (2022) presented a systematic study of different shipping structures in the presence of uncertainties of both market demand and spot freight market. They use a Stackelberg games model that considers the carrier's long-term decision (on freight rate), the shipper's long-term decision (on shipment demand) and the spot market supplementary procurement decisions. Their study shows how the spot market can increase the carrier-shipper's overall performance.

To the best of our knowledge, no paper studied the problem of operationalizing the strategic carrier's selection decisions output by a combinatorial auction mechanism. By operationalizing, we mean the allocation of shipments on shorter periods while considering (1) the decisions made in the strategic phase, (2) the operational constraints and costs other than those related to transportation operations (e.g., inventory and backorder, desegregated demand, depot capacity, replenishment, etc.). Our paper is the first to address this problem. It proposes a mathematical model that incorporates and adapts a number of objectives and constraints commonly used for distribution planning problems (Kumar et al., 2020) and additionally considers constraints related to the commitments made by the shipper at the strategic stage.

The proposed model is easily implementable although managing a number of issues not yet integrated in carrier's selection and distribution planning. Most importantly, the proposed mathematical model is solved to optimality with a commercial solver (CPLEX 12.7, in our case) in very short computing times enabling thus a deep and concise analysis of the optimal decisions. Based on this, we conduct an extensive experimental study to evaluate the economical merits/drawbacks of considering a strategic selection within different contexts. Our experimental study also give insights on how different recourses can be used to face variability in a number of parameters either strategic or operational-based. To the best of our knowledge, this has not been yet investigated in the existing literature.

3. PROBLEM DESCRIPTION

3.1 Context and assumptions

We consider a distribution problem where the company (the shipper) has to move different final products from its warehouses to its distribution centers (DCs) to satisfy the demand of each product at each DC for each period of the upcoming multiple-period planning horizon. These transport operations are outsourced to external carriers and products are shipped in full truckloads directly from the warehouses to the distribution centers (TL operations). The distribution problem tackled here consists in determining the quantity of each product that must be transported by each external carrier from each warehouse to each distribution center at each period to minimize inventory (at warehouses and DCs), backorder (at DCs) and transportation costs. A number of constraints such as warehouses and DCs' capacities and carriers' capacities, must be considered. Figure 1 depicts the problem addressed.

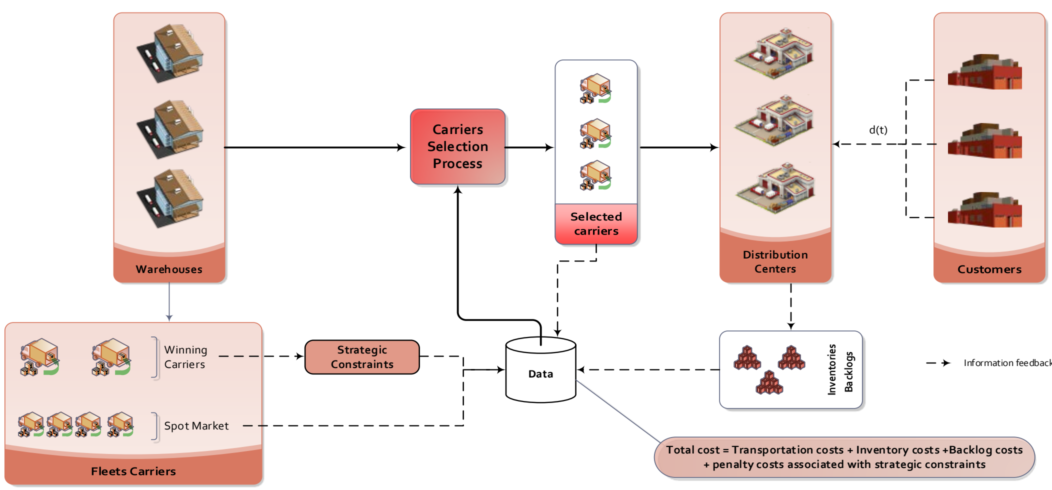

Figure 1: Problem description

Strategically, the shipper has two alternatives when outsourcing its transportation operations. The first alternative consists in using only the spot market. In other words, external carriers are selected on a period-to-period basis from the spot market when a shipment is needed. This alternative may be risky (the capacity of the spot market is insufficient) and economically inefficient (spot prices are generally high). The second alternative, which we propose and investigate in details in this paper, consists in addressing the carriers' selection problem in two phases: a strategic phase followed by an operational phase. The strategic phase aims at selecting core carriers with relatively low transportation rates with which the shipper will engage over a multiple-period planning horizon. Long-terms contracts are then established and should be respected by both parties during operations. The shipper has then to respect these contractual restrictions at the operational phase in addition to the other classic operational constraints.

In what follows, a long-term planning horizon is typically composed of multiple years and is considered at the strategic selection process (if a strategic phase is used for carriers' selection). The information available at this phase is aggregated and may be imprecise. A short-term planning horizon generally extends up to one year with a more detailed information on the problem data. The distribution problem tackled here considers a short-term planning horizon implying that the quantities to be shipped from each warehouse to each DC for each product must be decided for each period of this short-term planning horizon.

The distribution problem addressed aims to minimize inventory, backorder and transportation costs. We assume that the capacities of warehouses and DCs are constant over the planning horizon and the backorders at DCs are permitted but penalized. The set of carriers may include spot carriers only or both strategic and spot carriers, depending on the strategy adopted by the shipper in selecting external carriers. Regardless of the type of carrier, each will specify its capacity (in standard units) for each period of the planning horizon.

3.2 Mathematical formulation

This section proposes a mathematical formulation of the distribution problem assuming that no strategic selection phase was performed or that a strategic selection of carriers occurred but no commitment constraints (related to long-term contracts) were considered at the operational phase. Table 1 displays the sets, the parameters and the decision variables used to model the problem.

Sets	
I	Set of warehouses
J	Set of distribution centers (DC)
P	Set of final products
T	Set of discretized periods of equal lengths (the short-term planning horizon)
C	Set of carriers
$A(t,p)$	Set of lanes (i,j); $i \in I, j \in J$, on which product p can be shipped in period t
	Parameters
$D_{p,j,t}$	Demand of product p at DC j for period t
v_p	The volume occupied by one unit of product p
RW_i	Capacity of a warehouse i
RD_j	Capacity of a DC j
$\kappa_{c,t}$	Capacity of carrier c in period t (in number of units)
$IW_{p,i}$	Unit inventory cost of product p in warehouse i
$ID_{p,j}$	Unit inventory cost of product p in DC j
$BD_{p,j}$	Unit backorder cost of product p in DC j
$CO_{i,j}^{c}$	Unit transportation cost from a warehouse i to a DC j offered by carrier c
	Decision variables
$\chi_{p,c,i,j,t}$	Quantity of product p assigned to carrier c between warehouse i and DC j in period t
$Q_{p,i,t}$	Quantity of product p procured to warehouse i at the beginning of period t
$SW_{p,i,t}$	Inventory level of product p in warehouse i at the beginning of period t
$SD_{p,j,t}^{+}$	Inventory level of product p in DC j at the beginning of period t
$SD_{p,j,t}^{-}$	Backorder level of product p in DC j at the beginning of period t

Table 1: Sets, parameters and decision variables

The operational distribution problem can be formulated as follows:

$$Min \sum_t \sum_p \sum_{i\in I} IW_{p,i} SW_{p,i,t} + \sum_t \sum_p \sum_{j\in J} (ID_{p,j} SD^{+}_{p,j,t} + BD_{p,j} SD^{-}_{p,j,t}) + \sum_t \sum_p \sum_{c\in C} \sum_{(i,j)\in A(t,p)} CO^{c}_{i,j}\, \chi_{p,c,i,j,t} \quad (1)$$

Subject to:

$$\sum_p \sum_{(i,j)\in A(t,p)} \upsilon_p \chi_{p,c,i,j,t} \leq \kappa_{c,t} \qquad \forall t \in T, c \in C \quad (2)$$

$$\sum_{c\in C} \sum_{j:(i,j)\in A(t,p)} \chi_{p,c,i,j,t} - SW_{p,i,t} + SW_{p,i,t+1} - Q_{p,i,t} = 0 \qquad \forall t \in T, p \in P, i \in I \quad (3)$$

$$\sum_{p\in P} SW_{p,i,t} + \sum_{p\in P} Q_{p,i,t} \leq RW_i \qquad \forall i \in I, t \in T \quad (4)$$

$$\sum_{c\in C} \sum_{i:(i,j)\in A(t,p)} \chi_{p,c,i,j,t} + (SD^{+}_{p,j,t} - SD^{-}_{p,j,t}) - (SD^{+}_{p,j,t+1} - SD^{-}_{p,j,t+1}) = D_{p,j,t} \; \forall t \in T, p \in P, j \in J \quad (5)$$

$$\sum_{p\in P} \sum_{c\in C} \sum_{i:(i,j)\in A(t,p)} \chi_{p,c,i,j,t} + \sum_{p\in P} SD^{+}_{p,j,t} \leq RD_j;\; \forall j \in J, t \in T \quad (6)$$

$$\chi_{p,c,i,j,t} \geq 0; \forall p \in P, t \in T, c \in C, (i,j) \in A(t,p) \quad (7)$$

$$Q_{p,i,t}, SW_{p,i,t} \geq 0;\; \forall p \in P, i \in I, t \in T \quad (8)$$

$$SD^{+}_{p,j,t}, SD^{-}_{p,j,t} \geq 0;\; \forall p \in P, j \in J, t \in T \quad (9)$$

The objective function (1) aims at minimizing the total logistic costs on the whole planning horizon. The logistic costs are composed of the inventory costs at warehouses, the inventory and backorder costs at DCs, and the transportation costs. Constraints (2) ensure that the total amount transported by carriers satisfy their capacity for each period. Constraints (3) link stock levels of each product at each warehouse for two consecutive time periods with the corresponding inflow ($Q_{p,i,t}$) and outflow ($\chi_{p,c,i,j,t}$) quantities. Constraints (4) ensure that the maximum amount that can be stored at a warehouse during a period respects the warehouse capacity. Notice that our model assumes that no shortage is permitted at warehouses. In model (1)-(10), the quantity arriving at warehouses at the beginning of each period ($Q_{p,i,t}$) is considered as an unbounded decision variable which would correspond to a just-in-time replenishment strategy. However, the model can be easily adapted to tackle a periodic replenishment strategy with a fixed order quantity by considering $Q_{p,i,t}$ as an input parameter rather than a decision variable. In our experimental study, we consider both replenishment strategies. Constraints (5) ensure that the inventory (or backorder) level of product p at DC j at the beginning of period (t+1) is equal to the sum of its inventory (backorder) level at the beginning of period t and the corresponding quantity entering DC j during period t (the quantity transported to it) minus the product demand at period t. Constraints (6) ensure that the maximum amount that can be stored at a DC during a period respects the DC capacity. Finally, constraints (7)-(9) are non-negativity constraints on the decision variables.

The next section describes the two-phase framework we propose for carriers' selection that considers both strategic and operational phases.

4. THE TWO-PHASE CARRIERS' SELECTION FRAMEWORK

Figure 2 describes the conceptual framework proposed for external carriers' selection. The selection process is composed of three main stages: a pre-auction stage, an auction stage and an operational stage. The first two stages correspond to the strategic selection phase which uses an auction-based mechanism to decide on the core carriers to engage with over a long-term planning horizon (multiple years). The third stage corresponds to the operational selection phase to decide on the quantity to be attributed to each carrier over a short-term planning horizon (less than a year). In summary, strategic carriers, with which the shipper will engage on the upcoming long-term planning horizon, are selected through an auction-based process. Before running the auction, the shipper goes within a forecasting process to estimate its transportation needs over a long-term planning horizon. These forecasts are then converted into a set of shipment requests or queries in which the shipper specifies: the pick-up and delivery locations (either aggregated or not), referred to as lanes, possibly the volume to be transported on each lane, and some other information on shipping conditions, specific equipment, etc. (Caplice and Sheffi, 2006).

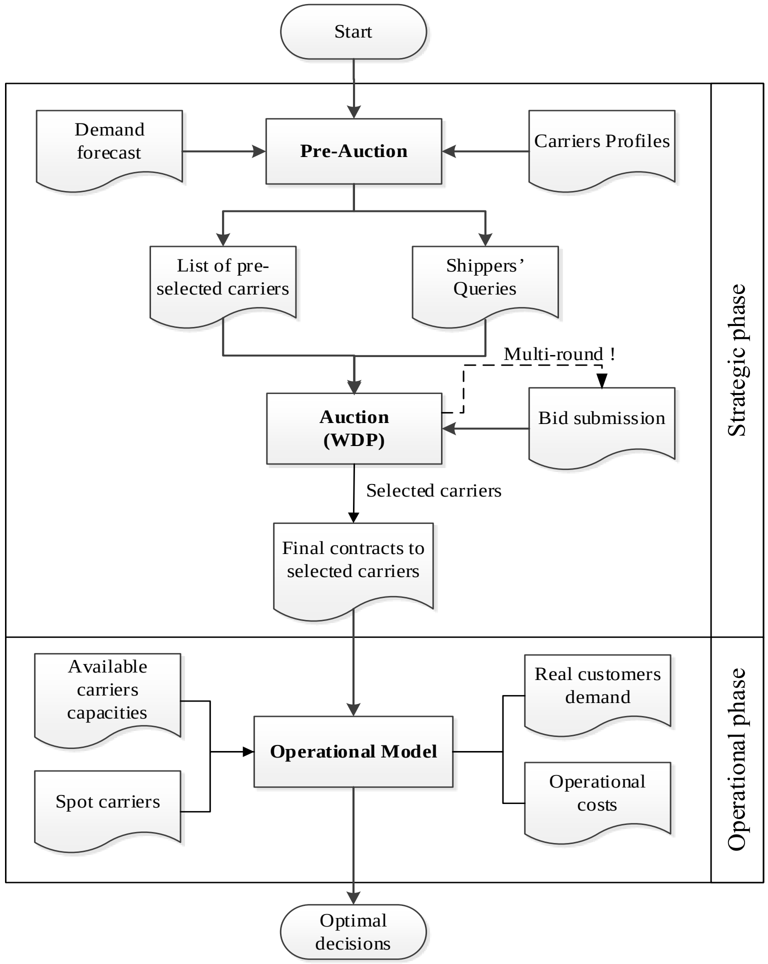

Figure 2: Conceptual framework for carriers' selection

During the pre-auction stage, the shipper also decides on the auction format (one-round or multi-round, stopping rules, etc.) and on the bid structure (e.g., simple or combinatorial). We refer the reader to the paper of Abrache et al. (2007) for a taxonomy of auctions. Several carriers are then invited to participate in the auction. A set of criteria could be used here to identify the carriers' profiles judged acceptable by the shipper (Hong et al., 2004; Voss et al., 2006). Then, based on the shipper requests, each carrier, that passed the pre-selection screening, determines the set of profitable bids to submit to the auction.

After receiving all the carriers' bids, the shipper solves the WDP to determine the winning bids. In case a single-round auction is organized, the auction process ends at this step. In case a multi-round auction is used, the process iterates until the auction stopping criteria are met. At the end of the auction process, winning carriers with associated winning shipments are known. The shipper communicates these results to the participants and final long-term contracts are established with the winners. The terms of these contracts impose some restrictions on both the shipper and the carriers that must be respected during operations over the planning horizon.

At the operational phase, the shipper has more precise information on its shipment requests, market demand and carriers' capacities. In addition to transportation costs, other costs such as inventory and backorder costs must be considered when selecting carriers on each period of the planning horizon. At this phase, the shipper may select carriers either from the set of strategic carriers determined at the strategic phase or from the spot market. The selection process should however satisfy the contract clauses established with strategic carriers.

Sections 4.1 and 4.2 hereafter present a detailed description of the key concepts related to each phase.

4.1 The strategic phase

4.1.1 Auction format

As already mentioned, the pre-auction stage enables restraining the set of carriers whose profiles fit the shipper preferences and the auction format. Carrier's profile may include, for example, the type of prices they could submit at the strategic phase (a price per lane or per unit volume shipped), their available capacity (number of trucks, capacity loading of each truck), the regions and areas they could deliver, etc. Common practice is to retain most incumbent carriers and invite some new carriers to participate into the auction (Caplice and Sheffi, 2006).

Regarding the auction type, we illustrate the most common and likeable case where a single-round combinatorial auction is used. In practice, single-round bidding processes are preferred since both the shipper and the participating carriers seek for simplicity and speed (Sheffi, 2004; Caplice and Sheffi, 2006). Combinatorial bidding enables a carrier to express its preferences for package of contracts in the same bid. Hence, if the bid is won, all the contracts in the package are allocated to the carrier, otherwise, none of the contracts in the package is allocated. Combinatorial auctions have proven their efficiency for TL transportation services procurement due to the economy of scope characterizing TL operations.

The carriers conduct then their own analysis of the shipper queries and prepare their bids according to the format required by the shipper. We consider the case where the carrier must specify in its bid: (1) the package of lanes (origin-destination pairs) it is ready to cover, (2) the minimum and maximum volumes for each lane, and (3) the transportation cost per lane and per volume unit shipped on this lane. Minimum volume restrictions imposed in bids is a guarantee for the carrier that the shipper will give it a minimum amount of business at the submitted bid price. The maximum volume restrictions reflect the carrier capacity or the volume of service it is ready to offer at the proposed price.

The way a carrier combines lanes and determine ask prices, minimum and maximum volumes, known as the bid construction or the bid generation problem, is not addressed in this paper. We refer the reader to the papers by Song and Regan (2005), Wang and Xia (2005) and Hammami et al. (2019) for more details on this topic. Once carriers' bids are received, the shipper solves the WDP in order to determine winning bids and the associated volumes.

4.1.2 The winner determination problem (WDP)

Let L be the set of lanes resulting from the shipper forecasting process. A lane l is defined by an origin location and a destination location. In our case, an origin location may correspond to a specific warehouse or to an aggregation of warehouses (for example, warehouses that are geographically close are grouped in a same origin zone). Similarly, a destination location may represent either a specific DC or an aggregation of DCs. The shipper also associates to each lane l an annual volume V_l corresponding to the quantity forecasted to be shipped on lane l for each year of the long-term planning-horizon. Observe that this volume results from a rough and aggregate approximation of products demand at DCs and products availability at warehouses.

Let C^{pre} be the set of carriers pre-selected at the pre-auction phase. Each carrier $c \in C^{pre}$ is assumed to submit a set of combinatorial bids B^c. A combinatorial bid $b \in B^c$ is defined by: (1) the set of lanes it covers, denoted $L^{c,b}$, (2) the minimum annual volume $\mathrm{LB}_\mathrm{l}^{\mathrm{c,b}}$ that must be allocated on lane l, (3) the maximum annual volume $\mathrm{UB}_\mathrm{l}^{\mathrm{c,b}}$ that can be allocated on lane l, and (4) the transportation rate $\mathrm{CS}_l^{c,b}$ asked for each volume unit transported on lane l. Observe that such bids correspond to the flexible package bids introduced by Caplice and Sheffi (2006).

The WDP is then modeled using two sets of decision variables. A binary variable $G^{c,b}$ is defined for each carrier $c \in C^{pre}$, and each bid $b \in B^c$. Variable $G^{c,b}$equals 1 if the bid b submitted by carrier c wins; 0 otherwise. A continuous variable $W_l^{c,b}$ is defined for each carrier $c \in C^{pre}$, each bid $b \in B^c$, and each lane l covered by bid b (i.e., $l \in L^{c,b}$). Variable $W_l^{c,b}$ represents the volume affected to lane l in bid b if won by carrier c. A constant 0-1 parameter $\delta_l^{c,b}$ is also defined to indicate if bid b submitted by carrier c covers lane l (i.e., $\delta_l^{c,b} = 1\ if\ l \in L^{c,b}$; 0 otherwise). The WDP is formulated as follows:

$$\text{Min} \quad \sum_{c \in C^{pre}} \sum_{b \in B^c} \sum_{l \in L^{c,b}} CS_l^{c,b}\, W_l^{c,b} \tag{10}$$

Subject to:

$$\sum_{c \in C^{pre}} \sum_{b \in B^c} \delta_l^{c,b} W_l^{c,b} \geq V_l \ ;\ \forall\, l \in L \tag{11}$$

$$-UB_l^{c,b} G^{c,b} + W_l^{c,b} \leq 0 \ ;\ \forall\, c \in C^{pre}, b \in B^c, l \in L^{c,b} \tag{12}$$

$$-LB_l^{c,b} G^{c,b} + W_l^{c,b} \geq 0;\ \forall\, c \in C^{pre}, b \in B^c, l \in L^{c,b} \tag{13}$$

$$G^{c,b} \in \{0, 1\} \ ;\ \forall\, c \in C^{pre}, b \in B^c \tag{14}$$

$$W_l^{c,b} \geq 0 \ ;\ \forall\, c \in C^{pre}, b \in B^c, l \in L^{c,b} \tag{15}$$

The objective function (10) minimizes the total transportation costs. Constraints (11) guarantee that the annual demand on each lane is satisfied. Constraints (12) ensure that if a bid b submitted by a carrier c is selected, then the annual volume allocated to each lane covered by this bid satisfies the maximum volume capacity imposed by the carrier in its bid. Constraints (12) also model the all-or-nothing particularity of combinatorial bidding. They ensure that if a bid b is not won (i.e., $G^{c,b}$ =0), then no volume can be affected to any lane covered by this bid (all $W_l^{c,b} \in L^{c,b}$ take null values). In other words, none of the lanes covered by a loosing bid are allocated to the carrier for that bid. With constraints (13), a winning bid $b \in B^c$ will be assigned at minimum $LB_l^{c,b}$ volume units annually for each lane l it covers. Constraints (14) and (15) define the nature of decision variables considered in the model. Observe that model (10)-(15) corresponds to one of the WDP formulations proposed by Caplice and Sheffi (2006) except that in their model the demand is satisfied to equality in constraints (11). Indeed, imposing equality constraints may result in infeasible problems in cases there is no sets of submitted bids that enable satisfying the demand to equality and respecting the minimum and maximum volume restrictions (12) and (13). One can thus rather use inequality constraints and permit the annual volume V_l to be overcovered to reduce the likelihood of infeasible problems.

4.1.3 Final contracts

Solving the WDP (10-15) yields an optimal solution $\left(G^{c,b*}, W_l^{c,b*}\right)$ from which one can derive the set of winning bids, the optimal volumes to be associated to each lane in each winning bid, the associated unit transportation costs and thus the set of winning carriers.

Let C^s denote the set of carriers selected at the strategic phase. These carriers correspond to those winning at least one bid. That is, $C^s = \{c \in C^{pre}: \exists b \in B^c : G^{c,b*} = 1\}$. For each selected carrier $c \in C^s$, we denote by $B^{c,s}$ the set of bids won by this carrier. That is, $B^{c,s} = \{b \in B^c : G^{c,b*} = 1\}$. Recall that at the strategic phase, the data available is generally aggregated, imprecise and results from a rough forecasting process. Hence, although the WDP gives the optimal volumes to be assigned annually to each winning carrier ($W_l^{c,b*}$), it is unlikely that these amounts correspond exactly to what would be optimal to allocate to strategic carriers during operations. One has however the guarantee that lanes are attributed to carriers in a way that respect their volume constraints and the shipper estimated demand at lower transportation costs.

Based on this, the approach we propose assumes that the shipper will ensure to each winning carrier $c \in C^s$ that during each year of the planning horizon on which they engage:

- An annual volume greater than $LB_l^{c,b}$ will be assigned to each lane *l* covered by a winning bid $b \in B^{c,s}$ if the lane *l* materializes. A lane *l* materializes if there is a request for a shipment on it during the operational phase. In case the volume assigned to the carrier is less than $LB_l^{c,b}$, the shipper may pay a penalty. If common or current practices do not impose direct monetary penalties, our model incorporates this penalty as an indirect future consequence that may arise if the shipper accumulates large gaps between its engagement at the strategic phase and the real allocated volumes.
- No more than $\mathrm{UB}_l^{\mathrm{c,b}}$ volume units are assigned to each lane l covered by a winning bid $b \in B^{c,s}$. If the volume assigned to the carrier during operation exceeds this amount, a penalty for each additional unit is incurred by the shipper. Indeed, there is no guarantee that the carrier would have a sufficient capacity left for non-planned shipments, at least not at a price as low as that submitted to the auction. Here also, if common or current practices do not impose direct monetary penalties, our model still incorporates this penalty as an incentive for the shipper to respect its engagement at the strategic phase.

4.2 Operational phase

As described in Section 3, the operational phase considers a distribution problem where the company has to move different final products from its warehouses to its distribution centers (DCs) to satisfy the demand of each product at each DC for each period of the short-term planning horizon (one year in our case). As already mentioned, during operations, the company has to manage inventory and backorder costs in addition to transportation costs. In section 3.2, we proposed a mathematical formulation in case no strategic selection of external carriers is performed. In this section, we adapt and extend this formulation to incorporate the constraints yielded by considering the strategic phase presented in Section 4.1.

To do this, we first partition the set of carriers C into two subsets: a subset C^s of strategic carriers selected at the strategic phase (output of model (10)-(15)) and a set C^o of spot carriers available at the operational phase from the spot market. Recall that at the strategic phase, aggregate shipments requests are formulated on lanes that are defined by pairs of origin-destination locations. These locations represent either specific or aggregate warehouses and/or DCs. At the operational phase, the information is disaggregated and more detailed.

In order to handle this issue, we introduce the following parameters:

- $\varphi_{i,l} = 1$ if warehouse i is associated with the origin location of lane l as defined in the strategic step; 0, otherwise,
- $\phi_{j,l} = 1$ if DC j is associated with the destination location of lane l as defined in the strategic step; 0, otherwise.

Based on this, a bid b of a carrier c covers a pair $(i,j); i \in I, j \in J$, if there exists a lane $l \in L^{c,b}$ such that $\varphi_{i,l} = \phi_{j,l} = 1$. The set of bids that cover a pair (i,j) is denoted $B(i,j)$ and the corresponding lane $l(i,j)$.

To formulate the distribution problem of the operational phase, we consider the same decision variables as in the model (1-9) to which we add the following continuous decision variables:

- $Y_{c,l}^{b}$ defined for each strategic carrier $c \in C^s$, each bid $b \in B^{c,s}$ won by this carrier, and each lane l covered by b. This variable represents the lacking amount to reach the lower bound $\mathrm{LB}_l^{c,b}$promised to carrier c on lane l in its bid b.

- $Z_{c,l}^{b}$ defined for each strategic carrier $c \in C^{s}$, each bid $b \in B^{c,s}$ won by this carrier, and each lane l covered by b. This variable represents the amount exceeding the upper bound $\mathrm{UB}_{l}^{\mathrm{c,b}}$ fixed by carrier c on lane l in its bid b.

Moreover, for the sake of generalization, we replace the decision variables $\chi_{p,c,i,j,t}$ representing the quantity of product p assigned to each carrier $c \in C$ between warehouse i and DC j at period t, with two sets of decision variables as follows:

- $XS_{p,c,i,j,t}^{b}$ defined for each period t, each product p, each strategic carrier $c \in C^{s}$, each bid $b \in B^{c,s}$ won by this carrier, and each pair (i,j) covered by b. This variable represents the amount of product p assigned to carrier c between i and j at period t and for which the transportation rate $CS_{l(i,j)}^{c,b}$ is applied.
- $XO_{p,c,i,j,t}^{o}$ defined for each period t, each product p, each spot carrier $c \in C^{o}$ and each pair (i,j). This variable represents the amount of product p assigned to carrier c between i and j at period t.

Defining different transportation variables for strategic carriers and spot carriers become mandatory since restrictions on the volumes to be assigned apply only to strategic carriers with respect to their winning bids. Moreover, at the strategic phase, a carrier may win two bids covering the same lane *l* with different volume restrictions and different transportation rates. This explains why the bid index is considered when defining transportation variables $XS_{p,c,i,j,t}^{b}$.

Based on the above observations, the transportation cost from a warehouse $i \in I$ to a DC $j \in J$ offered by carrier c (denoted $CO_{i,j}^{c}$ in model (1-9)), is now defined depending on the carrier type (strategic or spot) and on the bids won for strategic carriers as follows:

- $\mathrm{CS}_{\mathrm{i,j}}^{\mathrm{c,b}}$= the unit transportation cost from warehouse i to DC j proposed by carrier $c \in C^{s}$ in his winning bid b knowing that bid b covers the pair (i,j). In this case, $CS_{i,j}^{c,b} = CS_{l(i,j)}^{c,b}$ as concluded in the long-term contract established with the shipper.
- $CO_{\mathrm{i,j}}^{\mathrm{c,o}}$= the unit transportation cost from warehouse i to DC j proposed by the spot carrier $c \in C^{o}$ at the operational phase.

Finally, we define $\varepsilon_{i,j}^{c,b}$, respectively $\omega_{i,j}^{c,b}$, as the unit penalty cost for not respecting the minimum, respectively the maximum, volume constraints on lane (i,j) associated with the bid b of carrier c. The problem can thus be modeled as follows:

$$Min\ \sum_t \sum_p \sum_i IW_{pi} SW_{pit} + \sum_t \sum_p \sum_j (ID_{pj}\, SD^+_{pjt} + BD_{pj} SD^-_{pjt}) + \sum_t \sum_p \sum_{c\in C^s} \sum_{b\in B^{c,s}} \sum_{(i,j)\in L^{c,b}} CS^{c,b}_{i,j}\, XS^b_{p,c,i,j,t} + \sum_{c\in C^s} \sum_{b\in B^{c,s}} \sum_{(i,j)\in L^{c,b}} (\varepsilon^{c,b}_{i,j} Y^{-b}_{c,i,j} + \omega^{c,b}_{i,j} Z^{+b}_{c,i,j}) + \sum_t \sum_p \sum_{c\in C^o} \sum_{(i,j)} CO^{c,o}_{i,j}\, XO^o_{p,c,i,j,t} \tag{16}$$

Subject to:

$$\sum_p \sum_{b\in B^{c,s}} \sum_{(i,j)\in L^{c,b}} XS^b_{p,c,i,j,t} \le \kappa_{ct} \qquad \forall t\in T, c\in C^s \tag{17}$$

$$\sum_p \sum_{(i,j)} XO^o_{p,c,i,j,t} \le \kappa_{ct}; \forall t\in T, c\in C^o \tag{18}$$

$$\sum_{c\in C^s} \sum_{b\in B^{c,s}} \sum_{j:(i,j)\in L^{c,b}} XS^b_{p,c,i,j,t} + \sum_{c\in C^o} \sum_{j:(i,j)} XO^o_{p,c,i,j,t} - S_{p,i,t} + S_{p,i,t+1} - Q_{p,i,t} = 0 \qquad \forall t\in T, p\in P, i\in I \tag{19}$$

$$\sum_p SW_{p,i,t} + \sum_p Q_{p,i,t} \le RW_i \qquad \forall i\in I, t\in T \tag{20}$$

$$\sum_{c\in C^s} \sum_{b\in B^{c,s}} \sum_{i:(i,j)\in L^{c,b}} XS^b_{p,c,i,j,t} + \sum_{c\in C^o} \sum_{i:(i,j)} XO^o_{p,c,i,j,t} + (SD^+_{p,j,t} - SD^-_{p,j,t}) - (SD^+_{p,j,t+1} - SD^-_{p,j,t+1}) = D_{p,j,t} \quad \forall t\in T, p\in P, j\in J \tag{21}$$

$$\sum_p \sum_{c\in C^s} \sum_{b\in B^{c,s}} \sum_{i:(i,j)\in L^{c,b}} XS^b_{p,c,i,j,t} + \sum_p \sum_{c\in C^o} \sum_i XO^o_{p,c,i,j,t} + \sum_p SD^+_{p,j,t} \le RD_j \quad \forall j\in J, t\in T \tag{22}$$

$$\sum_t \sum_p XS^b_{p,c,i,j,t} + Y^{-b}_{c,i,j} \ge \mathrm{LB}^{\mathrm{c,b}}_{\mathrm{i,j}} \qquad \forall c\in C^s, b\in B^{c,s}, (i,j)\in L^{c,b} \tag{23}$$

$$\sum_t \sum_p XS^b_{p,c,i,j,t} - Z^{+b}_{c,i,j} \le \mathrm{UB}^{\mathrm{c,b}}_{\mathrm{i,j}} \qquad \forall c\in C^s, b\in B^{c,s}, (i,j)\in L^{c,b} \tag{24}$$

$$XS^b_{p,c,i,j,t}, Y^{-b}_{c,i,j}, Z^{+b}_{c,i,j} \ge 0 \qquad \forall p\in P, t\in T, c\in C^s, b\in B^{c,s}, (i,j)\in L^{c,b} \tag{25}$$

$$XO^o_{p,c,i,j,t} \ge 0 \qquad \forall p\in P, t\in T, c\in C^o, i\in I, j\in J \tag{26}$$

$$SW_{p,i,t} \ge 0 \qquad \forall p\in P, i\in I, t\in T \tag{27}$$

$$SD^+_{p,j,t}, SD^-_{p,j,t} \ge 0 \qquad \forall p\in P, j\in J, t\in T \tag{28}$$

The objective function (16) aims at minimizing the inventory costs at warehouses, the inventory and backorder costs at DCs, the transportation costs associated with strategic and spot carriers, and the penalty costs if lanes lower and upper bounds are not respected. Constraints (17), respectively (18), ensure that the total amount transported by strategic carriers, respectively, spot carriers, at each period is lower than or equal to their capacity at each period. Constraints (19) translate the inventory state at DCs at each period. Constraints (20) ensure that warehouses capacity is respected. Constraints (21) are the inventory/backorder constraints at DCs. Constraints (22) ensure that DCs capacity are respected. Constraints (23) define the shortage volume of shipments assigned to a strategic carrier $c \in C^s$ with respect to the lower bound promised to it, for each bid $b \in B^{c,s}$ won by this carrier at the strategic phase, and each pair (i, j) covered by b. Constraints (24) are similar to (23) but consider the surplus with respect to upper bounds. Finally, constraints (25)-(28) are non-negativity constraints on the decision variables.

5. EXPERIMENTAL STUDY

The objective of this section is twofold. First, we want to investigate the impact of different problem parameters on the total cost induced by the proposed framework in different operational contexts. This is done by varying the parameters related to the strategic phase (strategic contracts' clauses), the operational phase (backorder cost, replenishment strategy, strategic carriers' capacity) and analyzing their impact on operational costs. The second objective is to assess the relevance (in terms of cost saving/loss) of the proposed two-phase carriers' selection strategy (referred to as T-CS) compared to a single-phase strategy (referred to as O-CS) where carriers are selected in the spot market on a period-to-period basis. Comparison is done in different contexts and aims to give insights on the relevance of performing a strategic selection.

The numerical experiments were carried out on a dual Intel Xeon X5650 processor 2.66 GHz and 72 GB DDR3 ECC Reg Memory RAM. All the mathematical models were implemented in Microsoft Visual C++ Redistributable 2015 and linked with the ILOG CPLEX 12.7 optimization library.

5.1 Data generator and problem tests

A large set of instances is generated to underline the relevance of adopting the T-CS framework and to investigate the impact of certain problem parameters on the average total costs in different contexts. More specifically, we vary the following parameters: (1) the lower and upper bounds imposed by the strategic carriers in their winning bids, (2) the corresponding penalty costs, (3) the strategic transportation cost, and (4) the backorder cost.

Four operational contexts are considered depending on the replenishment strategy adopted by the shipper (just-in time or periodic) and on the strategic carrier capacity during operations (limited or unlimited). An unlimited capacity for a strategic carrier implies that the carrier would accept all requests during operations independently of its real capacity so that the shipper decision on allocating lanes is not governed by the strategic carrier's capacity parameter. A limited capacity reflects the carrier's availability at the operational level. The first context, denoted C1, considers a just-in time replenishment with limited carriers' capacity. The second context, denoted C2, considers a just-in time replenishment with unlimited carriers' capacity. The third context, denoted C3, assumes a periodic replenishment with limited capacity and the fourth one, denoted C4, considers a periodic replenishment with unlimited capacity.

For all the instances, we consider a distribution problem over a 12-period planning horizon (one year with a discretization period of 1 month) with 10 warehouses, 14 distribution centers, and two products. The lanes considered at the strategic phase correspond to all the pairs (i, j), i=1,..,10, j=1,…,14. The results of the strategic phase are known and three strategic carriers are assumed selected. The winning bids and winning carriers are kept the same for all the instances. One spot carrier with an infinite capacity is considered at the operational phase. The demand of each product at each DCs for each period ($D_{p,j,t}$) is randomly generated following a normal distribution N(700, 60).

In order to generate coherent and relevant values for the lower and upper bounds restrictions in winning bids, we use the α and β parameters to represent the ratio between the lower, respectively, upper, bounds with respect to the average demand that could be covered by a warehouse for the corresponding DC. Formally, if b denotes a bid won by a strategic carrier c and covers lane l=(i, j), then the lower bound of this winning bid for the pair (i,j) is generated as: $\mathrm{LB}_{l(\mathrm{i,j})}^{\mathrm{c,b}} = \alpha \frac{\sum_t \sum_p D_{p,j,t}}{|I|}$. Similarly, $\mathrm{UB}_{l(\mathrm{i,j})}^{\mathrm{c,b}} = \beta \frac{\sum_t \sum_p D_{p,j,t}}{|I|}$. We give α different values varying from 0.1 to 2 and to β values ranging from 0.2 to 3. Observe that a large value of α implies that the lower bound associated with winning bids are relatively large with regard to the actual demand. This implicitly implies that the shipper forecasting system used at the strategic phase overestimated the real demand which may result in smaller shipment volumes to be assigned to carriers at the operational phase than planned. Larger shipment volumes at the operational phase would rather occur when the forecasting system underestimated the demand at the strategic phase. This is modeled by assigning a small value to the β parameter reflecting the case where bids won at the strategic phase does not offer enough capacity to satisfy the real demand during operations. The values of α and β may also reflect the output of the negotiation process between the shipper and the winning carriers after the auction clears.

Unitary transportation costs on pairs (i, j) are generated in a way that guarantees that those deriving from the strategic phase are less than those proposed in the spot market. Based on this, we first generate the unit spot costs following a uniform distribution within the interval [90,100]. Then, strategic costs are generated as $CS_{\mathrm{i,j}}^{\mathrm{c,b}} = f \times CO_{\mathrm{i,j}}^{\mathrm{c,o}}, \forall c \in C^s, b \in B^{c,s}, (i, j) \in L^{c,b}$; where the value of f is generated following a uniform distribution within an interval $[f_1, f_2]$. The unit penalty cost incurred by the company for allocating to a strategic carrier a volume lower than its lower bound is computed as a factor γ of the carrier transportation cost proposed at the strategic phase ($\varepsilon_{i,j}^{c,b} = \gamma \times CS_{\mathrm{i,j}}^{\mathrm{c,b}}, \forall c \in C^s, b \in B^{c,s}, (i, j) \in L^{c,b}$). The same principle applies for the unit penalty costs of exceeding the carrier upper bound with the Δ parameter ($\omega_{i,j}^{c,b} = \Delta \times CS_{\mathrm{i,j}}^{\mathrm{c,b}}, \forall c \in C^s, b \in B^{c,s}, (i, j) \in L^{c,b}$). Finally, the unit backorder cost for a product p at DC j is generated as: $BD_{p,j} = g \times \frac{\sum_i CO_{\mathrm{i,j}}^{\mathrm{c,o}}}{|I|}$, where g is a parameter to be fixed for each instance. Finally, for all the generated instances, the inventory costs at warehouses and DCs are uniformly distributed within the interval [4,5].

Table 2 reports the different problem tests carried out in each context. Observe that the first problem test is qualified as a basic case since the other 24 problem tests are obtained by increasing or decreasing the value of one or more parameters (as displayed in the column "Remark") modeling thus their variability at the operational level. Ten replications are randomly generated for each test in each context for a total of 1000 instances.

Instances	$\boldsymbol{\alpha}$	$\boldsymbol{\beta}$	$\boldsymbol{\gamma}$	Δ	$\boldsymbol{f1}$	$\boldsymbol{f2}$	g	***Remark***
1	0.5	1.5	0.2	0.2	0.7	0.75	0.8	Basic case
2	**0.1**	1.5	0.2	0.2	0.7	0.75	0.8	$\alpha\downarrow$
3	**1.2**	1.5	0.2	0.2	0.7	0.75	0.8	$\alpha\uparrow$
4	0.5	**0.9**	0.2	0.2	0.7	0.75	0.8	$\beta\downarrow$
5	**0.1**	**0.2**	0.2	0.2	0.7	0.75	0.8	$\alpha\downarrow\beta\downarrow$
6	**1.5**	**2**	0.2	0.2	0.7	0.75	0.8	$\alpha\uparrow\beta\uparrow$
7	0.5	**2**	0.2	0.2	0.7	0.75	0.8	$\beta\uparrow$
8	0.5	1.5	0.2	**0.5**	0.7	0.75	0.8	$\Delta\uparrow$
9	0.5	1.5	**0.5**	**0.7**	0.7	0.75	0.8	$\gamma\uparrow\Delta\uparrow$
10	0.5	1.5	**0.1**	**0.1**	0.7	0.75	0.8	$\gamma\downarrow\Delta\downarrow$
11	0.5	1.5	**0.1**	0.2	0.7	0.75	0.8	$\gamma\downarrow$
12	0.5	1.5	0.2	**0.1**	0.7	0.75	0.8	$\Delta\downarrow$
13	0.5	1.5	**0.5**	0.2	0.7	0.75	0.8	$\gamma\uparrow$
14	0.5	1.5	0.2	0.2	0.7	**0.9**	0.8	$f2\uparrow$
15	0.5	1.5	0.2	0.2	**0.5**	**0.6**	0.8	$f1\downarrow f2\downarrow$
16	0.5	1.5	0.2	0.2	**0.9**	**0.95**	0.8	$f1\uparrow f2\uparrow$
17	0.5	1.5	0.2	0.2	**0.65**	0.75	0.8	$f2\downarrow$
18	0.5	1.5	0.2	0.2	0.7	0.75	**3**	$g\uparrow$
19	0.5	1.5	0.2	0.2	0.7	0.75	**0.1**	$g\downarrow$
20	**0.1**	**0.2**	0.2	**0.5**	0.7	0.75	0.8	$\alpha\downarrow\beta\downarrow\Delta\uparrow$
21	0.5	1.5	**0.1**	**0.1**	**0.4**	**0.5**	**0.05**	$\gamma\downarrow\Delta\downarrow f1\downarrow f2\downarrow g\downarrow$
22	0.5	1.5	**0.1**	**0.1**	0.7	0.75	**3**	$\gamma\downarrow\Delta\downarrow g\uparrow$
23	**2**	**3**	**0.5**	0.2	0.7	0.75	0.8	$\alpha\uparrow\beta\uparrow\gamma\uparrow$
24	0.5	1.5	**0.5**	**0.5**	**0.95**	**1.5**	**3**	$\gamma\uparrow\Delta\uparrow\ f1\uparrow f2\uparrow g\uparrow$
25	**1**	**1**	**0.5**	**0.9**	0.7	0.75	**0.1**	$\alpha\uparrow\beta\downarrow\gamma\uparrow\Delta\uparrow g\downarrow$

Table 2: Description of problem tests

5.2 Results

The results obtained in the different contexts are summarized in Tables 3-6. In each table, we provide for each problem test and for each context the following information. For T-CS, we report: the average total cost (Z^1), the average transportation cost paid to the spot market (Z^{sp_s}), the average transportation cost paid to strategic carriers (Z^{str}), the average inventory cost (Z^{iv_s}), the average backorder cost (Z^{bk_s}), the average penalty cost associated with the lacking amount to reach the promised lower bounds (Z^{lk}), and the average penalty cost associated with the amount exceeding the upper bounds (Z^{ex}). For O-CS, we report the average total cost (Z^2), the average transportation cost (Z^{sp_o}), the average inventory cost (Z^{iv_o}), and the average backorder cost (Z^{bk_o}). These averages being computed over the 10 executions of each problem test. All the values are in M$. We also report (in the last column) the saving/loss (S_v) in average total costs induced by T-CS compared to O-CS computed as: $S_v = \frac{(Z^2 - Z^1)}{Z^2} * 100$. Observe that a positive (negative) value of S_v implies a saving (loss) in total costs induced by T-CS compared to O-CS. More details on the volumes assigned to each carrier are given in the appendix (Tables 7 to 10).

Figures 3 and 4 summarize the results obtained for the four contexts (C1-C4). Figure 3 depicts the deviation (in percentage) in total average costs obtained for each problem test in comparison to the basic case (problem test 1) with the T-CS strategy. Figure 4 reports the saving/loss in average total costs (in percentage) obtained for each context and each problem test when comparing T-CS to O-CS.

Figure 3 shows that when parameters values are varied, total costs tend to increase and decrease in the same way for all the contexts. The amplitude of increase/decrease is almost the same for all the contexts with a few exceptions (problem tests 19, 21, 23 and 24). As will be detailed in the next sections, it is the recourse used to handle these variations that may differ depending on the context.

Figure 4 demonstrates that gains/losses induced by T-CS compared to O-CS follow the same trend for all the contexts for almost all the problem tests (except problem test 25). The extent of this gain/loss slightly varies with the capacity of strategic carriers (limited versus unlimited) but may be considerably affected by the replenishment strategy (just-in-time versus periodic) as for problem test 21, for example. Figure 4 clearly shows that integrating a strategic phase for carriers'selection results for the majority of the problem tests in lower operational costs than a strategy using only the spot market. A just-in time replinshment strategy and an unlimited capacity for strategic carriers (context C2) results in the largest saving (43%). A periodic replenishment stragey gives more advantage to T-CS in terms of the number of problem tests where T-CS outperforms O-CS. As will be explained, this is in part due to a larger recourse to strategic carriers to transport larger volumes from whareouses to DCs so that warehouses can accommodate the quantity supplied at each period.

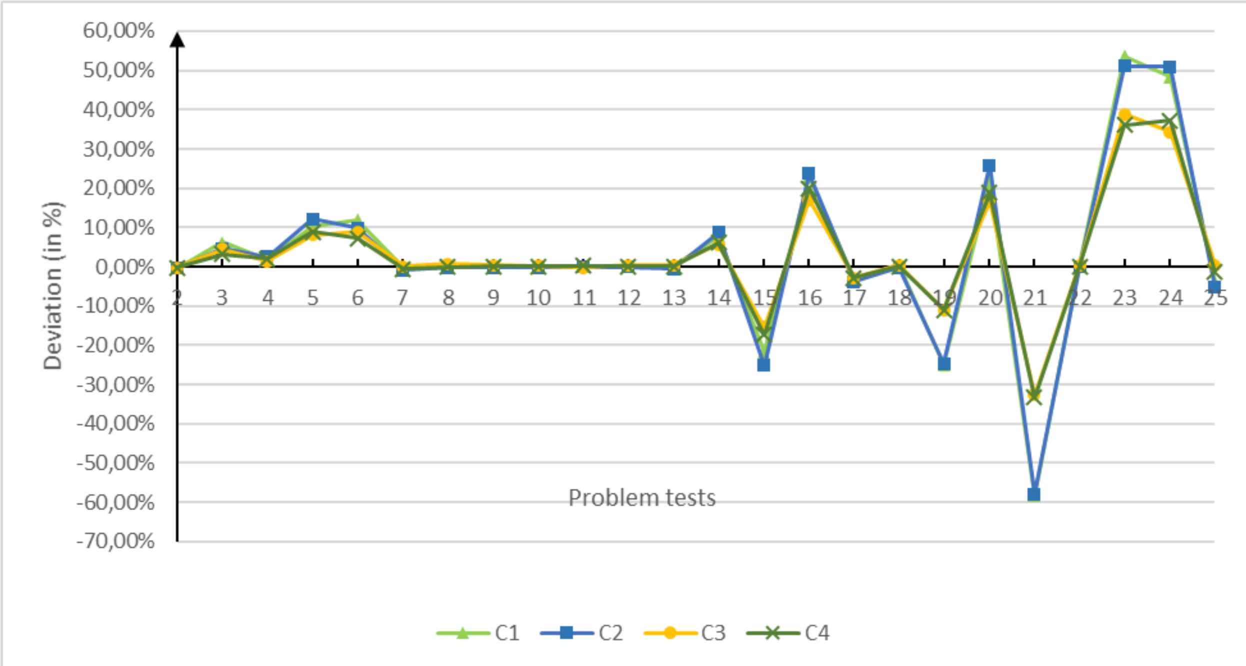

Figure 3: Impact of parameters variation on total costs for all the contexts

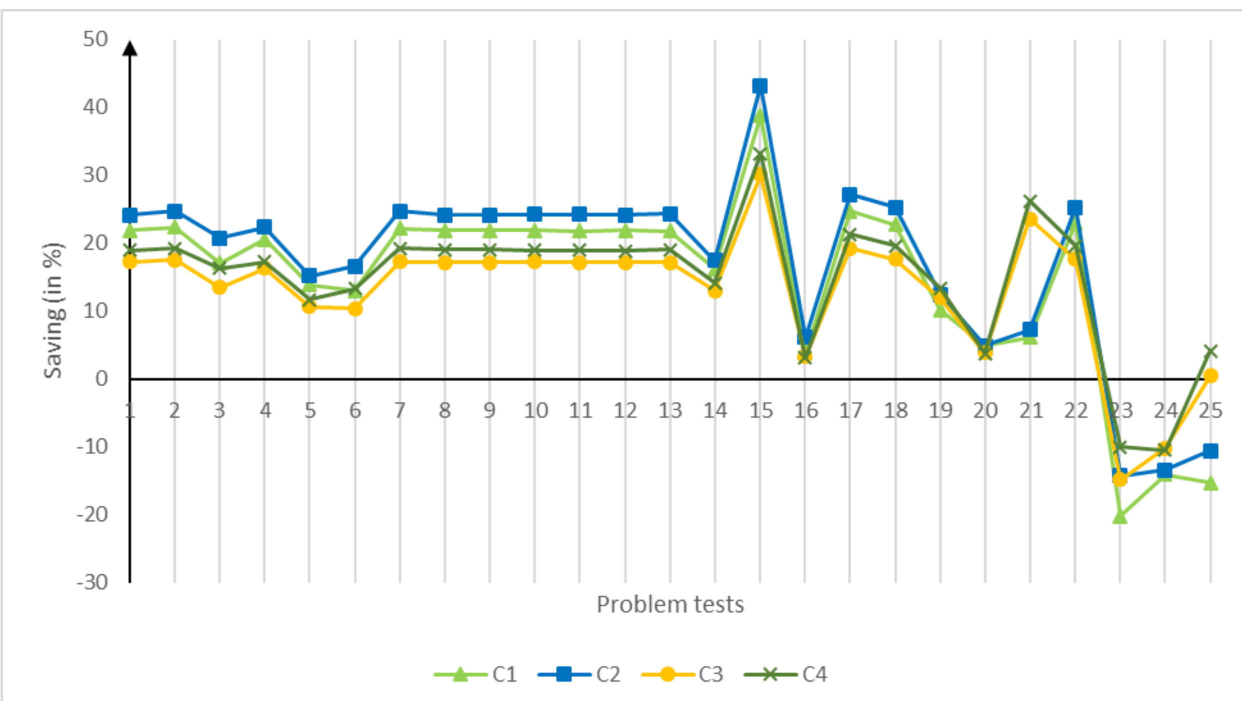

Figure 4: Savings (in %) obtained with T-CS versus O-CS for all the contexts

The following sections analyze and discuss in more details the results obtained in each context. In Section 5.2.1, we deeply analyze the impact of parameters' variation on total costs under context C1. In Sections 5.2.2 to 5.2.4, we present the new elements of analysis due to the context change.

5.2.1 Context C1: Just-in-Time replenishment and limited capacity

The results of Table 3 first show that the impact of parameters variation on total costs is substantial in some cases (e.g., problem tests 21 and 23) especially when multiple parameters values are simultaneously changed. Almost no impact on total costs is induced when only unit penalty costs γ and Δ are varied either simultaneously or separately (problem tests 8 to 13). Similarly, no substantial deviation in total costs is obtained when only the minimum volumes promised to strategic carriers (modeled by α) are decreased (problem test 2) or the maximum volumes (modeled by β) are increased (problem test 7). This was expectable given that in the basic case, the volumes assigned to the strategic carriers already respect these constraints with more restricted values (no penalty costs were incurred by the shipper in the basic case). Increasing only the unit backorder cost (problem test 18) has also almost no impact on the total cost although in the basic case backorder costs are nonnull.

Indeed, for problem test 18, the increase in unit backorder costs yields a recourse to the spot market so that no backorder is used (as displayed in Tables 3 and 7). For problem test 22, in addition to the unit backorder cost increase, both unit penalty costs are decreased. Here also no backorder is used and the shipper rather assigns larger volumes to the spot carriers.

Important variations (up or down) in average total costs are observed when: (i) strategic costs are decreased (problem test 15) or increased (problem test 16), (ii) lower and upper bounds constraints are more restrictive and their associated unit penalty costs increased (problem tests 20 and 23), (iii): unit backorder cost is substantially decreased (problem test 19). When these variations in parameters values are simultaneously applied, the deviation in total costs (with respect to the basic case) reaches 48.36% (problem test 24) and – 58.45% (problem test 21).

The results of Table 3 also show that T-CS yields lower average total costs than O-CS for 22 problem tests over the 25 considered. For these problem tests, savings vary between 3.9% and 38.8% with an average equal to 18.77%. For the three problem tests where T-CS yields larger costs than O-CS, losses range between 14.1% and 20.2%. The variability in gains/losses may be explained by the increase/decrease in the values of the different parameters. Indeed, we notice that the largest saving of 38.8% is obtained for problem test 15 where strategic unit transportation costs are much lower than spot costs. On a counterpart, the largest loss of 20.2% is reached for problem test 23 where constraints on minimum volumes (parameter α) and their penalty costs (parameter γ) take relatively large values.

Instance	T- CS							O-CS				S_v
	Z^1	Z^{sp_s}	Z^{str}	Z^{iv_s}	Z^{bk_s}	Z^{lk}	Z^{ex}	Z^2	Z^{sp_o}	Z^{iv_o}	Z^{bk_o}	
1	16.44	1.95	14.34	-	0.149	-	-	21.06	19.57	-	1.49	21.9
2	16.37	1.95	14.27	-	0.147	-	-	21.10	19.62	-	1.48	22.4
3	17.48	1.95	14.37	-	0.148	1.013	-	21.09	19.60	-	1.49	17.1
4	16.71	1.95	14.16	-	0.559	-	0.043	21.04	19.55	-	1.50	20.6
5	18.12	1.95	12.86	-	1.383	-	1.925	21.06	19.57	-	1.49	13.9
6	18.42	1.96	14.30	-	0.148	2.012	-	21.18	19.69	-	1.49	13.0
7	16.41	1.96	14.31	-	0.147	-	-	21.10	19.62	-	1.48	22.2
8	16.42	1.95	14.32	-	0.149	-	-	21.04	19.55	-	1.49	21.9
9	16.48	1.95	14.37	-	0.148	-	-	21.09	19.61	-	1.48	21.9
10	16.41	1.94	14.31	-	0.148	0.004	-	21.02	19.54	-	1.48	21.9
11	16.44	1.94	14.35	-	0.148	0.002	-	21.03	19.54	-	1.49	21.8
12	16.45	1.95	14.35	-	0.149	-	-	21.08	19.60	-	1.48	21.9
13	16.46	1.95	14.36	-	0.150	-	-	21.06	19.56	-	1.50	21.8
14	17.72	1.96	15.34	-	0.422	-	-	21.14	19.63	-	1.50	16.2
15	12.87	1.95	10.77	-	0.149	-	0.002	21.05	19.55	-	1.49	38.8
16	20.21	1.95	16.77	-	1.485	-	-	21.02	19.53	-	1.48	3.9
17	15.91	1.96	13.80	-	0.147	-	-	21.13	19.65	-	1.48	24.7
18	16.51	2.13	14.38	-	-	-	-	21.37	21.37	-	-	22.8
19	12.32	0.53	7.48	-	4.154	0.159	-	13.72	5.33	-	8.39	10.2
20	20.02	15.29	3.23	-	1.493	-	-	21.05	19.56	-	1.49	4.9
21	6.83	-	2.96	-	3.611	0.263	-	7.27	-	-	7.27	6.1
22	16.50	2.13	14.36	-	-	0.003	-	21.42	21.42	-	-	23.0
23	25.28	1.94	14.09	-	0.146	9.098	-	21.02	19.53	-	1.49	-20.2
24	24.39	10.10	14.28	-	-	-	-	21.38	21.38	-	-	-14.1
25	15.83	0.53	10.73	-	1.838	2.728	-	13.72	5.34	-	8.38	-15.3

Table 3: Results for context C1: Just-in-Time replenishment and limited capacity

One can also observe that, when the unit backorder cost is not too large ($g < 3$), T-CS always use backorders to decrease the total cost. For a fixed value of $g = 0.8$, the backorder cost considerably increases when: (i) the value of α decreases -implying that the quantities promised to strategic carriers in the strategic phase are less constraining- or (ii) the values of f_1 and f_2 increase –implying that strategic costs get larger. This is particularly observable in problem tests 16 and 20. For these problem tests, savings obtained with T- CS are among the smallest ones: 3.9% and 4.9% for problem tests 16 and 20, respectively. For these instances both T-CS and O-CS strategies induce almost the same backorder costs and the gain yielded by T-CS is essentially due to lower transportation costs offered by the strategic carriers. When backorder costs get large ($g = 3$), as is the case for problem tests 18, 22 and 24, no backorders are used in T- CS neither in O-CS. In these cases, T-CS is either better or worse than O-CS depending on the transportation costs offered by strategic carriers with respect to the spot carriers.

Besides, penalty costs are relatively large for problem tests 3, 6, 23 and 25 where parameters α and/or γ take large values. For problem tests 3 and 6 where the unit penalty cost remains relatively small, T-CS outperforms O-CS resulting in a relative gain of 17.1% and 13%, respectively. However, when the unit penalty cost gets larger as is the case for problem tests 23 and 25, T-CS yields larger average total costs (20.2% increase for problem test 23 and 15.3% increase for problem test 25). A relatively large penalty cost is also obtained for problem test 5 where the parameter β- modeling the maximum volume offered by the carrier at the strategic phase with the strategic transportation rate- takes a relatively low value (*β=0.2)*. In this case, the shipper still assigns relatively large volumes to strategic carriers compared to the basic case but uses more backorders.

Finally, one should notice that the just-in-time replenishment strategy explains the absence of inventory costs for all the instances. Also, limiting the capacity of strategic carriers may explain in part the use of spot carriers although they are much more expensive in some cases.

5.2.2 Context C2: Just-in-Time replenishment and unlimited capacity

Although the level of variation in average total costs with respect to the basic case are obtained for the same problems tests as for context C1, the recourses used by the shipper to respond to some parameters' variations are not always the same. Indeed, given that the strategic carrier capacity is unlimited under context C2, the shipper rarely assigns shipments to the spot carriers.

Instance	T- CS							O-CS				S_v
	Z^1	Z^{sp_s}	Z^{str}	Z^{iv_s}	Z^{bk_s}	Z^{lk}	Z^{ex}	Z^2	Z^{sp_o}	Z^{iv_o}	Z^{bk_o}	
1	15.98	-	15.98	-	-	-	-	21.08	19.60	-	1.48	24.2
2	15.91	-	15.91	-	-	-	-	21.13	19.65	-	1.48	24.7
3	16.72	-	16.04	-	-	0.682	-	21.12	19.64	-	1.48	20.8
4	16.39	-	14.91	-	1.407	-	0.064	21.11	19.60	-	1.51	22.4
5	17.92	-	14.29	-	1.420	-	2.209	21.15	19.66	-	1.48	15.2
6	17.56	-	15.88	-	-	1.680	-	21.05	19.58	-	1.47	16.6
7	15.83	-	15.83	-	-	-	-	21.01	19.54	-	1.47	24.7
8	15.93	-	15.93	-	-	-	-	21.03	19.52	-	1.51	24.2
9	15.95	-	15.95	-	-	-	-	21.05	19.56	-	1.49	24.2
10	15.95	-	15.95	-	-	-	-	21.07	19.58	-	1.49	24.3
11	15.97	-	15.97	-	-	-	-	21.11	19.60	-	1.51	24.3
12	15.96	-	15.95	-	-	-	0.001	21.06	19.54	-	1.52	24.2
13	15.89	-	15.89	-	-	-	-	21.00	19.52	-	1.48	24.4
14	17.36	-	16.72	-	0.624	-	0.020	21.06	19.56	-	1.50	17.5
15	11.96	-	11.96	-	-	-	-	21.06	19.57	-	1.48	43.2
16	19.78	0.11	18.28	-	1.389	-	-	21.07	19.59	-	1.48	6.1
17	15.37	-	15.37	-	-	-	-	21.10	19.63	-	1.48	27.2
18	15.95	-	15.95	-	-	-	-	21.36	21.36	-	-	25.3
19	12.02	-	8.10	-	3.910	0.009	-	13.74	5.35	-	8.39	12.5
20	20.10	15.36	3.25	-	1.490	-	-	21.13	19.64	-	1.49	4.9
21	6.73	-	3.30	-	3.198	0.235	-	7.26	-	-	7.26	7.3
22	15.96	-	15.96	-	-	-	-	21.36	21.36	-	-	25.3
23	24.14	-	15.80	-	-	8.342	-	21.14	19.64	-	1.50	-14.2
24	24.11	9.98	14.13	-	-	-	-	21.25	21.25	-	-	-13.4
25	15.14	-	11.92	-	1.112	2.105	-	13.69	5.36	-	8.33	-10.6

Table 4: Results for context C2: Just-in-Time replenishment and unlimited capacity

The three problem tests for which a nonnull volume was assigned to spot carriers are problem tests 16, 20 and 24 for which the variation in average total costs (with regard to the basic case) is important and reaches 23.78%, 25.78% and 50.88%, respectively. For problem test 16 (where only strategic transportation costs are increased), the recourse to spot carriers is very limited and is accompanied with a more important recourse to backorders. For problem test 20, the volume assigned to spot carriers is almost 3.6 times that allocated to the strategic carriers (see Table 8 in the appendix). This is because the maximum volumes (parameter β) at a low strategic transportation rate specified in the bids are decreased and the unit penalty costs (parameter Δ) for exceeding them are increased. Here also, a recourse to backorders is used. For problem test 24, shipment volumes are almost equally distributed between strategic and spot carriers and no backorder is used. This can be explained by the increase in both unit penalty costs (parameters γ and Δ) and in unit backorder costs (parameter g). The largest variations in average total costs (absolute values) are obtained for problem tests 23 (an increase of 51.06%) and 21 (a decrease of 57.88%) as for context C1.

The results of Table 4 also show that T-CS yields lower average total costs than O-CS for 22 problem tests. Savings vary between 4.9% and 43.2% with an average equal to 21.07%. For all these instances, gains with respect to O-CS are larger in context C2 than in context C1. For the three problem tests (23,24 and 25) where O-CS performs better than T-CS, the relative loss induced by the T-CS strategy is less important than in context C1. This can be explained by the fact that in context C2, a recourse to spot carriers is less frequent and average total costs are generally lower with T-CS than in context C1.

5.2.3 Context C3: Periodic replenishment and limited capacity

Unlike contexts C1 and C2, inventory costs are no longer null: with fixed periodic replenishment, inventories are inevitable in the warehouses and/or the DCs. When compared to context C1 (a just-in-time replenishment), context C3 yields larger average total costs: a difference of 6.41 to 8.61 M$ which mainly corresponds to the additional inventory costs incurred in context C3. One can also observe that the shipper uses the spot market for almost the same problem tests as in C1 and at almost the same levels. However, the recourse to backorders is less used in C3 than in C1 (problem tests 4,5,14,19,21, and 35). This is because a periodic replenishment with an finite storage capacity in warehouses require transporting larger volumes to DCs, reducing therefore backorders. This would also explain the increase in volume shipments (when comparing C3 to C1) allocated to strategic carriers to address some parameters variation. This was the case for problem tests 4,5,10,14,15, 21 and 22. We also observe larger penalty costs with respect to the upper bound constraints and lower penlty costs with reagrd to the lower bound constraints supporting thus the fact that the shipper assigns larger volumes to strategic carriers eventhough it pays execess volume penalties.

Instance	T- SCS							O-CS				S_v
	Z^1	Z^{sp_s}	Z^{str}	Z^{iv_s}	Z^{bk_s}	Z^{lk}	Z^{ex}	Z^2	Z^{sp_o}	Z^{iv_o}	Z^{bk_o}	
1	22.96	1.95	14.37	6.49	0.149	-	-	27.76	19.68	6.59	1.50	17.3
2	22.89	1.95	14.25	6.54	0.151	-	-	27.79	19.64	6.64	1.51	17.6
3	24.00	1.95	14.37	6.52	0.148	1.011	-	27.76	19.67	6.60	1.49	13.5
4	23.28	1.96	14.52	6.53	0.149	-	0.120	27.81	19.71	6.61	1.49	16.3
5	24.81	1.97	13.98	6.54	0.176	-	2.147	27.78	19.68	6.62	1.49	10.7
6	24.98	1.95	14.29	6.57	0.148	2.006	-	27.87	19.71	6.67	1.49	10.4
7	22.96	1.95	14.31	6.55	0.148	-	-	27.77	19.65	6.63	1.49	17.3
8	23.12	1.96	14.38	6.64	0.149	-	-	27.93	19.71	6.74	1.49	17.2
9	23.07	1.96	14.39	6.58	0.150	-	-	27.87	19.69	6.67	1.50	17.2
10	23.03	1.95	14.37	6.55	0.149	0.006	0.002	27.83	19.69	6.64	1.50	17.3
11	22.90	1.95	14.32	6.48	0.148	0.005	-	27.66	19.59	6.57	1.49	17.2
12	23.06	1.96	14.39	6.55	0.150	-	-	27.83	19.70	6.64	1.50	17.2
13	23.06	1.95	14.35	6.60	0.149	-	-	27.85	19.66	6.70	1.49	17.2
14	24.26	1.96	15.50	6.64	0.147	-	0.007	27.87	19.69	6.71	1.48	13.0
15	19.41	1.95	10.75	6.56	0.149	-	0.003	27.78	19.63	6.66	1.49	30.1
16	26.88	1.95	16.78	6.65	1.496	-	-	27.79	19.65	6.65	1.50	3.3
17	22.32	1.95	13.76	6.46	0.148	-	-	27.65	19.61	6.55	1.49	19.3
18	23.06	2.13	14.37	6.56	-	-	-	28.01	21.42	6.59	-	17.7
19	20.43	1.07	9.67	7.62	2.059	0.008	-	23.21	10.78	8.52	3.91	12.0
20	26.82	15.41	3.24	6.67	1.486	-	-	27.90	19.73	6.68	1.49	3.9
21	15.44	0.51	5.74	7.77	1.258	0.145	0.011	20.22	5.21	10.91	4.26	23.6
22	23.04	2.13	14.38	6.53	-	0.004	0.001	28.01	21.48	6.53	-	17.7
23	31.87	1.95	14.15	6.52	0.148	9.106	-	27.77	19.64	6.63	1.50	-14.8
24	30.82	9.87	14.41	6.54	-	-	-	27.98	21.43	6.55	-	-10.2
25	23.04	1.06	11.94	7.02	0.904	2.106	-	23.14	10.74	8.51	3.89	0.5

Table 5: Results for context C3: Periodic replenishment and limited capacity

The results of Table 5 also prove that the proposed T-CS strategy guarantees lower costs compared to O-CS for 23 problem tests. The relative gain varies from 0.5% to 30.1%. Problem tests 23 and 24 show better results for O-CS with a relative decrease in average total costs of 14.8% and 10.2%, respectively. Contrarely to context C1, strategy T-CS is more beneficial for problem test 25 than O-CS. Recall that for this problem, lower and upper bounds constraints are too restrictive, their unit penalty costs increased and the unit backorder cost decreased. Given the periodic replenishment strategy, larger volumes are shipped from warheouses to DCs and lower backorders are used, compared to C1. Consequently, the gain induced by low transportation rates with T-CS are more important and those resulting from a lower backorder cost are less important arguing why O-CS is no longer better than T-CS for problem test 25.

5.2.4 ***Context C4: Periodic replenishment and unlimited capacity***

When comparing the results of context C4 with those of context C2 (just-in-time replinshement), we observe that context C4 results in larger total costs mostly because of the inventory costs induced by the periodic replenshipment (as was the case when comparing C1 and C3). Besides, the three problem tests for which a nonnull volume was assigned to spot carriers are the same for contexts C4 and C2 (problem tests 16, 20 and 24). This strengthens our observation that considering an infinite capacity for strategic carriers reduces the frequency of recourse to the spot market. This also shows that the recourse to the spot market is more impacted by the capacity of strategic carriers (limited versus unlimited) than the replenishment strategy.

When comparing T-CS and O-CS under context C4, T-CS performs better for 23 problem tests and worse for two problem tests: 23 and 24, the same as for context C3. For problem test 25, the gain compared to O-CS is more signicative (4.2%) than for C3 (0.5%) due to a larger use of strategic carriers (unlimited transportation capacity, limited storage capacity and periodic replinishment).

Instance	T- CS							O-CS				S_v
	Z^1	Z^{sp_s}	Z^{str}	Z^{iv_s}	Z^{bk_s}	Z^{lk}	Z^{ex}	Z^2	Z^{sp_o}	Z^{iv_o}	Z^{bk_o}	
1	22.51	-	15.95	6.55	-	-	-	27.79	19.68	6.64	1.47	19.0
2	22.44	-	15.90	6.54	-	-	-	27.80	19.66	6.64	1.50	19.3
3	23.23	-	16.03	6.53	-	0.678	-	27.77	19.68	6.62	1.48	16.3
4	22.95	-	16.08	6.54	0.029	-	0.303	27.79	19.67	6.63	1.49	17.3
5	24.49	-	15.54	6.48	0.007	-	2.461	27.74	19.67	6.56	1.51	11.7
6	24.15	-	15.94	6.54	-	1.678	-	27.85	19.74	6.62	1.49	13.3
7	22.39	-	15.90	6.49	-	-	-	27.76	19.69	6.59	1.48	19.3
8	22.48	-	15.96	6.52	-	-	-	27.78	19.68	6.62	1.49	19.1
9	22.51	-	15.96	6.55	-	-	-	27.82	19.69	6.64	1.49	19.1
10	22.54	-	15.96	6.59	-	-	0.002	27.83	19.67	6.68	1.48	19.0
11	22.57	-	15.99	6.58	-	-	-	27.87	19.69	6.69	1.49	19.0
12	22.51	-	15.97	6.54	-	-	0.002	27.76	19.65	6.62	1.48	18.9
13	22.53	-	15.97	6.56	-	-	-	27.86	19.71	6.66	1.49	19.1
14	23.89	-	17.27	6.60	-	-	0.020	27.86	19.69	6.69	1.47	14.2
15	18.59	-	11.99	6.61	-	-	-	27.84	19.64	6.71	1.48	33.2
16	27.00	0.11	18.70	6.70	1.503	-	-	27.88	19.69	6.68	1.50	3.1
17	21.87	-	15.32	6.55	-	-	-	27.79	19.67	6.63	1.49	21.3
18	22.52	-	15.96	6.56	-	-	-	28.00	21.44	6.56	-	19.6
19	20.04	-	10.65	7.53	1.859	-	-	23.14	10.74	8.51	3.89	13.4
20	26.76	15.36	3.25	6.67	1.491	-	-	27.82	19.66	6.67	1.49	3.8
21	15.01	-	6.38	7.54	0.928	0.135	0.022	20.33	5.21	10.84	4.27	26.2
22	22.51	-	15.94	6.57	-	-	-	27.98	21.42	6.57	-	19.6
23	30.62	-	15.79	6.53	-	8.303	-	27.83	19.70	6.65	1.49	-10.0
24	30.91	10.12	14.30	6.49	-	-	-	27.98	21.48	6.50	-	-10.5
25	22.20	-	13.38	6.87	0.557	1.399	-	23.18	10.75	8.52	3.91	4.2

Table 6: Results for context C4: Periodic replenishment and unlimited capacity

6. MANAGERIAL INSIGHTS AND RECOMMENDATIONS

Establishing long-term contracts with external carriers through combinatorial auctions is generally motivated by the low transportation rates offered in such a strategic selection. Our experimental study points out a number of insights and recommendations for the shippers questioning the relevance and the economic merits of the strategic phase for externals carriers' selection. Below, we provide five recommendations for shippers interested in outsourcing their TL operations:

(1) **The decision to consider a strategic selection phase should not be based solely on transportation rates.** It may happen that a two-phase selection approach (with a strategic selection phase) induces monetary losses compared to a single-phase approach (i.e., where carriers are selected in the spot market on a period-to-period basis) even if the transportation rates in the strategic phase are 70% to 75% lower that the spot market rates. This can be observed in situations where the shipper forecasting system used at the strategic phase is not sufficiently precise (it overestimates or underestimates the real demand) and the shipper wants to respect its commitments with strategic carriers with regard to the minimum and maximum volumes promised in the final post-auction contracts. Besides, too restrictive constraints on the minimum and maximum volumes negotiated with strategic carriers combined with low unit backorder costs give advantage to either the two- or the single-phase selection approach depending on the replenishment strategy used: a just-in-time replenishment favors the single-phase selection approach.

(2) **The decision to consider a strategic selection phase can induce substantial gains in total operational costs independently of the replenishment strategy. These gains considerably vary with transportation rates and the capacity offered by strategic carriers during the bidding process of the strategic phase.** The relative savings induced by the two-phase selection approach is relatively stable when only one parameter or two parameters associated with the same type of input data are varied, with the exception of transportation rates. Savings substantially increase or decrease when only strategic transportation rates decrease or increase. When transportation rates are maintained relatively low (70% to 75% of spot market rates), a substantial decrease is also observed when the capacity offered by strategic carriers in their bids during the auction stage are too low compared to the actual demand and the additional price the strategic carriers require to exceed this capacity at the operational level is relatively large.

(3) **When a strategic selection is conducted, the resulting total operational costs are much sensitive not only to spot market transportation rates, but also to backorder costs and the level of restrictions on minimum and maximum volumes committed with strategic carriers. Variations in total costs are independent of the replenishment strategy or the**

strategic carriers' available capacity. For all the contexts, important variations (up or down) in average total costs are observed when: (i) strategic transportation costs are much smaller or larger than spot ones, (ii) minimum and maximum volumes restrictions in the strategic phase are too restrictive and the shipper does not want to deviate from its volume commitments, and (iii) unit backorder costs are substantially low.

(4) **When a strategic selection is conducted, spot carriers are not always the sole and more efficient recourse to face the variation in some strategic and operational parameters.** Backorders are also a good alternative to avoid an increase in total operational costs especially when the unit backorder cost is realtively low with regard to the spot transportation rate. The recourse to backorder is a practice which is more applied in a collaborative context (Nimmy et al., 2019).

(5) **When a two-phase selection process is used, total operational costs are not substantially sensitive to the replenishment strategy or the strategic carriers' available capacity. It is the recourses used by the shipper to respond to some parameters' variations that may differ.** When the strategic carrier's capacity at the operational level is unlimited, the shipper rarely assigns shipments to the spot carriers even if spot and strategic transportation rates are relatively close. Backorders rather prevail in this case. The recourse to spot carriers is more important when this capacity is limited. Besides, the recourse to backorders is less used when a periodic replenishment strategy is used rather than a just-in-time replenishment. The recourse to the spot market is more impacted by the capacity of strategic carriers (limited versus unlimited) than the replenishment strategy.

7. CONCLUSION

This paper proposes a general framework for carriers' selection that includes both strategic and operational phases. The strategic phase uses a combinatorial auction mechanism in which a set of carriers compete by submitting package bids on the shipper's requests. The shipper then solves a WDP to determine winning carriers with the objective to minimize its transportation costs. At the operational phase, the shipper periodically assigns shipments to carriers in order to minimize inventory, backorder and transportation costs while considering the final contracts established with winning carriers at the strategic phase. To the best of our knowledge, our paper is the first to address the problem of operationalizing the strategic carriers' selection decisions output by a combinatorial auction mechanism. It is also the first to investigate the economical merits/drawbacks of considering a strategic selection within various contexts. Four operational contexts are considered depending on the replenishment strategy (just-in time or periodic) and on the strategic carrier capacity (limited or unlimited). An intensive experimental study is conducted to analyze the impacts of varying the strategic contracts' clauses on total costs and on the recourses that should be used by the shipper to operationalize its strategic decisions. We also analyze the relevance of the two-phase framework (a strategic phase followed by an operational one) in the four contexts for different values of the input data.

Our results reveal that a two-phase selection process generally results in lower total operational costs than a single-phase process (selection through the spot market only). This gain is not only attributable to the lower transportation costs offered at the strategic phase but also to backorder costs, demand forecast accuracy, contracts negotiated after the auction clearance, the shipper willingness to respect its volume commitments, and to the additional capacity offered by strategic carriers at the operational level. Accordingly, the shipper should not take for granted that low transportation rates necessarily imply performing a strategic selection.

As future work, there are several research avenues that could be investigated. A first extension of this paper would be to consider uncertainty on demand at the operational phase. A stochastic programming approach could be applied in this case. Besides, the proposed model could be used as an evaluation tool to solve the winner determination problem at the strategic phase or as a support tool for contracts negotiation after the auction clears.

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Statements and declarations

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APPENDIX: DETAILED RESULTS

Tables 7 to 10 give, for each context, detailed information on the solutions obtained for each problem test and each carriers selection strategy. Each table reports for strategy T-CS: (i) the volumes assigned to strategic (V^{str}) and spot carriers (V^{sp_s}), (ii) the inventory phases in warehouses and distribution centers (V^{iv_s}), (iii) backorder volumes (V^{bk_s}) (iv) the lacking volumes with respect to the lower bounds (V^{lk}), (v) the volumes in excess assigned to strategic carriers (V^{ex}). For strategy O-CS, it reports the volumes assigned to spot carriers (V^{sp_o}), the inventory phases in warehouses and distribution centers (V^{iv_o}) and backorder volumes (V^{bk_o}). Note that these values are expressed 10^3×volume units.

Instance	T- CS						O-CS		
	V^{sp_s}	V^{str}	V^{iv_s}	V^{bk_s}	V^{lk}	V^{ex}	V^{sp_o}	V^{iv_o}	V^{bk_o}
1	21.52	211.37	-	1.96	-	-	215.21	-	19.64
2	21.57	211.66	-	1.94	-	-	215.75	-	19.43
3	21.55	211.51	-	1.95	70.50	-	215.48	-	19.53
4	21.50	205.85	-	7.38	-	2.98	215.04	-	19.69
5	21.52	195.07	-	18.21	-	148.10	215.17	-	19.63
6	21.65	212.50	-	1.96	141.67	-	216.49	-	19.61
7	21.57	211.66	-	1.95	-	-	215.68	-	19.50
8	21.50	211.28	-	1.97	-	-	215.05	-	19.71
9	21.55	211.51	-	1.95	-	-	215.52	-	19.50
10	21.52	211.18	-	1.95	0.25	-	215.16	-	19.48
11	21.49	211.03	-	1.96	0.32	-	214.89	-	19.59
12	21.53	211.30	-	1.95	-	-	215.28	-	19.50
13	21.51	211.31	-	1.97	-	-	215.07	-	19.73
14	21.59	208.52	-	4.53	-	0.02	215.91	-	19.77
15	21.51	211.26	-	1.97	-	0.23	215.07	-	19.66
16	21.54	193.82	-	19.56	-	-	215.35	-	19.56
17	21.63	212.30	-	1.95	-	-	216.33	-	19.56
18	23.52	211.69	-	-	-	-	235.21	-	-
19	5.86	109.31	-	437.37	10.92	-	58.61	-	882.45
20	168.00	46.91	-	19.64	-	-	214.92	-	19.65
21	-	74.17	-	759.61	58.14	-	-	-	1 528.61
22	23.55	212.00	-	-	0.50	-	235.57	-	-

23	21.48	210.95	-	1.95	257.83	-	214.83	-	19.56
24	111.38	124.20	-	-	-	-	235.58	-	-
25	5.87	158.75	-	193.85	76.46	-	58.75	-	882.01

Table 7: Details results for context C1

Instance	**T- CS**						**O-CS**		
	V^{sp_s}	V^{str}	V^{iv_s}	V^{bk_s}	V^{lk}	V^{ex}	V^{sp_o}	V^{iv_o}	V^{bk_o}
1	-	235.20	-	-	-	-	215.75	-	19.45
2	-	235.86	-	-	-	-	216.29	-	19.56
3	-	235.60	-	-	47.12	-	216.16	-	19.44
4	-	216.84	-	18.53	-	5.00	215.52	-	19.85
5	-	216.95	-	18.69	-	169.82	216.12	-	19.52
6	-	234.80	-	-	117.40	-	215.41	-	19.39
7	-	234.29	-	-	-	-	214.89	-	19.40
8	-	235.01	-	-	-	-	215.14	-	199.87
9	-	234.76	-	-	-	-	215.21	-	19.55
10	-	234.88	-	-	-	-	215.32	-	19.56
11	-	235.53	-	-	-	-	215.65	-	19.88
12	-	234.77	-	-	-	0.17	214.77	-	20.00
13	-	234.19	-	-	-	-	214.72	-	19.47
14	-	226.37	-	8.21	-	1.53	214.93	-	19.65
15	-	234.48	-	-	-	-	215.00	-	19.48
16	0.02	215.54	-	19.51	-	-	215.56	-	19.51
17	-	235.10	-	-	-	-	215.65	-	19.47
18	-	234.83	-	-	-	-	234.83	-	-
19	-	117.85	-	411.89	0.62	-	58.87	-	883.67
20	168.92	47.13	-	19.61	-	-	216.05	-	19.61
21	-	82.32	-	673.17	51.83	-	-	-	1528.08
22	-	234.93	-	-	-	-	234.93	-	-
23	-	235.78	-	-	235.78	-	216.06	-	19.72
24	109.70	123.79	-	-	-	-	233.49	-	-
25	-	175.78	-	117.05	58.58	-	58.89	-	877.29

Table 8: Detailed results for context C 2

Instance	**T- CS**						**O-CS**		
	V^{sp_s}	V^{str}	V^{iv_s}	V^{bk_s}	V^{lk}	V^{ex}	V^{sp_o}	V^{iv_o}	V^{bk_o}
1	21.53	211.54	1 527.01	1.97	-	-	215.33	1 544.75	19.71
2	21.51	211.49	1 526.64	1.99	-	-	215.11	1 537.10	19.88
3	21.54	211.46	1 529.46	1.96	71.18	-	215.40	1 547.07	19.56
4	21.56	211.60	1 528.56	1.95	-	9.18	215.58	1 538.14	19.54
5	21.53	211.09	1 527.59	2.32	-	164.10	195.33	1 440.89	17.61
6	21.59	211.88	1 530.77	1.95	114.25	-	215.86	1 548.37	19.56
7	21.52	211.30	1 526.17	1.96	-	-	215.22	1 546.77	19.56
8	21.59	211.94	1 531.81	1.96	-	-	215.88	1 549.45	19.60
9	21.58	211.95	1 531.22	1.97	-	-	215.77	1 548.97	19.72
10	21.55	211.70	1 528.2	1.97	0.81	0.87	215.52	1 546.02	1.97
11	21.46	210.82	1 522.34	1.96	0.27	-	214.63	1 539.99	19.61
12	21.57	211.90	1 531.11	1.97	-	-	215.72	1 548.87	1973
13	21.54	211.53	1 528.03	1.96	-	-	215.44	1 545.67	19.59
14	21.55	211.50	1 527.46	1.94	-	0.55	215.55	1 544.97	19.45
15	21.50	211.17	1 524.35	1.96	-	0.28	214.99	1 542.03	19.64
16	21.50	193.46	1 543.39	19.69	-	-	214.95	1 543.39	19.69
17	21.50	211.21	1 526.31	1.96	-	-	215.02	1 544.00	19.65
18	23.48	211.37	1 522.10	-	-	-	234.86	1 522.10	-
19	11.77	141.31	1 744.06	216.65	0.56	-	117.68	1 938.65	411.24
20	168.97	47.13	1 550.98	19.55	-	-	216.11	1 550.98	19.55
21	5.67	141.19	1 790.39	265.18	31.47	2.89	57.01	2 423.34	898.13
22	23.50	211.47	1 525.60	-	0.46	0.16	234.96	1 525.59	-
23	21.52	211.43	1 527.15	1.97	258.42	-	215.19	1 544.92	19.73
24	108.21	126.33	1 523.58	-	-	-	234.54	1 523.58	-
25	11.75	175.66	1 620.54	95.28	59.30	-	117.52	1 935.71	410.44

Table 9: Detailed results for context C3

Instance	T-CS						O-CS		
	V^{sp_s}	V^{str}	V^{iv_s}	V^{bk_s}	V^{lk}	V^{ex}	V^{sp_o}	V^{iv_o}	V^{bk_o}
1	-	235.00	1 526.73	-	-	-	215.60	1 546.14	19.41
2	-	235.15	1 524.24	-	-	-	215.36	1 544.02	19.79
3	-	234.93	1 526.11	-	46.99	-	215.41	1 545.62	19.52
4	-	234.49	1 525.10	0.38	-	23.11	215.22	1 544.34	19.65
5	-	235.28	1 525.99	0.1	-	188.20	215.52	1 545.75	19.85
6	-	235.66	1 529.60	-	117.83	-	216.02	1 549.25	19.65
7	-	235.05	1 526.65	-	-	-	215.58	1 546.12	19.46
8	-	235.02	1 525.81	-	-	-	215.39	1 545.44	19.64
9	-	235.19	1 528.05	-	-	-	215.51	1 547.73	19.69
10	-	234.71	1 527.26	-	-	0.34	215.26	1 546.71	19.45
11	-	235.44	1 528.74	-	-	-	215.85	1 548.32	19.59
12	-	234.94	1 525.38	-	-	0.24	215.40	1 544.93	19.54
13	-	235.26	1 528.93	-	-	-	215.67	1 548.53	19.59
14	-	235.06	1 528.53	-	-	1.55	215.64	1 547.95	19.42
15	-	234.71	1 523.69	-	-	-	215.16	1 543.23	19.55
16	0.07	215.73	1 549.99	19.76	-	-	215.80	1 550.00	19.76
17	-	234.97	1 524.67	-	-	-	215.36	1 544.28	19.60
18	-	235.20	1 527.69	-	-	-	235.20	1 527.69	-
19	-	156.32	1 719.67	195.69	-	-	117.46	1 933.30	409.32
20	168.69	47.07	1 548.36	19.61	-	-	215.77	1 548.36	19.61
21	-	156.72	1 721.77	195.46	29.15	5.8	56.94	2 425.86	899.54
22	-	234.67	1 523.17	-	0.09	1.39	234.67	1 523.17	-
23	-	235.05	1 523.17	-	235.05	-	215.43	1 546.68	19.62
24	110.91	124.17	1 526.35	-	-	-	235.08	1 526.35	-
25	-	195.84	1 584.01	58.65	39.09	-	117.39	1 937.07	411.71

Table 10: Detailed results for context C4