Solving the winner determination problem with discounted bids in transportation auctions

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Abstract

Continuing advances in modern technologies have transformed the procedure of transportation procurement through auctions in supply chain management (SCM). This study examines the online combinatorial auction (CA), which serves customers placed at the nodes of a transportation network, with particular consideration given to carbon emissions. The CA mechanism allows early shipments of the carriers to improve their load consolidation and reduce their repositioning trips. Sustainability and carbon emissions are considered by prioritizing the carrier's carbon reduction performances. Two models are examined under the carbon emission regulations (Carbon tax and Cap-and-offset) to choose the winners in the CA. Our aim is to minimize the cost of transportation procurement and reduce carbon emissions by incorporating the green reputation-based winner determination problem within the procurement model. Computational experiments reveal the positive impact of prioritization and discounted offers in reducing both transportation costs and the number of empty trips. Indeed, our results show the introduction of the discounted bids allows a reduction of about 2% in the transportation cost for the shipper and 24% of empty movements, on average, for the carriers.

Keywords Transportation procurement · Empty trips · Combinatorial auctions · Discounted bids · Carbon emissions · Green prioritization

1 Introduction

The last few decades have witnessed a tremendous shift from profit-centered supply chains toward sustainability-oriented supply chains. This increased awareness of the environmental implications of logistics and supply chain activities are predominantly driven by the rise of environmentally conscious consumers as well as the diverse regulations and policies set by governments to force companies to lower their carbon emissions. The World Bank (2020)

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has reported that more than 61 carbon reduction policies, including carbon taxation, have been implemented worldwide.

Among the various logistics and industrial activities, transportation is singled out as the most polluting activity (EPA, 2021). For instance, transport has been found to account for around one-fifth of global carbon emissions (IEA, 2020). Therefore, special attention must be given to optimizing transportation's carbon footprints within supply chains. In these settings, focus on reducing empty movements, known as the repositioning of transport assets, would prove to be an interesting strategy. For instance, according to the National Private Truck Council of the United States, truck fleets travel while empty for around 28% of their total distance during their operations (Fdot, 2018). These empty movements are responsible for increasing supply chain costs, reducing productivity, adding roadway congestion and, more importantly, increasing carbon emissions. The complete elimination of empty movements is not realistic, however, reducing it to a reasonable level is possible. Such reduction would not only improve the competitiveness of transportation companies but also enhance their efficiency sustainably.

In this paper, we discuss the problems of repositioning transportation assets in the context of the combinatory auction (CA) transportation procurement with special attention to sustainability and carbon emissions. CA is one of the prominent trading mechanisms for transport procurement that can lend enough flexibility for both the shippers and carriers. The carriers are allowed to generate and submit bundles of shipments (bids) on the basis of the fleet's availability and profitability while serving such shipments and with the aim of reducing their empty movements. On the other hand, shippers are allowed to set the bidding rules and select the winning bids. This can be achieved by defining an optimization model for determining the winning carriers, one that is known to be a complex problem in the context of CAs. In the current paper, we explore the sustainable winner determination problem (WDP) for transportation procurement. Additionally, we introduce innovative tools to enhance environmental considerations by granting some privileges to the carrier(s) with a high green index (i.e. carbon reduction rate)—who may potentially be chosen as the winner(s).

In the context of CA-based transportation procurement, besides bidding on serving the shipments while respecting the timing imposed by the shipper, in this study, we allow the carrier to place additional bids with a price discount while also enjoying flexibility in deciding on a different service time. The carrier's goal would be to increase their chances as a winner in the auction and, at the same time, improve the consolidation level in their fleet operations. This refers to ensuring a better loading of the fleet in case of less-than-full truck shipments and avoiding empty movements in the case of full-truck transportation. CAs allow the carriers to submit multiple (even conflicting) bids that consist of bundles of the shipments being auctioned (including the discounted ones). Each bid/bundle obeys the all-or-nothing rule, i.e. it can either be entirely successful or not at all. Subsequently, the WDP will ensure that only the feasible and competitive bids are successful and also guide the shipper to select the discounted bids only if they are advantageous to their supply chain.

This paper defines and solves a WDP in the context of CA transportation procurement. Carriers are allowed to generate bids for on-time service and early shipments with discounted prices with the sake of better load consolidation and reduction in empty trips. The paper also provides a novel direction of research in the field of sustainable transportation by incorporating, within the WDP, a prioritization mechanism that grants an advantage during the auction clearing to the carriers investing in green technology. More specifically, we propose two different WDP models under different carbon regulations that consider the possible advantages of submitting discounted bids by the carriers in addition to their green reputation. A summary of the different features characterizing our contribution is presented in Fig. 1.
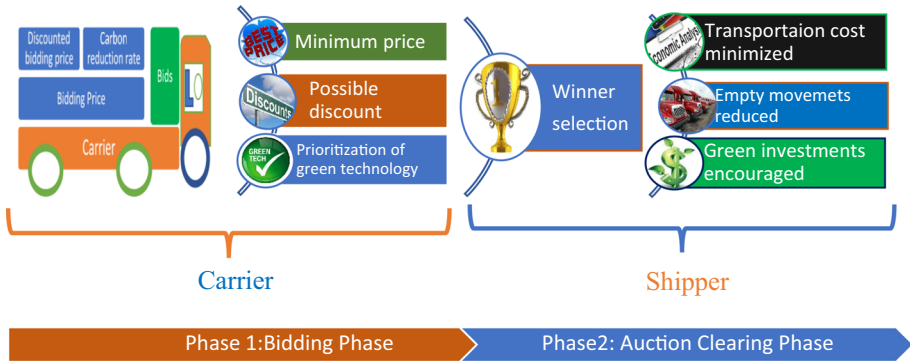
Fig. 1 Summary of our sustainable transportation procurement approach

This work has attractive outcomes for the shipper, carrier and environment that can be summarized as:

- The shipper/auctioneer can procure transport services for their shipments at the lowest possible cost in the market. The proposed CA might even select a reduced shipping price if some discounted bids are found suitable for its SC operations.
- The proposed online CA offers carriers the chance to gain a higher market share since they can compete to win new business remotely without market barriers. Moreover, carriers are allowed to submit multiple (even conflicting) bids with the possibility of generating discounted bids covering timing patterns that differ from the shipper requests. Successful discounted bids will enhance the carriers' fleet consolidation and, thus, reduce their empty movements.
- The load consolidations and empty trips' reduction will decrease the total traveled distance and, consequently, cut the carbon emissions from the transportation sector. Additionally, the mechanism of introducing the green prioritization within the WDP motivates carriers to invest more in green technology/policy.

The remainder of this paper is organized as follows: Sect. 2 provides a survey of the literature related to our work. Section 3 is devoted to the problem description and introducing the specific auction mechanism to be implemented for transportation procurement. The computations related to determining the extra cost incurred by early shipments with discounts for the shipper is presented in Sect. 4. Our novel mathematical formulations for the proposed WDPs are reported in Sect. 5. The model's validation, numerical simulations and results are presented and discussed in Sect. 6. Finally, the conclusions of this study are provided in Sect. 7.

2 Literature review

2.1 Auction-based approaches for transportation procurement

Auctions for transportation procurement are an interesting area of research getting increasing attention nowadays owing to the recent online trading developments and continuous advances in IT solutions. Lafkihi et al.(2019) pointed out that 83% of the articles published in the field of transportation procurement are based on the use of auction mechanisms, whereas

the remaining ones employ either negotiations or catalogs. Moreover, most of the studies on applying the auction mechanism for transportation procurement focused on the WDP (also called the carrier assignment problem), and only a limited number dealt with non-price objectives or considered the sustainability aspect within the problem (Jothi Basu et al., 2015b). This finding is roughly valid for all papers produced over the last 25 years but has become even more evident recently.

The pioneering works in this context have ascertained the superiority of CAs with respect to the traditional single-item or multi-item non-CAs both in terms of fairness and economic efficiency (Caplice & Sheffi, 2013; Wang & Wang, 2015; Badiee et al. 2023). However, the same works have stressed on the high complexity characterizing the design and running of CAs. Such challenges have been alleviated only partially by the recent improvements achieved in the IT sector. Identifying qualified staff that is able to understand the enigmas of designing the CA, defining the bundled bids and clearing the auction as well as developing the supporting optimization tools remain a challenge requiring more investigation (Gansterer & Hartl, 2018). Any effort in this direction can produce fruitful outcomes for both the shippers and carriers as well as to the society and environment (Özener et al., 2010; Sheffi, 2004; Triki, 2021). In the context of optimizing the transportation procurement through CAs, a large portion of the literature has focused on designing and optimizing the shippers' supply chains (Hu et al., 2016; Triki et al., 2014; Wang & Kopfer, 2014; Zhang et al., 2014, 2015). Most studies (Chen et al., 2009; Figliozzi et al., 2007) have focused on one-sided reverse CAs in which one buyer (shipper) purchases transportation services from multiple sellers (carriers). Their one-sided forward counterpart has been rarely adopted in the transportation industry (an example is reported in Garrido, 2007). Studies on real-life cases have revealed that online reverse CAs can not only achieve up to 15% savings for the shippers' transportation procurement costs but also improve their level of service (Sheffi, 2004). On the other hand, CAs allow the carriers to take advantage of their economies of scope while defining their preferences on the bundles to be submitted (An et al., 2005), reduce the total traveled distance (Triki, 2016) and avoid some of the empty movements (Kuyzu et al., 2015).

The determination of the winners is the core part of any auction. Once the submission phase is over, the auctioneer will clear the auction by solving the WDP in such a way that they minimize their shipment procurement costs while respecting the feasibility of each carrier's bids. This indicates that, in the context of CA, every successful bundle should be integrally accepted (all-or-nothing rule), and none of the shipments are assigned to more than one carrier. Surveys on modeling and solving the WDP in the mentioned context have been provided by Abrache et al. (2007); Ball et al. (2020); De Vries and Vohra (2003) and Takalloo et al. (2021) and specifically in the field of transportation by Jothi Basu et al. (2015a); Remli et al. (2019); Yang and Huang (2021); Triki et al. (2023) and Hasan et al. (2023). The complexity of CA-based WDP has been examined by Elmaghraby and Keskinocak (2004) and Rekik and Mellouli (2012) who also developed optimization models and efficient approaches for its solution.

The WDP has also been combined with several other modeling features related to the SCM. For example, Rekik and Mellouli (2012) discussed a WDP involving the carriers' reputations for on-time delivery, canceled shipment and damage to commodities. Triki et al. (2020) incorporated the WDP within a production scheduling framework (see also Fu et al., 2017, Triki et al., 2021a and Shahrabi et al., 2022) and Triki et al. (2021b) combined it with a ridesharing student transportation system. Gansterer et al. (2020) proposed a WDP for a bidding process with and without bundling that supports collaboration among carriers. Recently, Triki (2021) considered a transportation network with crowd shipping and developed a WDP to assign the shipments to the competing occasional drivers. Additionally, Liu et al. (2021)

designed an iterative CA for multi-agent parallel machine scheduling and designed a simulated annealing algorithm to solve the WDP. Finally, the stochastic version of the WDP has been addressed by Remli and Rekik (2013); Zhang et al. (2014, 2015) and Amor et al. (2016) and Yin et al. (2021) presented a stochastic WDP to capture the disruption risk with a quantity discount mechanism.

2.2 Empty movements in transportation

Reducing empty movements in carriers' networks is a well-known challenge in the context of transportation. It is an intrinsic feature of fleet management that dampers the rate of utilization of the trucks. For example, in big cities, around one-third of all truck trips are found to be carry empty loads (Holguín-Veras et al., 2004).Moreover, in the European road network, vehicles are loaded only by 56% of their weight capacity on average (Palmer & Saenz, 2012). Thus, any effort toward reducing empty movements can decrease the transportation costs and stimulate profits. Numerous studies have examined the challenge of this reduction using spot marketing (Ağrali et al., 2008; Mes et al., 2009; Robu & La Poutré, 2009; Xu & Huang, 2013). Collaboration among the stakeholders is also an effective means of minimizing the operating transportation costs. Interested readers are directed to the excellent review by Gansterer and Hartl (2018), which covers the collaboration among carriers both with and without auctions and the authors clearly claim that "*due to the necessity of a trading mechanism, auctions are generally supposed to be more complex than their conventional (i.e. non-auction-based) counterparts.*" For instance, Berger and Bierwirth (2010) suggested freight collaboration among carriers that enables them to offer uniform services throughout their region. Uddin and Huynh (2020) proposed a model that reduces the number of empty container trips through collaboration among freight carriers. After completing a trip, the carrier must return to their depot through an empty trip. Such an empty trip can be converted into a shipment if the carrier succeeds in receiving a new order to cover their empty movement. Offering a discounted price for such empty movements may increase the chances of attracting a new business for such a trip. To the best of our knowledge, Garrido (2007) proposed the first work to examine the cost of a regular trip as well as the discounted price for avoiding empty trips. However, Garrido's work considered the simplified variant of the double auction, in which the bidding process is performed on every single shipment separately and sequentially. In this study, we generalize Garrido's work to consider the more complex format of auctions allowing carriers to bid even on bundles of shipments.

2.3 Sustainable aspects in SCM

Carbon emissions are the main hindrance to environmental sustainability. Various regulations have been proposed and implemented to reduce carbon emissions (World Bank, 2020), including the carbon tax, cap and trade and limits on emissions (Benjaafar et al., 2013; Hasan et al., 2021; Toptal et al., 2013). Supply chain managers encounter the challenge of obeying the carbon regulations imposed by governments/authorities. Green practices within the traditional SCM, referred to as sustainable-SCM (Khan et al., 2018), has stimulated the interest of several scholars, including Dubey et al. (2017); Giannakis and Papadopoulos (2016); Mei et al. (2021). The Organization for Economic Cooperation and Development (OECD, 2010, 2020) has launched several concerns about the considerable carbon emissions provoked by the transportation sector. According to Ritchie et al. (2020), carbon emissions from transportation activities amount to up to 16% of the total emissions. Jazairy and Haartman (2021)

claim that the logistics services are responsible for a considerable share of the emissions, also stating that this trend is still increasing. The adverse effects of transportation and logistics on the environment has been widely discussed in the recent literature (see, for example Gatta et al., 2018; Lee, 2011; Marchet et al., 2014; Wangsa, 2017). Consequently, several carbon regulations are being defined to force the logistics actors to reduce emissions even from the transportation sector's side.

The research history on auction-based sustainable studies is not very long, but it is currently a growing research phenomenon. Gao (2018) proposed a sustainable WDP to choose the contractor in public–private infrastructure partnership projects. Qian et al. (2019) developed a WDP for the cleaner energy devices procurement. More recently, green WDP models for identifying third-party logistics providers and for procuring sustainable responsive transportation services Qian et al. (2021a, 2021b, 2023).

The idea of allowing the prioritization of customers according to their green technology index was introduced to help achieve environmental sustainability through the reduction of carbon emissions (Etraj & Jayaprakash, 2016; Jazairy & von Haartman, 2021) and, in the long term, boost further investments in green technologies. However, green investments represent another cost component in the carriers' operations often requiring advanced decision support tools. Optimizing the investments in green technology has been investigated by Bhattacharyya and Sana (2019) and Toptal et al. (2013). Datta (2017) and Lin (2018) have discussed the effect of this investment under the policy of a carbon tax on transportation activities. In the field of SCM research, the diffusion of green solutions for freight transportation has been examined by Brauer and Khan (2021), and the attractiveness of green penetration in supply chains has been explored in Green Transportation (2022) and by Lu et al. (2019) and Saada (2020).

2.4 Paper's contributions

The current study considers the concern put forward by shippers who are interested in implementing a reverse first-price CA for the procurement of their transportation needs while considering the participating carriers' green prioritization. Interested carriers can submit bids, consisting of both regular and discounted early bundled shipments (as suggested first by Garrido, 2007). By offering discounted bids, the carriers attempt to perform a better consolidation of the shipments with the aim of reducing the number of empty trips and minimizing carbon emissions. Here, we propose a new approach that aids both the shippers and carriers in operating efficiently under the well-known taxation-based and cap-and-offset regulations (inspired from earlier works such as Chen et al., 2013 and Benjaafar et al., 2013).

Our study, thus, defines a novel sustainable WDP that clears the CA to identify the winning regular and early bids while taking into account the prioritization of the carriers according to their green index by means of carbon reduction rate by the carriers, which is regulated by the government or regulatory authority. To the best of our knowledge and based on the summary of the literature review that has been reported in Table 8 (see the Appendix), this study represents the first integrated WDP model that considers all the above features within the same transportation procurement framework with CAs.

3 Problem statement

The transportation system we are considering here is defined as pairs of the origin–destination nodes belonging to a road network operating under the carbon tax-based regulation, and every pair is connected by a set of arcs or routes. We assume that each shipment $s \in S$ will have any of the network's nodes as an origin and shipper's warehouse as a destination. The shipper's objective is to procure their transportation needs to replenish their warehouse such that their total transportation costs due to the shipments and carbon emissions are minimized. For this purpose, the shipper will organize an online reverse CA to procure each of their origin–destination shipments to be served on a specific due date T_s. The quantity to be shipped Q_s to the warehouse as well as each shipment's due date T_s is determined on the basis of the Economic Order Quantity (EOQ) model, which is by far the most employed policy by SCM practitioners. Clearly, adopting more advanced inventory management policies, such as lot sizing models, is straightforward in the context of this study. However, our goal here is to focus mainly on the transportation/bidding aspects of the problem while keeping the inventory part simple so it can be easily understood and implemented.

On the other hand, there is a set of carriers operating in the market who are interested in gaining additional spot business by participating in the CA to serve part of the shipments. The carriers also aim at reducing their empty movements due to the unavoidable repositioning trips in their own networks. The auctioning process involves sharing and exchanging structured information among the parties through the online CA platform. Each carrier will place their bids to serve any bundle of shipments while respecting each shipment's due date T_s. Moreover, for the sake of a better load consolidation and empty trips' reduction, some carriers can find it convenient to define and submit additional bids involving some of the planned shipments but to be served before their due date T_s. In order to incentivize the shipper accepting such early shipments, the carrier will propose discounted prices for such bundles. Thus, interested carriers have the option to offer two different kinds of bids: regular bids for serving the shipments on time as per the shipper's EOQ and additional discounted bids suggesting the same shipments but some (or all) of them must be served earlier than the EOQ due date.

Subsequently, the shipper will hold the responsibility of checking the feasibility of the received early shipments (in terms of cost convenience) based on the extra cost they will bear due to holding inventories for a longer time. This aspect should be incorporated within the WDP formulation which will increase, thus, its level of complexity, compared to the existing WDP models. More specifically, assume that each carrier $k \in K$ submits a set of B^k bids at the price of P_b^k each (with $b \in B^k$) for the on-time bundled shipments. They may also submit the same bundles at the discounted price $\check{P}_b^k$ with some of the shipments served t_s^k days earlier than their required time. Clearly, the inequality $P_b^k > \check{P}_b^k$ will hold for each bundle b. Figure 2 summarizes the bidding/clearing process via the online CA platform.

Apart from submitting the bundled bids, every registered carrier/bidder should provide additional relevant information, including the green index, to the online auctioning platform. The green index presents their capability of reducing the carbon emissions per unit distance while using their transportation fleet. A carrier with a high green index should be privileged during the auction clearing phase by assigning to them a priority that may enhance their chances of winning. Consequently, the shipper/auctioneer will select the winning carriers not only according to their bidding regular and discounted prices but also considering their rate of reducing carbon emissions.
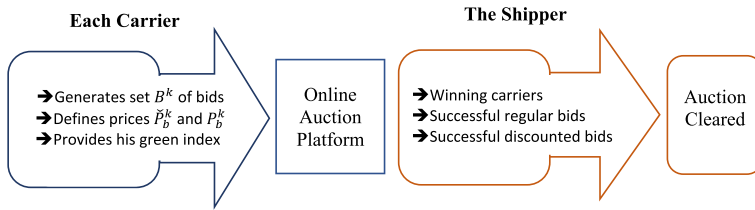
Fig. 2 Bidding/clearing process in the online reverse CA

4 Quantifying extra cost due to early shipment

Any early shipment will cause an extra inventory in one or more shipper's warehouses and, thus, provoke additional holding and carbon emissions costs in their operations. We assume that the shipper needs cyclic replenishments of a homogeneous product according to their EOQ dynamics having T_s as the period and Q_s as the re-ordering quantity (Garrido, 2007). Before moving onto the discussion of our models, we must introduce the additional notation. The total distance and shipped quantity corresponding to bid b submitted by carrier k are $d_b^k = \sum_s d_s a_{bs}^k$ and $Q_b^k = \sum_s Q_s a_{bs}^k$, respectively, where the d_s is the distance of shipment s and Q_s is its quantity. Here, a_{bs}^k represents the mapping of the shipments S within bid b by carrier k. Each constant $a_{bs}^k \in \{0,1\}$ takes the value 1 if shipment s is included in bundled bid b and is 0 otherwise. $C_c = C_{tax} C_{prod}^k$ is the cost of carbon emissions per unit distance and $\partial_k = C_c R_k$ is the reduction in carrier k's transportation cost during the auction clearing process. Here C_{tax} indicates the penalty per unit of carbon, C_{prod}^k is the carbon produced per unit distance by carrier k according to the type and condition of the carrier and $R_k (0 \le R_k < 1)$ represents the rate of reduction in carbon emissions/index by carrier k per unit distance due to their efforts in investing in green technology. The notation employed throughout this study is depicted in Table 1.

Whenever the shipper accepts an early shipment at time t_s^k ahead of the scheduled period (through bid b by carrier k), then the inventory scenario specified in the second period of Fig. 3 is observed. Such an extra quantity in the stock for an extended time of t_s^k days (earlier than the next planned replenishment) will have the following costs (clearly the extra costs will apply only to the early shipments within each bid b since t_s^k will take value zero if shipment $s \in S$ is served on time without any early replenishment):

a. Extra inventory holding cost: since the extra quantity Q_s of stock is held for t_s^k longer (more days) at a holding cost of h per unit per time (days), then the extra holding cost related to shipment s and bid b are given respectively as:

$$HC_s^k = t_s^k h Q_s \text{ and } HC_b^k = \sum_s HC_s^k \tag{1}$$

b. Extra carbon cost: the extra stock will also produce an additional cost owing to the supplementary carbon emissions. Given that g is the unit emission in the warehouse per item per time unit, then the additional carbon emissions due to early shipment by carrier k are: $E_S^k = g Q_s t_s^k$ and, thus, the extra emissions cost related to shipment s and bid b are given respectively as:

$$EC_s^k = Q_s g t_s^k C_{tax} \text{ and } EC_b^k = \sum_s EC_s^k \tag{2}$$

Table 1 Notation and interpretation

Symbol	Unit	Description
K	–	Set of carriers, indexed by k
S	–	Set of shipments, indexed by s
B^k	–	Set of bids submitted by carrier k, indexed by b
P_b^k	\$/mile	Bidding price per unit distance for on-time delivery of bid b by carrier k
$\check{P}_b^k$	\$/mile	Discounted bidding price per distance for some early shipments included in bid b (t_s^k earlier the regular replenishment time) by carrier k
t_s^k	days	Number of days of early service of shipment s included in bid b by carrier k with respect to the scheduled shipment
h	\$/item/day	Holding cost per unit item and unit time
g	kg/item/day	Carbon emission rate per time per item of products in the shipper's warehouse
C_{tax}	\$/kg	Carbon tax for the (weight) unit of carbon emission
C_{prod}^k	kg/mile	Carbon produced from carrier k's truck per unit distance
C_c	\$/mile	Carbon cost per unit distance
R_k	–	The rate of reduction in carbon emissions of carrier k
d_s	mile	Distance to be travelled to serve shipment s
Q_s	–	Quantity to be shipped for shipment s
Q_b^k	–	Quantity to be shipped through bid b by carrier k
d_b^k	mile	Distance covered by carrier k to serve bid b
a_{bs}^k	binary	Constant representing the shipments-bids mapping for each bid b by carrier k
∂_k	\$/mile	Cost reduction per unit distance by carrier k as a result of his/her green investments
TEC_b^k	\$	Extra cost for shipper due to receiving early shipment of bid b by carrier k
X_b^k	–	Binary variable that takes the value 1 if bid b by carrier k is successful to be served on time for shipments $s \in S$, i.e. on day T_s, as scheduled by the shipper, and is 0 otherwise
$\check{X}_b^k$	–	Binary variable that takes the value 1 if the discounted bid b by carrier k is successful to be served including some early shipments $s \in S$ for day $(T_s - t_s^k)$, i.e., t_s^k days ahead with respect to the scheduled day. It is 0 otherwise

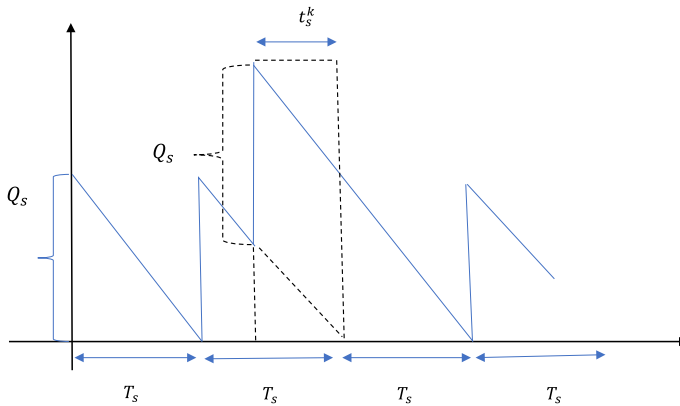Consequently, the total extra cost due to the early service of shipment s by carrier k is:

$$TEC_s^k = HC_s^k + EC_s^k = ht_s^k Q_s + g Q_s t_s^k C_{tax}$$

or equivalently:

$$TEC_s^k = Q_s t_s^k (h + g C_{tax}) \tag{3}$$

Consequently, the total extra costs corresponding to bid b by carrier k are:

$$TEC_b^k = \sum_s TEC_s^k \tag{4}$$

Fig. 3 Inventory dynamics of shipments due to early replenishment

This extra cost for the shipper's operations should be compared to the sum of the total discount for covering the distance d_b^k through bid b by carrier k, calculated as $\left(P_b^k - \check{P}_b^k\right)d_b^k$. Such a discount can be considered attractive for the supplier only if:

$$\left(P_b^k - \check{P}_b^k\right)d_b^k > TEC_b^k \tag{5}$$

Such an inequality will be included in our WDP in the next section to ensure that the shipper will accept bids with early shipments only if they contribute to their cost reduction.

5 WDP models with discounted bids and under carbon regulations

As discussed in Sect. 2.3, there are various types of emissions reduction policies proposed in the literature and/or implemented by the authorities. The carbon tax (Chen et al., 2013) is the most straightforward and widely used tool of reducing carbon emissions in many countries. In the sequel, we will develop novel WDP formulations under two different carbon regulations: (i) the taxation policy in Sects. 5.1 and (ii) the Cap-and-offset policy in sub-Sects. 5.2 whereby tax will be exempted for a specific limit of carbon emissions and the tax charge applies whenever the emissions reach or exceed the limit threshold (Benjaafar et al., 2013; Hasan et al., 2021; Toptal et al., 2013).

5.1 WDP under carbon taxation policy (WDP-CT)

In this WDP model, the winning carriers are chosen while implementing the carbon tax regulation and considering the total transportation costs:

$$\text{Min} TC_1 = \sum_{k=1}^{K}\sum_{b=1}^{N}\left\{\left[\left(P_b^k + C_c - \partial_k\right)d_b^k X_b^k\right] + \left[\left(\check{P}_b^k + C_c - \partial_k\right)d_b^k \check{X}_b^k\right] + TEC_b^k \check{X}_b^k\right\} \tag{6}$$

The objective function (6) minimizes the cost of transportation procurement to identify the winners considering the bidding prices submitted by each carrier and their green index. It selects the most convenient bids submitted by all carriers to cover all the shipments either

with on-time or early service (Fu et al., 2023). The above objective function is the minimized subject to the following constraints:

$$\sum_{k,b}\left[a_{bs}^k X_b^k + a_{bs}^k \check{X}_b^k\right] = 1 \text{ for every shipment } s \in S \tag{7}$$

$$\sum_b (X_b^k + \check{X}_b^k) \leq M, \text{ for every } k \in K \tag{8}$$

$$\left(P_b^k - \check{P}_b^k\right) d_b^k X_b^k \leq TEC_b^k X_b^k, \text{ for every } k \in K, b \in B^k \tag{9}$$

$$X_b^k, \check{X}_b^k \in \{0, 1\}, \text{ for every } k \in K, b \in B^k \tag{10}$$

Constraint (7) state that every shipment is won through only one regular or discounted bid as submitted by only one carrier. Constraint (8) ensure that any carrier can win a maximum M number of bids. This condition is often imposed in the transportation industry to reduce the risk of failure due to being sub-ordinated to a very limited number of carriers. Constraints (7) and (9) ascertain that discounted bids involving early shipments are accepted only if the discount amount is greater than the extra cost incurred due to early shipments. Specifically, each variable X_b^k will be forced to be set to zero if $\left(P_b^k - \check{P}_b^k\right)d_b^k \geq TEC_b^k$, for every k and b, as stated by inequality (5). Constraint (7) jointly with Constraint (9) ensure that variables X_b^k and $\check{X}_b^k$ both cannot be equal to 1 since they refer to the same bundle of shipments and the discounted bid $\check{X}_b^k$ can be set to one only if the discounted bid is advantageous to the shipper's cost reduction. Finally, constraint (10) guarantees the binary nature of the decision variables to describe which among the submitted bids are successful.

Formulation (6)–(10) is a binary linear programming model whose size increases with the number of shipments, carriers and bids.

5.2 WDP under Cap-and-offset policy (WDP-CAO)

Imposing limitations on carbon emissions offer more flexibility to the logistics managers than the carbon taxation policy since companies can avail an exemption from the carbon tax for a certain limit, say U, set by the regulatory authority. Subsequently, the tax is imposed only if the amount of carbon emissions reaches or exceeds such a limit (Benjaafar et al., 2013, Mala et al., 2022). For the definition of this model, we will need to introduce an additional set of decision variables, as follows:

- X_{bU}^k: binary variable that takes the value 1 if the carbon emissions exceed the limit U and is 0 otherwise.

The carbon emissions of our proposed system are the sum of the carbon emitted from both the carriers' fleet while serving the shipments as well as the extra emissions due to the stock holding because of the early shipment (we do not consider the normal inventories here because they must be stocked anyway and are not subject to any relevant decision in our model). The additional carbon emissions due to early shipment s and bid b by carrier k are $EE_s^k = gQ_s t_s^k$ and $EE_b^k = \sum_s EE_s^k$, respectively. By performing the appropriate substitutions, we can determine the expression of the carbon emissions related to bid b by carrier k as:

$$CE_b^k = C_{prod}^k (1 - R_k) d_b^k X_b^k + C_{prod}^k (1 - R_k) d_b^k \check{X}_b^k + EE_b^k \check{X}_b^k \tag{11}$$

and that per unit item as:

$$E_{bQ}^K = \frac{CE_b^k}{Q_b^k} \tag{12}$$

Given the limit on emissions per unit U and the value E_{bQ}^K of the per unit emissions by carrier k for bid b per item, the tax is applied only if $\left(U \leq E_{bQ}^K\right)$ for every k and b.

Based on the above preliminary computations and keeping in mind expressions (1) and (2), the current objective is to identify the appropriate bids submitted by all carriers under the Cap-and-offset emissions policy while minimizing the following shipper's transportation costs:

$$\text{Min}\,TC_2 = \sum_{k=1}^K \sum_{b=1}^N \left[\begin{array}{l} \left\{ P_b^k d_b^k X_b^k + C_{prod}^k(1-R_k)C_{tax}d_b^k X_b^k X_{bU}^K \right\} + \\ \left\{ \check{P}_b^k d_b^k \check{X}_b^k + C_{prod}^k(1-R_k)C_{tax}d_b^k \check{X}_b^k X_{bU}^K \right\} + \\ (HC_b^k \check{X}_b^k + EC_b^k \check{X}_b^k X_{bU}^K) \end{array} \right] \tag{13}$$

Which is non-linear because of the product of variables. In order to linearize (13), we introduce two additional sets of variables Y_b^k and Z_b^k, and we re-write (13) as follows:

$$\text{Min}\,TC_2 = \sum_{k=1}^K \sum_{b=1}^N \left[\begin{array}{l} \left\{ P_b^k d_b^k X_b^k + C_{prod}^k(1-R_k)C_{tax}d_b^k Y_b^k \right\} + \\ \left\{ \check{P}_b^k d_b^k \check{X}_b^k + C_{prod}^k(1-R_k)C_{tax}d_b^k Z_b^k \right\} + \\ (HC_b^k \check{X}_b^k + EC_b^k Z_b^k) \end{array} \right] \tag{13a}$$

This is subject to the following constraints:
Constraints (7)–(9)

$$Q_b^k U X_{bU}^k - C_{prod}^k(1-R_k)d_b^k Y_b^k - C_{prod}^k(1-R_k)d_b^k Z_b^k - EE_b^k Z_b^k \leq 0, \text{for every } k \in K, b \in B^k \tag{14}$$

$$Y_b^k \geq X_b^k + X_{bU}^k - 1; Y_b^k \leq X_b^k; Y_b^k \leq X_{bU}^k, \text{ for every } k \in K, b \in B^k \tag{15}$$

$$Z_b^k \geq \check{X}_b^k + X_{bU}^k - 1; Z_b^k \leq \check{X}_b^k; Z_b^k \leq X_{bU}^k, \text{ for every } k \in K, b \in B^k \tag{16}$$

$$X_b^k, \check{X}_b^k, X_{BU}^k, Y_b^k, Z_b^k \in \{0,1\}, \text{ for every } k \in K, b \in B^k \tag{17}$$

Constraints (7)–(9) have the same interpretation as specified above under the carbon tax model. Constraint (14) ensures that the carbon tax is applied if the total carbon emissions by the system reach or exceed the limit U. It is the direct application of the relation $\left(U - E_{bQ}^K\right) \leq 0$, for every k and b, as defined above. Constraints (15) and (16) define the new variables used to linearize the objective function, and Constraint (17) ensure that all decision variables are binary.

6 Computational experiments

This section details the numerical experiments carried out to validate the proposed models. Since no benchmarking data is available for our problem, our experiments were performed on arbitrarily generated data. Given the complexity in generating the necessary data with different patterns of the input parameters, we developed an ad-hoc Python program that generates the suitable data for several dimensions of the carriers-bids-shipments combinations. All instances were solved by using the CPLEX software package. In the sequel, we

Table 2 Distances and quantities for every auctioned shipment

Shipments	1	2	3	4	5	6
Distances	176	165	170.5	154	170.5	154
Quantities	155	160	165	155	145	160

first discuss the experimental results of an illustrative example that allows the understanding of the dynamics of winner determination in addition to the effects of the early shipments. Subsequently, we generate and solve a large-scale instance with the aim of comparing the outcomes of the two models implementing two different carbon emissions reduction policies.

6.1 Illustrative example

Here, we consider a supplier that designs and runs an auction to procure transportation for $S = \{6\}$ shipments to be served on a specific due date T_s for every $s \in S$. The details related to the distance and quantities for each shipment are reported in Table 2. Suppose there are 10 carriers who are interested in participating in the auction by placing their bids as a set of bundles each including different combinations of shipments. All the 24 submitted bundled bids together with their associated regular and discounted prices, are illustrated in Table 3. The elements of the set $\{t_s^k\}$ indicate the time of early delivery of the shipments (in order to remove the empty movements) included in the related bid (the value 0 implies that the corresponding shipment does not involve any early delivery). The table also includes the randomly generated inputs related to each bid submitted by every carrier. Finally, we assume that the carbon tax $C_{tax} = 0.12$ \$/kg (Iwata, 2021; ODYSSEE-MURE, 2023), holding cost $h = 0.2$\$/item/day, carbon emission rate from the shipper's warehouse is $g = 0.4$ kg/item/day and $M = 1$.

6.2 Solution of the models

The binary linear programming model WDP-CT and WDP-CAO were solved considering the input datasets as reported in Tables 1 and 2. We solved the instance exhibiting the value of the permitted limit for carbon emissions by each unit of product, i.e. $U = 1$ (kg/item) for WDP-CAO. The collected results are displayed in Table 4 (the sign "x" indicates that the shipment is included in the associated bid).

The results revealed in Table 4 declare that carriers 5 and 10 won their bids with all shipments to be delivered on time, whereas carrier 8 won his/her first bid with discounted price (i.e. $\check{X}_1^8 = 1$). This outcome is observed for both the WDP-CT and WDP-CAO models which give a clear signal on the robustness of the formulations. Indeed, both models converge to the conclusion that only the discounted bid of carrier 8 fits the management dynamics of the shipper and no flexibility can be admitted towards the other carriers. As a result, two empty movements were removed (that can be deduced from the non-zero elements of $\{t_s^k\}$ as indicated in Table 3) from the network of carrier 8, which helps to avoid the carbon emission related to those empty trips. The tax on emissions applies only for X_{1U}^8 in model WDP-CAO, whereas the tax is applied for all units of carbon emitted in model WDP-CT. Therefore, it is clear that the model implementing the Cap-and-offset policy results to be more attractive for the transportation system considered in this illustrative example since the shippers can

Table 3 Input data related to the illustrative test problem

Carrier	Bid	Shipments in bid	P_b^k	$\{t_s^k\}$	$\check{P}_b^k$	C_{prod}^k	R_k	C_c	∂_k	Q_b^k	d_b^k	TEC_b^k
1	1	{1,2,3}	7	{4,0,3}	6.16	1.7	0.6	0.20	0.12	480	511.5	276.5
	2	{4,5,6}	4	{0,4,0}	3.52	1.7	0.6	0.20	0.12	460	478.5	143.8
2	1	{2,3,4}	6	{2,0,4}	5.28	1.5	0.6	0.18	0.11	480	489.5	233.1
	2	{1,4}	4	{3,0}	3.52	1.5	0.6	0.18	0.11	310	330	115.3
	1	{4,5,6}	5	{0,3,1}	4.4	1.6	0.9	0.19	0.17	460	478.5	147.6
3	2	{1,3,5,6}	6	{0,4,0,1}	5.28	1.6	0.9	0.19	0.17	625	671	203.4
	3	{1,2}	4	{0,4}	3.52	1.6	0.9	0.19	0.17	315	341	158.7
4	1	{1,5,6}	3.5	{3,0,2}	3.08	1.65	0.7	0.20	0.14	460	500.5	194.7
	2	{1,3,5}	4	{0,1,2}	3.52	1.65	0.7	0.20	0.14	465	517	112.8
5	1	{2,5}	3	{0,4}	2.64	1.65	0.75	0.20	0.15	305	335.5	143.8
	2	{2,5,6}	4	{1,0,2}	3.52	1.55	0.75	0.19	0.14	305	324.5	79.4
	1	{1,3,5}	4.6	{0,2,3}	4.048	1.7	0.65	0.20	0.13	465	517	189.7
6	2	{2,3}	5	{0,5}	4.4	1.7	0.65	0.20	0.13	325	335.5	204.6
	3	{1,2}	4.4	{4,0}	3.872	1.7	0.65	0.20	0.13	315	341	153.8
7	1	{2,4}	7	{0,5}	6.16	1.6	0.8	0.19	0.15	315	319	198.4
	2	{1,2}	6	{3,0}	5.28	1.6	0.8	0.19	0.15	315	341	115.3
	3	{1,2,3}	5	{0,4,6}	4.4	1.6	0.8	0.19	0.15	480	511.5	404.2
8	1	{1,3}	4.5	{1,1}	3.96	1.65	0.7	0.20	0.14	320	346.5	81.8
	2	{2,4,6}	5	{5,0,1}	4.4	1.65	0.7	0.20	0.14	475	473	238.1
9	1	{2,4}	5.6	{0,3}	4.928	1.55	0.8	0.19	0.15	315	319	115.3
	2	{5,6}	6	{5,0}	5.28	1.55	0.8	0.19	0.15	305	324.5	179.8
10	1	{4,5,6}	6.5	{0,5,0}	5.72	1.5	0.7	0.18	0.13	460	478.5	192.2
	2	{4,6}	5.9	{0,5}	5.192	1.5	0.7	0.18	0.13	315	308	119.0
	3	{3,4,5,6}	5	{5,2,0,0}	4.4	1.5	0.7	0.18	0.13	625	649	281.5

Table 4 Results: winning bids, procurement cost and removed empty movements (REM)

Carrier	Bid	Shipments						REM	WDP-CT Decisions		WDP-CAO Decisions		
		1	2	3	4	5	6		X_b^k	$\check{X}_b^k$	X_b^k	$\check{X}_b^k$	X_{bU}^k
5	1		×			×		0	1	0	1	0	0
8	1	×		×				2	0	1	0	1	1
10	2				×		×	0	1	0	1	0	0
Total procurement cost ($)									4353.57		4318.82		

achieve savings on the procurement cost. Furthermore, some of the involved carriers can avoid tax penalization and empty movements, leading to reduced carbon emissions from their side as well. We expect that applying the proposed models for the real data can eliminate even more empty movements and carbon emissions.

6.3 Experiments on large-scale instances

In this subsection, we will perform further experiments to confirm if the behavior of both the algorithms observed in the previous subsection will continue to be valid even when solving large-scale test problems. Even here, we made use of the same Python program that we developed to generate all the required data in an arbitrary manner (the input data can be made available under request). The instance we consider here has 25 auctioned shipments, 150 carriers and 600 submitted bids, as Triki et al. (2014) considered almost similar data size for testing the problem in large-scale instances. It reflects a typical scenario of a very competitive spot market with every carrier submitting 4 bids on average with the goal of gaining additional income and reducing empty movements. More specifically, every carrier, on average, submits 4 bids with regular and discounted prices, and the number of auctioned shipments per bid range between 2 and 23. The regular prices of the submitted discounts we randomly generated in the interval [3, 7] and on average, the discounted prices are 12% less than their regular counterpart and include at least 33.3% of shipments to be served earlier than the shipper's plan. All the other input data are assumed to be similar to the values used in Sect. 6.1. However, they have been appropriately adapted to the size of this test problem. The collected results are summarized in Table 5, in which we report both the regular and discounted winning bids X_b^k and $\check{X}_b^k$, together with the number of empty trips removed from the corresponding discounted bid. Additionally, we report the total procurement costs for the shipper and specify the bids that were exempted from the carbon tax (indicated by "*") in the case of the WDP-CAO model.

The results of Table 6 declare that models WDP-CT and WDP-CAO both succeed in eliminating 6 empty trips from the transportation networks of all carriers. This can be considered as a significant outcome for the system as a whole, given the high number discounted bids that resulted to be successful. Indeed, over the 25 shipments put up for auction, the winning carriers avoided 24% of empty movements. Considering the procurement cost, even in this test problem, the model that implements a Cap-and-offset policy results to be more attractive to the shipper since it produced a procurement cost that is lower than the WDP-CT.

Table 5 Numerical results of a large-scale instance

| Model	Winning bids		Removed empty movements	Total procurement cost
	Regular (*bids exempted from the carbon tax)	Discounted (*bids exempted from the carbon tax, removed empty trip per bid)		
WDP-CT	$X_2^{36}, X_4^{44},$ X_4^{73}, X_4^{137}	$X_1^{31}(2), X_3^{51}(1),$ $X_2^{116}(1), X_4^{145}(2)$	6	19,399.9
WDP-CAO ($U = 1$)	$X_2^{36}, X_4^{44}(*),$ $X_4^{73}(*), X_4^{137}$	$X_1^{31}(2), X_3^{51}(1),$ $X_2^{116}(1), X_4^{145}(2)$	6	19,307.7

Table 6 Outcomes of WDP-CT Model for all Scenarios

Scenario	Price discount	Tax	Cost ($)	REM
1	Yes	Yes	19,399.90	6
2	No	Yes	19,773.76	0
3	Yes	No	18,732.63	6
4	No	No	19,318.54	0

6.4 Comparison

In the sequel we consider different scenarios to compare the outcomes of the models with discount and without the discount mechanism on both the cost and the carbon emissions as a consequence of empty movements reduction. We use here the 25 shipments, 150 carriers and 600 bids instance for all further discussion. We start by analyzing model WDP-CT that was solved with and without (i.e. $\check{X}_b^k = 0, \forall\, k, b$) discounted bids, and with and without the tax penalty as well. Thus, the outcomes result in four possible scenarios as shown in Table 6.

Table 6 shows that the total cost is higher in the case of input data without the discount mechanism. The cost reduction in the transportation service procurement is about 2%. Considering the fact that the procurement is a repetitive process, 2% can represent a remarkable saving in the long run. The empty movements that have been removed from the system amount to 24%. On the other hand, not surprisingly, the procurement cost is lower without any emission tax, but this will clearly increase the carbon emissions. In order to understand better the interaction between the tax rate, the discounted prices and the REM, we depicted Fig. 4.

Figure 4a shows how the cost increases with the high tax rate but the REM starts to increase and then decreases. Thus, clearly high values of tax rate are not attractive due to the higher cost with limited REMs. But for moderate values of tax rate, the REMs is high enough to alleviate the effect of greater cost values. This can be explained by the fact that both the REM and cost do not only dependent on the tax rate but also on other parameters like the discounted prices. Figure 4b shows the effects of discounts on REM and costs. Both are very sensitive to changes in the discounts. We observed that for a discount decrease of about 5%, the cost increases by almost 2% whereas the REMs decreases by 100%. This means that, the increase in cost will not be compensated by any empty movement removal. Inversely, whenever the discount increases by 5%, the cost decreases by about 4%, whereas the REM

(a)

(b)
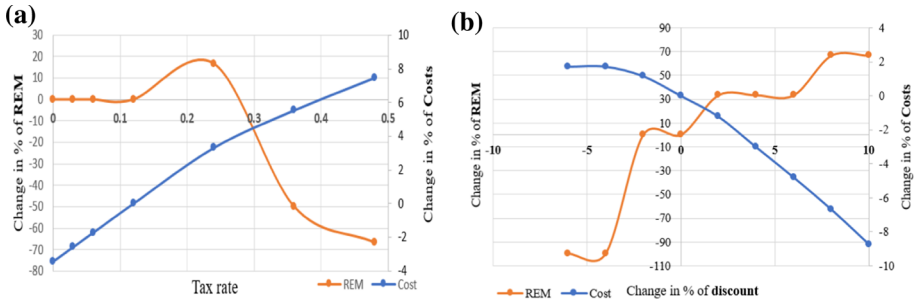
Fig. 4 a Effect of the carbon tax on Cost and REM (WDM-CT model) and **b** Effect of discounts on Costs and REM (WDM-CT model)

increases by 33%. Thus, it is clear that the discount mechanism effectively reduces both costs for the shipper and empty movements from the carriers.

Considering now the WDP-CAO model that has different carbon cap features due to the fact that different values of carbon limits (U) can be imposed, 16 scenarios have been analyzed, as reported in Table 7.

Table 7 shows first that the absence of the discount mechanism always produces higher costs, and second that the total cost decreases as the value of U increases. However, starting from $U = 3$ onward, no variations of the cost are observed (i.e. for $U = 3, 4, 5$, the model produces the same results). This is due to the fact that all the emitted carbon per unit results to be lower than the cap U, and, thus, even if such a cap increases over the threshold 3, the model's outcome remains unaltered. This policy is more attractive for the managers because it allows some flexibility from the emission viewpoint, even though it can negatively impact the carbon reduction objective. Hence, setting an appropriate cap value becomes a crucial factor if we aim to minimize both the cost and emissions simultaneously.

It is also worth comparing the above results with those related to the WDP-CT model reported in Table 6. The comparison shows that the total costs are lower than those of model

Table 7 Scenario outcomes of the *WDP-CAO* model

Scenario	Discount	Penalty (tax)	Cost ($)	REM	Carbon limit (U)
5	Yes	Yes	19,307.70	6	$U = 1$
6	No	Yes	19,882.79	0	
7	Yes	No	18,732.63	6	
8	No	No	19,388.50	0	
9	Yes	Yes	19,068.39	6	$U = 2$
10	No	Yes	19,542.77	0	
11	Yes	No	18,732.63	6	
12	No	No	19,388.50	0	
13	Yes	Yes	18,732.63	6	$U = 3, 4, 5.$
14	No	Yes	19,388.50	0	
15	Yes	No	18,732.63	6	
16	No	No	19,388.50	0	
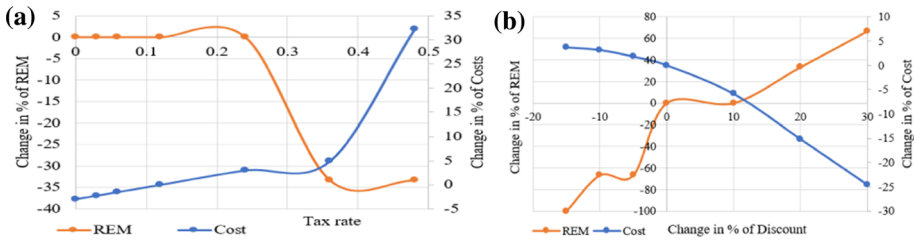
Fig. 5 a Effect of the tax rate on the cost and the REM (WDP-CAO model) and **b** Effect of discount on the cost and the REM (WDP-CAO model)

WDP-CT for several values of the carbon limits. Furthermore, the cost reduction is slightly more significant for higher values of U. This means that the adoption of the Cap-and-Offset policy often results to be more advantageous for the shipper rather than the threshold value imposed by the authorities.

Finally, Fig. 5 aims at analyzing further the effect of the carbon tax rate on the cost, REM and discounts for WDP-CAO model. More specifically, similarly to Fig. 4a, even in Fig. 5a the cost increases and the REM decreases when higher values of tax rate are applied. However, in this case the cost increases only slightly at the beginning and starts to increase remarkably only for higher values of tax rate. Concurrently, the REM decreases quickly when the tax rate exceeds the value of 0.2. This highlights the crucial importance that tax rate has on the operation of whole transportation economics. Concerning the impacts of the discounts on the cost and REM, Fig. 5b illustrates how, for increasing values of discounts, the cost decreases and the empty movements increases following trends that are even more evident with respect to the case of WDP-CT model.

7 Conclusions

Transportation facilities are becoming more automated and convenient due to intelligent technologies. Real-time information on supplies and carriers' availability offer the opportunity to reduce inefficiencies in transportation systems. This work proposed an online auction mechanism for the transport procurement that can be quite attractive for all the actors in the spot market in the carriers' fleet and vehicles such that both the buyer and seller can enjoy benefits. Indeed, the supplier can reduce their procurement cost by selecting the lowest bidding prices offered, and the carriers possess the opportunity to capture more demand and reduce some of their empty movements. Besides achieving savings to cover the shipper's transportation needs, the reduction of carbon emissions through optimally managing the inventories in the warehouse and eliminating some empty movements are the main outcomes of this research. This latter aspect has been enforced within the developed WDP models by prioritizing the carriers who invest in green technologies who, thus, have high green indices. Identifying the most suitable carbon regulations for reducing carbon emissions from transportation systems and encouraging the investment in green technology is nowadays a promising direction of research, and our green reputation-based WDP models represent a valuable contribution in this direction. Indeed, our CA proposed mechanism succeeded in determining the most advantageous bids for the shipper to reduce the carbon emissions and in identifying the most suitable carbon policy to promote a sustainable growth of the logistics sector. As a matter of fact, our findings show how the developed models can ensure a reduction of about 2% in the

transportation cost for the shipper and a decrease of 24% of empty movements, on average, for the carriers. This work can be extended in several research directions as follows:

- From the carriers' viewpoint, constructing the bundles to be submitted as bids is not an easy task for such a complex auctioning system. Moreover, selecting the regular and discounted prices associated with each bid is a challenging problem in the context of CAs, in which the prices are assigned to the whole bundles and not to each shipment singularly. Consequently, modelling and solving the well-known Bid Generation and Pricing Problem (BGPP) for the specific scenario analyzed in this paper can prove to be extremely useful in guiding the carriers in defining their bidding strategies in the CAs. Such a BGPP model can be based on the concept of synergy approximation (Keskin et al., 2023; Triki, 2016) or integrated within a more sophisticated paradigm based on the vehicle routing and inventory framework.
- The green prioritization factors with some imposed weights enhance the green index's effect on optimizing the WDP with the green reputation. The optimization of such a proposed system to set the optimal priority factor can yield new problems in the context of research on transportation systems. The aim is to help in further reducing carbon emissions by eliminating the high carbon producers.
- Green investments to reduce emissions is a current trend of scientific research, but optimizing green investment under carbon regulations for the transportation procurement has not been addressed yet. Thus, developing optimization problems, like the WDP, to identify the optimal green investment for the stakeholders can be another active stream of research.
- Our study implemented the well-known EOQ model as an inventory management policy for determining the quantity to be shipped s to the warehouse and time Ts to elapse between every two shipments. Further investigation can employ more advanced approaches, such as lot sizing models, that can be embedded within our WDP formulations.
- Further, the stochastic nature of some parameters characterizing the problem can be considered and incorporated within the WDP model.

Declarations

Appendix A

See Table 8.

Table 8 Summary of the relevant literature

Articles	Data type		Sustainability concern	Early shipment	Discount	Modeling		Solution method		Important specification
	D	S				IP/MILP	NLP	Exact	Heuristic/Approx.	
Yang and Huang, (2021)	✓				✓	✓	✓	✓		Distance and volume-based discount
Triki, (2021)	✓		✓		✓	✓		✓	✓	CA with crowd shipping, Environmental advantages
Qian et al., (2020)		✓				✓			✓	Proactive hybrid mitigation strategy
Triki et al., (2020)	✓					✓		✓	✓	Integration of production scheduling
Remli et al., (2019)		✓				✓		✓		Uncertain volume and capacity
Buer and Pankratz, (2010)	✓						✓		✓	Service quality
Zhang et al., (2015)		✓				✓			✓	Uncertain volume
Jothi Basu et al., (2015a)	✓		✓			✓			✓	Emission reduction
Zhang et al., (2014)		✓				✓			✓	Penalty cost
Rekik and Mellouli, (2012)	✓					✓		✓		Carriers reputation
Othmane et al., (2014)	✓					✓		✓		Valuations of the carrier's reputation
Qian et al., (2021b)	✓		✓		✓	✓			✓	Disruption risk
Yin et al., (2021)		✓			✓	Analytical				Quantity discount
Garrido, (2007)	✓			✓	✓	Analytical		✓		Create early shipment demand
This study	✓		✓	✓	✓	✓	✓	✓		Carbon regulation, Green reputation, Discount on early shipments

D: Determi., S: Stochast.

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