International Journal of Industrial Engineering Computations 14 (2023) 571–588

Contents lists available at GrowingScience

International Journal of Industrial Engineering Computations

homepage: www.GrowingScience.com/ijiec

An efficient multi-attribute multi-item auction mechanism with ex-ante and ex-post satisfaction for 4PL transportation service procurement

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CHRONICLE

Article history:
Received October 10 2022
Accepted March 10 2023
Available online
March, 10 2023

Keywords:
Transportation service procurement
Efficient multi-attribute reverse auction
Ex-ante and ex-post satisfaction
Mechanism design

ABSTRACT

Reverse auction is an effective tool for a 4PL to purchase transportation services. This paper investigated a new transportation services procurement problem for 4PL, which involves three features: the 4PL's loss-averse behavior, price and non-price attributes, and multiple transportation requests. An efficient multi-attribute multi-item reverse auction mechanism considering the 4PL ex-ante and ex-post satisfaction (EES-MMRA) is proposed to purchase transportation services for the 4PL. In the EES-MMRA, integrating the allocation rule with the 4PL ex-ante satisfaction, a 0-1 programming model is constructed to determine winning 3PLs and obtain efficient allocations. Then, a payment rule considering the 4PL ex-post satisfaction is established to ensure truthful bidding of 3PLs. And we discuss some desirable properties (e.g., incentive compatibility, individual rationality, efficiency, and budget balance properties) to justify the EES-MMRA mechanism, subsequently. Next, several numerical experiments are conducted to demonstrate the effectiveness and applicability of the EES-MMRA mechanism. Furthermore, sensitivity analysis presents the influences of the weights of the non-price attributes, risk attitude coefficients, and loss aversion coefficients. Finally, we conduct comparison analysis to show the advantages of the EES-MMRA mechanism over the known Vickrey–Clark–Groves (P-VCG) mechanism.

1. Introduction

Although the third-party logistics (3PL) providers have rapidly developed since the 1980s (Berglund et al., 1999; Selviaridis and Spring, 2007), enterprises shall pay more attention to the integration of logistics and supply chain activities with the increasing of the market competition, and a single 3PL cannot meet the logistics demands of enterprises (Wang et al., 2022; Quttineh and Lidestam, 2020). Under this context, the fourth party logistics (4PL) emerged, which is defined as a supply chain integrator that provides and operates comprehensive supply chain solutions by integrating the different resources, capabilities, and technologies (Singh et al., 2010; Dong et al., 2022). The 4PL can effectively bring together customers' demands and 3PLs' available resources so as to improve the operational efficiency of the corresponding supply chain network.

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ISSN 1923-2934 (Online) - ISSN 1923-2926 (Print)
2023 Growing Science Ltd.
doi: 10.5267/j.ijiec.2023.3.001

Since the 4PL does not have its own vehicles generally, transportation service management becomes the core business of a 4PL (Mehmann and Teuteberg, 2016). Specifically, the 4PL can effectively collect the information of customers' transportation demands and 3PLs' available transportation service resources. To fill the demands of customers with different preferences, the 4PL shall match transportation requests generated by customers' demands with 3PLs' available transportation services capacities, i.e., to allocate transportation requests to 3PLs for implementation. The transportation service procurement process for the 4PL is shown in Fig. 1.

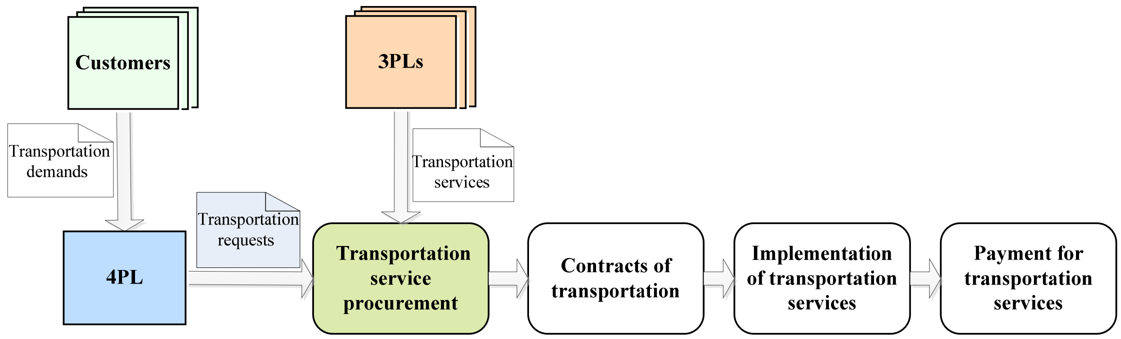

Fig. 1. The overall 4PL transportation service procurement process

In recent days, reverse auction has become an effective method for the 4PL to purchase transportation services (Qian et al., 2021; Huang et al., 2016). It is estimated that the use of reverse auctions is growing by 10-15% annually (Beall and Monczka, 2003). A survey reported that buyers can save 15% of the procurement cost and up to 90% of the procurement time via reverse auction (Talluri et al., 2007). In the meanwhile, because of potential risks and damages during the transportation process, the 4PL concerns about the price and non-price attributes of 3PLs' transportation services, such as transportation cost, transportation time, transportation quality, etc. In this circumstance, multi-attribute reverse auction (MARA) becomes the 4PL's best option (Sadaoui and Kumar, 2016), which allows the 4PL to purchase transportation services from 3PLs more quickly and conveniently. Although many articles have conducted related research (Xu et al., 2015; Karakaya and Köksalan, 2016; Huang et al., 2018; Qian et al., 2020; Yu et al., 2022), there are still some limitations listed below.

(i) Compared with a multi-attribute single-item auction, multi-attribute multi-item auction is more complex and seldom investigated. Two exceptions are Xu et al. (2015) and Karakaya and Köksalan (2016), where the former only considered the price attribute, and the latter studied the bi-attribute scenario in multi-item auctions. Since existing studies can hardly extend to more than two attributes, the 4PL cannot solve the transportation service procurement problem that involves multiple lanes and heterogeneous attribute preferences by existing methods directly. Hence, designing an efficient multi-attribute multi-item auction mechanism for the 4PL is very important.

(ii) Most existing studies assume that the 4PL is perfectly rational during the transportation service procurement process. However, many empirical studies showed that the 4PL can be loss averse due to the uncertain logistics market, and the decision results could always deviate from those assuming perfect rationality. In this case, to design a practical transportation procurement auction mechanism, considering the 4PL's loss aversion behavior is imperative.

(iii) Few studies simultaneously consider the 4PL's ex-ante and ex-post satisfaction level in transportation service procurement auctions. Specifically, the ex-ante satisfaction level describes the difference between the 4PL's expectations and the bids submitted by potential 3PLs at the bidding phase of auctions. The ex-post satisfaction level measures whether the winning 3PL's real transportation service quality can reach the commitment of that 3PL's bids after completing the transportation services. In real applications, to ensure the operational efficiency of the entire supply chain, the 4PL has to establish long-term partnerships with 3PLs at a high satisfaction level. In this situation, a mechanism that integrates the 4PL's ex-ante and ex-post satisfaction levels shall be constructed to improve the long-term preference of MARA.

To narrow down the research gaps mentioned above, an efficient multi-attribute multi-item reverse auction with ex-ante and ex-post satisfaction (EES-MMRA) is proposed for the 4PL to purchase transportation services. The main contributions of our research are listed below.

(i) To fulfill transportation service procurement effectively, an efficient EES-MMRA mechanism is proposed for the 4PL. In the EES-MMRA, the price and the non-price attributes which are important for transportation service performance are considered. And a 0-1 programming model is developed to efficiently allocate transportation requests in the 4PL multi-lane transportation service procurement.

(ii) A new reverse auction mechanism is particularly developed for the loss averse 4PL, in which the winner determination and request allocation rule involves the 4PL's ex-ante satisfaction level and the payment rule considers the 4PL's ex-post satisfaction level. It is worth noting that the proposed mechanism will encourage 3PLs to bid truthfully, since otherwise 3PLs will be penalized based on the 4PL's ex-post satisfaction level.

(iii) A case study is developed to demonstrate the effectiveness of the EES-MMRA mechanism. Sensitivity analysis reveals the impact of different parameters on the result of EES-MMRA, and the advantage of EES-MMRA mechanism is demonstrated by comparing it with some known mechanisms.

The research is arranged as follows. Section 2 presents a literature review. Section 3 introduces the problem description and the process of EES-MMRA. The EES-MMRA mechanism is described specifically in Section 4. The numerical experiments and the related analysis are presented in Section 5. Section 6 summarizes the conclusions of this paper and some future extensions.

2. Literature Review

This study investigates the design problem of multi-attribute multi-item reverse auction mechanisms for the 4PL transportation service procurement. The existing studies related to this research are briefly reviewed, including multi-attribute auctions and transportation service procurement auctions.

(1) Multi-attribute auctions

The research on multi-attribute auctions mainly focuses on two aspects, namely optimal multi-attribute auctions and efficient multi-attribute auctions.
In terms of optimal multi-attribute auctions, Che (1993) designed three multi-attribute auction mechanisms considering price and quality attributes. Branco (1997) investigated the design of multi-attribute procurement auctions considering the correlation on the sellers' cost. Asker and Cantillon (2008) introduced multidimensional non-price attributes into the procurement auctions and proved that the buyer's ex-ante utility is equivalent when the sellers are symmetrical, and the scoring rule is quasi-linear. Kostamis et al. (2009) studied total-cost procurement auctions considering the price attribute and the fixed cost adjustment attribute and analyzed two auction formats comparatively: sealed-bid auction and open-bid auction. Qian et al. (2018) designed an incentive-based MMRA mechanism, which considered the loss-averse behavior of 3PLs, cost uncertainty and delivery risk. Qian et al. (2021) proposed a PTC-BOCK decision-making framework considering 4PL risk attitude to solve the green winner determination problem in MMRA.

In terms of efficient multi-attribute auctions, Parkes and Kalagnanam (2005) designed two efficient interactive multi-attribute auction mechanisms for single-item single-unit procurement, namely auction NLD and auction AD. Cheng et al. (2016) developed truthful multi-attribute double mechanisms which are used to purchase multi-unit and single-unit goods in perishable supply chain trading. Huang et al. (2018) proposed efficient multi-attribute procurement auction mechanisms that considered buyer satisfaction risks, and the ex-post satisfaction of the buyer was affected by the promised quality and effort of suppliers. Xiao et al. (2021) developed efficient single-unit/multi-unit multi-attribute auctions for crowdsourced delivery systems.

Most of the previous studies on efficient multi-attribute auctions focus on single-item multi-unit auctions or single-item single-unit auctions, and rarely consider buyer psychological behavior. Therefore, we study an efficient multi-attribute multi-item simultaneous auction mechanism considering 4PL's loss aversion behavior. In addition, the 4PL ex-ante and ex-post satisfaction levels are introduced into the mechanism design, which are different from satisfaction risk in Huang et al. (2018).

(2) Transportation service procurement auctions

Auctions are the common and effective way to purchase transportation services. Therefore, more and more research has been conducted on transportation service procurement auctions.
In terms of multi-unit auctions, Huang and Xu (2013) proposed trade reduction combined double auction mechanisms for multi-unit transportation procurement. Hu et al. (2016) introduced transit time into a multi-unit transportation service procurement auction and developed a bi-objective model to minimize the total cost and transit time together. Xu and Huang (2017) studied multi-unit transportation service procurement auctions considering multiple attributes, and developed two efficient auction mechanisms, namely, one-sided Vickrey-Clarke-Groves auction and primal-dual Vickrey auction. Zhang et al. (2019) designed an optimal and efficient multi-unit transportation procurement auction mechanism and considered the influence of non-price attributes on cost in the process of winner determination and orders allocation. Liang et al. (2020) studied double auctions considering quantity discounts for multi-unit logistics services transactions and introduced quantity discounts into Vickrey–Clark–Groves and trade reduction mechanism. Yu et al. (2022) proposed a family of efficient multi-attribute multi-unit double auction mechanisms, where multi-attribute bidding was introduced into the McAfee mechanism or the trade reduction mechanisms.

In terms of multi-item auctions, Xu and Huang (2014) designed efficient combinatorial auction mechanisms to match the demands and supplies for a transportation network. Xu et al. (2015) considered transaction cost into multi-item intermodal transportation auctions, and by minimizing the total supply chain logistics cost including transaction cost to achieve efficient allocation of transportation requests. Kuyzu et al. (2015) developed a stochastic bid price optimization model for multi-lane simultaneous transportation service procurement, in which the synergies among lanes and carriers' bid patterns were considered. Olcaytu and Kuyzu (2020) developed an efficient heuristic to determine the carriers' bids in simultaneous transportation procurement auctions for multiple independent lanes.

In the literature of transportation service procurement auctions, there are few studies about multi-item auctions. And the research on multi-item transportation procurement auctions mainly focuses on the combinatorial auction mechanism. However, when multiple transportation requests are independent of each other, the combinatorial auction is not applicable and will increase the complexity of the auction process. Therefore, we study the multi-item simultaneous auction mechanism for 4PL transportation service procurement in the case of the limited capacity of carriers (i.e., 3PLs). In addition, most of the existing research on multi-item auctions only focuses on the price attribute, but the non-price attributes are also crucial for transportation service procurement. Therefore, we comprehensively consider the price and non-price attributes, and propose an efficient multi-attribute multi-item reverse auction mechanism.

3. Problem description and process of EES-MMRA

3.1. Problem description

A transportation service procurement auction market is particularly considered, including one 4PL and a set of potential 3PLs. The 4PL is the auctioneer that needs to procure transportation services for its customers. The potential 3PLs are bidders providing transportation services. The auctioned goods are transportation requests generated from customers' demands. The transportation requests are the forms of origin-destination pair (i.e., lane) that have to be served by 3PLs' fleet of trucks (see Fig. 2). The 4PL first issues the transportation requests via its logistics platform, and then 3PLs will submit bids to provide transportation services through a single-round sealed reverse auction. The key challenge for the 4PL is how to allocate transportation requests efficiently to 3PLs through reverse auctions and ensure that the winning 3PL can fulfill transportation service as promised (see Fig. 3).

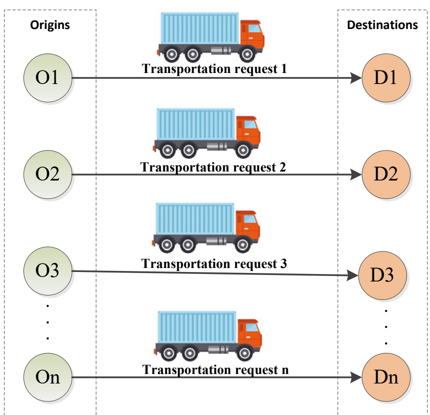

Fig.2. Transportation requests to be auctioned

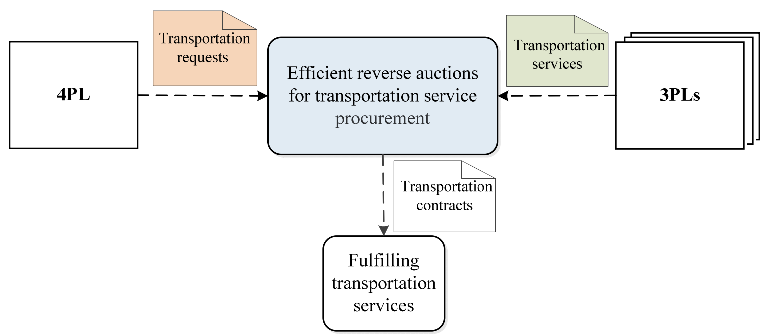

Fig. 3. The process of based-auction transportation service procurement

Following the literature (Kuyzu et al., 2015; Olcaytu and Kuyzu, 2020; Evren Olcaytu, 2018), the transportation requests are assumed to be independent of each other. Since the transportation capacity of each 3PL is constrained, the simultaneous auction will be adopted, where each 3PL is allowed to bid separately for each transportation request. In general, each 3PL can choose a set of transportation requests to submit their bids based on its capability in order to obtain transportation contracts, and each indivisible transportation request can be assigned to only one 3PL. Also, in addition to the transportation price, non-price attributes are very important for transportation service procurement. In this paper, three most important attributes are extracted, namely transportation cost, transportation time and transportation quality. Without loss of generality, the 4PL has a reference point for each attribute of each request. The logistics market is assumed to be sufficiently large, i.e., each transportation request can be allocated, and if any of the candidate 3PLs are withdrawn from the auction, all transportation requests are still able to be allocated. To ensure the service quality, the 4PL is assumed to have loss aversion behavior, and will be more sensitive to loss attributes compared to gain attributes.

Let R be the set of transportation requests. Each transportation request $r \in R$ is associated with one lane, which has transportation volume d_r, reference point of transportation cost c_r, maximum acceptable transportation cost c_r^H, reference point of transportation time (i.e., pickup and delivery time) t_r, maximum acceptable transportation time t_r^H, reference point of transportation quality (i.e., cargo damages rate) q_r, and minimum acceptable transportation quality (i.e., highest rate of cargo damages) q_r^H. The information of each transportation request is available for each 3PL. Let I be the set of potential 3PLs, where 3PL $i \in I$ has the upper limit of transportation capacity l_i. For each 3PL i $(i \in I)$ and transportation request

r $(r \in R)$, $\hat{c}_{ir}$, $\hat{t}_{ir}$, and $\hat{q}_{ir}$ are the real transportation cost, real transportation time, and real transportation quality respectively. $\hat{\mathbf{b}}_{\mathbf{ir}} = (\hat{c}_{ir}, \hat{t}_{ir}, \hat{q}_{ir})$ denotes the type of 3PL i for transportation request r, $i \in I$; $r \in R$. $\hat{\mathbf{b}}_{\mathbf{ir}}$ is the private information. For the sake of simplicity, we assume that the information of the parameters is independent and follows the same distributions.

Other notations used throughout this paper are listed below.

I_r : set of 3PLs bidding on transportation requests r $(r \in R)$, $I_r \subseteq I$

R_i : set of the bid transportation requests of 3PL i, $R_i \subseteq R$

A : set of attributes, $A = \{c, t, q\}$, where c, t, and q represent transportation cost, transportation time, and transportation quality

$\mathbf{w}$: weight vector of non-price attributes, $\mathbf{w} = (w_t, w_q)^T$

$\mathbf{b}_{\mathbf{ir}}$: bid of 3PL i on transportation request r, $\mathbf{b}_{\mathbf{ir}} = (c_{ir}, t_{ir}, q_{ir})$. $\mathbf{b}_{\mathbf{ir}}$ is empty, if 3PL i has not submitted a bid on transportation request r

$\mathbf{b}$: bid matrix formed by all 3PLs' bids on transportation requests, $\mathbf{b} = (\mathbf{b}_{\mathbf{ir}})_{i \in I, r \in R}$

The main problem of this paper is to design an efficient multi-attribute reverse auction mechanism for multi-item transportation service procurement considering the 4PL's psychological behavior. To ensure the efficiency of the auction mechanism, two main issues have to be addressed. (1) How to determine the winners and allocate the transportation requests based on 3PLs' bid matrix $\mathbf{b}$, attribute reference points and the 4PL psychological behavior. (2) How should the 4PL pay the winning 3PLs based on the bid information and real transportation performances of 3PLs.

3.2. The process of EES-MMRA mechanism

To solve the 4PL transportation service procurement problem, a novel EES-MMRA mechanism is designed. The proposed EES-MMRA mechanism mainly includes three main processes, i.e., preparation process, bidding and allocation process, and payment process, as shown in Fig. 4. The details are presented below.

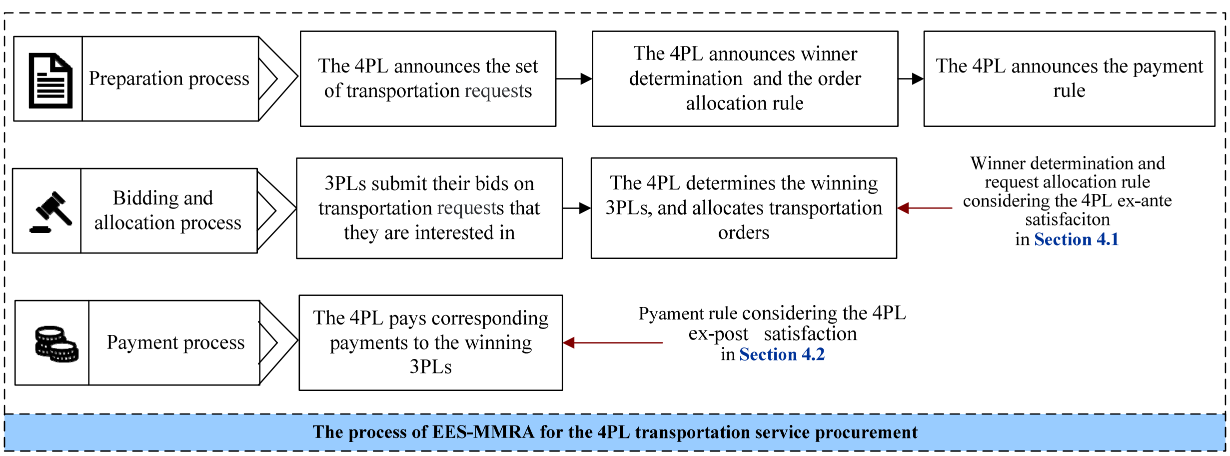

Fig. 4. The process of EES-MMRA mechanism for the 4PL transportation service procurement

(1) Preparation process. Firstly, the 4PL announces the set of transportation requests R to be auctioned on the logistics platform. Subsequently, the 4PL announces the winner determination and request allocation rule considering the 4PL ex-ante satisfaction. Simultaneously, the 4PL announces the payment rule which considers the 4PL ex-post satisfaction $\eta_{ir} : (\mathbf{b}_{\mathbf{ir}}, \hat{\mathbf{b}}_{\mathbf{ir}}) \to R$. Ex-post payment is adopted, i.e., when the transportation services are finished, the 4PL will pay the winning 3PLs based on their bids $\mathbf{b}_{\mathbf{ir}} = (c_{ir}, t_{ir}, q_{ir})$ $(i \in I,\ r \in R)$, and the ex-post 4PL's satisfaction level based on the real transportation service performance of the winning 3PLs $\hat{\mathbf{b}}_{\mathbf{ir}} = (\hat{c}_{ir}, \hat{t}_{ir}, \hat{q}_{ir})$ $(i \in I;\ r \in R)$.

(2) Bidding and allocation process. All 3PLs submit their bids $\mathbf{b_{ir}} = (c_{ir}, t_{ir}, q_{ir})$ on transportation requests that they are interested in, $i \in I,\ r \in R$. Furthermore, 3PL i also needs to submit its total transportation capacity l_i. And then, the 4PL determines the winning 3PL for each transportation request r, and allocates the transportation requests to the corresponding winners.

(3) Payment process. When the winning 3PLs finish the transportation services, the 4PL will pay the winning 3PLs according to the payment rule, their bids, and their real transportation performances.

4. The EES-MMRA Mechanism

4.1. Winner determination and request allocation rule

In this section, we propose winner determination and request allocation rule considering the 4PL ex-ante satisfaction. First, we define the 4PL ex-ante satisfaction. Then, we define the revised cost. Finally, a 0-1 programming model that minimizes the total cost is proposed to determine winners and allocate transportation requests.

4.1.1. The 4PL ex-ante satisfaction

Since the 4PL is loss averse, its psychological behavior will definitely affect the transportation service procurement decision. In this case, the 4PL ex-ante satisfaction shall be considered in the process of winner determination and request allocation. The 4PL ex-ante satisfaction can be determined by the 4PL loss aversion behavior, reference points and the bids of 3PLs. Prospect theory (PT) is often used to describe people's psychological behavior, and verifies that people are more sensitive to losses than to gains relative to the reference point (Kahneman and Tversky, 1979). According to PT, the value function can be employed to describe the 4PL ex-ante satisfaction level. In addition, the bid attributes all belong to the cost type, thus If the bids of 3PLs are lower than the reference points, the value function of the 4PL ex-ante satisfaction is concave for gains, otherwise, it is convex for losses. The definition of the 4PL ex-ante satisfaction is defined as follows.

Definition 1. Let $v(a_{ir})\ (i \in I, r \in R)$ be the 4PL ex-ante satisfaction for attribute $a \in A$ of 3PL i's bid on transportation request r, which measures the difference between the bid of the 3PL i on attribute $a \in A$ and the reference point of attribute for transportation request r. The value function $v(a_{ir})$ is given below.

$$v(a_{ir}) = \begin{cases} (a_r - a_{ir})^{\alpha} & a_r \geq a_{ir},\ a \in A,\ i \in I,\ r \in R \\ -\theta(a_{ir} - a_r)^{\beta} & a_r < a_{ir},\ a \in A,\ i \in I,\ r \in R \end{cases} \tag{1}$$

where $0 < \alpha < 1$, $0 < \beta < 1$, and $\theta > 1$ denote the loss averse behavior.

It is worth noting that in just-in-time production, customers hope that goods can arrive on time at the right time. Both the advance and delay will affect the 4PL satisfaction. Therefore, in just-in-time production, the 4PL ex-ante satisfaction of attribute t can be calculated by the following formula.

$$v(t_{ir}) = \begin{cases} (t_r - t_{ir})^{\alpha} & t_r = t_{ir},\ i \in I,\ r \in R \\ -\theta\left|t_r - t_{ir}\right|^{\beta} & t_r \neq t_{ir},\ i \in I,\ r \in R \end{cases} \tag{2}$$

4.1.2. The revised cost

In this subsection, we define the revised cost considering the influence of non-price attributes. Since potential risks and damages can exist during transportation, the 4PL will pay attention to both price and non-price attributes. Following the literature (Zhang et al., 2019), we map two non-price attributes (i.e., attribute t and attribute q) to the cost in this paper.

Let μ_{ir}^{t} and μ_{ir}^{q} are the costs incurred by attribute t and attribute q of the bid submitted by 3PL i.

$$\mu_{ir}^{t} = -\kappa^{t} \times v(t_{ir}) \quad i \in I \text{ and } r \in R \tag{3}$$

$$\mu_{ir}^{q} = -\kappa^{q} \times v(q_{ir}) \quad i \in I \text{ and } r \in R \tag{4}$$

where $\kappa^{t} > 0$, $\kappa^{q} > 0$ are the transformation parameters related to the unit cost of the 4PL ex-ante satisfaction on attribute t and attribute q of the bid submitted by 3PL i. If $v(t_{ir}) \geq 0$, then $\mu_{ir}^{t} \leq 0$ representing the profit. If $v(t_{ir}) < 0$, then $\mu_{ir}^{t} > 0$ representing the cost. μ_{ir}^{q} follows the same way.

Let $\mu(t_{ir}, q_{ir})$ be the non-price attribute cost considering the 4PL ex-ante satisfaction, which is defined by

$$\mu(t_{ir}, q_{ir}) = w_t \times \mu_{ir}^t + w_q \times \mu_{ir}^q \quad i \in I \text{ and } r \in R \tag{5}$$

where w_t, w_q are the weights of attribute t and attribute q respectively, which represent the preferences of the two non-price attributes, and $w_t + w_q = 1$.

Let $\tilde{c}_{ir}$ $(i \in I, r \in R)$ be the revised cost which is associated with the bid cost $c_{ir}(i \in I, r \in R)$ and the non-price attribute cost $\mu(t_{ir}, q_{ir})(i \in I, r \in R)$. The formula for calculating the revised cost is presented below.

$$\tilde{c}_{ir} = c_{ir} + \mu(t_{ir}, q_{ir}) \quad i \in I \text{ and } r \in R \tag{6}$$

4.1.3. The model for winner determination and request allocation

In this subsection, a 0-1 programming model is developed to provide decision support for 4PL so as to determine the winning 3PLs and allocate the transportation requests in transportation service procurement auctions.

Let x_{ir} $(i \in I, r \in R)$ be a 0-1 variable denoting the allocation of transportation request r, If $x_{ir} = 1$, then the transportation request r is allocated to 3PL i.

In 4PL transportation service procurement auction, the 0-1 programming model denoted by P1 is presented below to obtain the efficient allocation.

$$\min \sum_{i \in I} \sum_{r \in R} \tilde{c}_{ir} x_{ir} \tag{7}$$

s.t.

$$\sum_{r \in R} d_r x_{ir} \le l_i \quad i \in I \tag{8}$$

$$0 \le c_{ir} x_{ir} \le c_r^H \quad i \in I;\ r \in R \tag{9}$$

$$0 \le t_{ir} x_{ir} \le t_r^H \quad i \in I;\ r \in R \tag{10}$$

$$0 \le q_{ir} x_{ir} \le q_r^{\mathrm{H}} \quad i \in I;\ r \in R \tag{11}$$

$$x_{ir} = 0 \quad i \in I;\ r \in R \setminus R_i \tag{12}$$

$$\sum_{i \in I} x_{ir} = 1 \quad r \in R \tag{13}$$

$$x_{ir} \in \{0,1\} \quad i \in I;\ r \in R \tag{14}$$

where the objective of P1 is to minimize the total cost. Constraint (8) ensures that the total demand for transportation requests assigned to 3PL i is not greater than the upper limit of 3PL i's total transportation capacity. Constraints (9)-(11) guarantee that the attribute value of winning 3PL i's bid on transportation request r is not greater than the maximum acceptable attribute value. Constraint (12) means that the 4PL will not allocate the transportation request r to 3PL i if the bid does not exist. Constraints (13) and (14) ensure that a transportation request can only be assigned to one 3PL.

4.2. Payment rule

In this section, the payment rule considering the 4PL ex-post satisfaction is proposed. First, we define the 4PL ex-post satisfaction, and the penalty function based on the 4PL ex-post satisfaction. Then, the payment functions for different cases considering the 4PL ex-post satisfaction are proposed.

4.2.1. The penalty based on the 4PL ex-post satisfaction

The 4PL is the supply chain integrator, and can observe the real transportation service performance of each 3PL after the 3PLs complete the transportation service, including the real values of attribute c, attribute t, and attribute q of each 3PL. The deviation between the ex-post real transportation performance of 3PLs and the bids of 3PLs will result in the different satisfaction of the 4PL. PT is used to describe ex-post psychological behavior of the 4PL. If the transportation service performances of 3PLs are better than their bids, the value function of ex-post 4PL satisfaction is normally concave for gains, and otherwise convex for losses. The definition of the 4PL ex-post satisfaction is given.

Definition 2. Let $v(\hat{a}_{ir})$ $(i \in I, r \in R)$ be the 4PL ex-post satisfaction of real value of attribute $a \in A$ on the transportation request r undertaken by 3PL i, which results from the difference between the bid of the 3PL i on attribute $a \in A$ and the real attribute value of transportation request r. $v(\hat{a}_{ir})$ is determined by

$$v(\hat{a}_{ir})=\begin{cases}(a_{ir}-\hat{a}_{ir})^{\alpha} & \hat{a}_{ir}\le a_{ir},\ a\in A,\ i\in I,\ r\in R\\ -\theta(\hat{a}_{ir}-a_{ir})^{\beta} & \hat{a}_{ir}>a_{ir},\ a\in A,\ i\in I,\ r\in R\end{cases} \tag{15}$$

where $0<\alpha<1$, $0<\beta<1$, and $\theta>1$ denote that the 4PL is loss-averse.

And in just-in-time production, the 4PL ex-post satisfaction of attribute t can be calculated by

$$v(\hat{t}_{ir})=\begin{cases}(\hat{t}_{ir}-t_{ir})^{\alpha} & t_{r}=t_{ir},\ i\in I,\ r\in R\\ -\theta\left|\hat{t}_{ir}-t_{ir}\right|^{\beta} & t_{r}\ne t_{ir},\ i\in I,\ r\in R\end{cases} \tag{16}$$

If the ex-post real performances of the transportation attributes are worse than the values of 3PLs' bids, 3PLs will be penalized based on the 4PL ex-post satisfaction. The penalty function $p(\hat{a}_{ir})$ is defined by

$$p(\hat{a}_{ir})=-\lambda^{a}\times v(\hat{a}_{ir}) \qquad a\in A,\ i\in I,\ r\in R \tag{17}$$

where λ^{a} is the unit penalty incurred by the 4PL ex-post satisfaction on attribute a and may vary with transportation requests. When the real performance of 3PL i on the transportation request r is worse than its bid, according to Eqs. (15)-(17), we have $v(\hat{a}_{ir})<0$ and $p(\hat{a}_{ir})>0$, representing the plenty of 3PL i.

4.2.2. Payment rule considering the 4PL ex-post satisfaction

In this subsection, we consider four cases to define the payment function, the details are shown below.

Case 1. $a_{ir}\ge\hat{a}_{ir}$ $\forall a\in A$ and $r\in R$. In this case, the real performance of 3PL i on transportation request r is not worse than its bid in the auction. Then we have

$$\eta_{ir}(\mathbf{b_{ir}},\hat{\mathbf{b}}_{\mathbf{ir}})=\hat{c}_{ir}+C(I_0\mid I_{r-i},\mathbf{b_{\text{-}ir}})-C(I_0\mid I,\mathbf{b}) \tag{18}$$

where $\hat{c}_{ir}$ is the real transportation cost of 3PL i on transportation request r, $C(I_0\mid I_{r-i},\mathbf{b_{\text{-}ir}})-C(I_0\mid I,\mathbf{b})$ is the expected cost saved due to 3PL i's participation in bidding for transportation request r, i.e., the contribution of 3PL i. And $C(\cdot)$ can be calculated by model P1, which is the objective value of model P1. The payment rule is similar to the VCG auction which consists of the contribution and cost, but the cost in our proposed payment rule is the real cost rather than the bid cost.

Case 2. $a_{ir}<\hat{a}_{ir}\le a_{ir}^{H}$ and $e_{ir}\ge\hat{e}_{ir}$ $\forall a\in A'$, $\forall e\in A-A'$, $r\in R$. In this case, some real attribute values of 3PL i on transportation request r are worse than its bid values, but not greater than the maximum acceptable attribute values. Then we define

$$\eta_{ir}(\mathbf{b_{ir}},\hat{\mathbf{b}}_{\mathbf{ir}})=\hat{c}_{ir}-\sum_{a\in A'}p(\hat{a}_{ir}) \tag{19}$$

where $A'=\{a\mid a_{ir}<\hat{a}_{ir}\le a_{ir}^{H},a\in A\}$ is the set of attributes, whose real values are worse than the bid values, but not greater than the maximum acceptable attribute values. $\sum_{a\in A'}p(\hat{a}_{ir})$ is the total penalty that 3PL i gets on transportation request r to prevent 3PL i from untruthful bidding, the payment to 3PLs in this case equals to its real cost minus the penalty based on the 4PL ex-post satisfaction.

Case 3. $\hat{a}_{ir}>a_{ir}^{H}$ $\exists a\in A$, $r\in R$. In this case, some real attribute values of 3PL i on transportation request r are greater than the maximum acceptable attribute values. Then,

$$\eta_{ir}(\mathbf{b_{ir}},\hat{\mathbf{b}}_{\mathbf{ir}})=-\sum_{a\in A''}p(\hat{a}_{ir}) \tag{20}$$

where $A''=\{a\mid\hat{a}_{ir}>a_{ir}^{H},a\in A\}$ is the set of attributes, the real values of which are greater than the maximum acceptable attribute values. $\sum_{a\in A''}p(\hat{a}_{ir})$ is the total penalty which 3PL i gets on transportation request r. In this case, the payment that 3PLs get is only the penalty based on the 4PL ex-post satisfaction.

Case 4. The transportation request is not completed. Then,

$$\eta_{ir}(\mathbf{b}_{\mathrm{ir}},\hat{\mathbf{b}}_{\mathbf{ir}}) = -P \tag{21}$$

where P is a fixed penalty. In this case, since the winning 3PL i can't complete the transportation request r, the 4PL suffers losses and will pose a fixed penalty for winning 3PLs. To avoid this situation, P is assumed to be sufficiently large.

4.3. The discussion on the properties of EES-MMRA

In this section, the properties of the EES-MMRA mechanism are discussed, which is presented in Properties 1-4, respectively.

Property 1. The EES-MMRA mechanism meets incentive compatibility (IC), i.e., truthful bidding is a dominant strategy.

Proof. Suppose that all the 3PLs bid truthfully for the transportation requests during the bidding process, except for 3PL i's bid on transport request r, i.e., $\mathbf{b}_{\text{-ir}} = \hat{\mathbf{b}}_{\text{-ir}}$. We suppose the bid of 3PL i on transportation request r $\mathbf{b}_{\mathbf{ir}} = (a_{ir} \mid a \in A) = (c_{ir}, t_{ir}, q_{ir})$. Now we consider four cases to prove the property.

Case 1. $a_{ir} \geq \hat{a}_{ir}$ $\forall a \in A$ and $r \in R$, i.e., the real performance of 3PL i on transportation request r is not worse than its bid.

In the auction process, the objective of winner determination and the request allocation is to minimize the total cost. If $a_{ir} \geq \hat{a}_{ir}$ $\forall a \in A$, 3PL i may not be the winner on transportation request r. Even though 3PL i wins transportation request r, the utility of 3PL i on transportation request r $U_{ir}(\mathbf{b}_{\mathbf{ir}},\hat{\mathbf{b}}_{\mathbf{ir}})$ is as follows:

$$U_{ir}(\mathbf{b}_{\mathbf{ir}},\hat{\mathbf{b}}_{\mathbf{ir}}) = \eta_{ir}(\mathbf{b}_{\mathbf{ir}},\hat{\mathbf{b}}_{\mathbf{ir}}) - \hat{c}_{ir} = C(I_0 \mid I_{r-i}, \mathbf{b}_{\text{-ir}}) - C(I_0 \mid I, \mathbf{b}) \tag{22}$$

Let $U_{ir}(\hat{\mathbf{b}}_{\mathbf{ir}},\hat{\mathbf{b}}_{\mathbf{ir}})$ be the utility of 3PL i on transportation request r when it bids truthfully. The function $U_{ir}(\hat{\mathbf{b}}_{\mathbf{ir}},\hat{\mathbf{b}}_{\mathbf{ir}})$ is defined as follows:

$$U_{ir}(\hat{\mathbf{b}}_{\mathbf{ir}},\hat{\mathbf{b}}_{\mathbf{ir}}) = \eta_{ir}(\hat{\mathbf{b}}_{\mathbf{ir}},\hat{\mathbf{b}}_{\mathbf{ir}}) - \hat{c}_{ir} = C(I_0 \mid I_{r-i}, \mathbf{b}_{\text{-ir}}) - C(I_0 \mid I, \hat{\mathbf{b}}) \tag{23}$$

Where $\hat{\mathbf{b}}$ is the bid matrix when all the 3PLs including 3PL i all bid truthfully.

Because $a_{ir} > \hat{a}_{ir}$ $\forall a \in A$, according to P1, we can know that $C(I_0 \mid I, \mathbf{b}) > C(I_0 \mid I, \hat{\mathbf{b}})$. From the above we know that $U_{ir}(\mathbf{b}_{\mathbf{ir}},\hat{\mathbf{b}}_{\mathbf{ir}}) < U_{ir}(\hat{\mathbf{b}}_{\mathbf{ir}},\hat{\mathbf{b}}_{\mathbf{ir}})$. From the above arguments, we know that in this case $\mathbf{b}_{\mathbf{ir}} = \hat{\mathbf{b}}_{\mathbf{ir}}$ is the dominant strategy.

Case 2. $a_{ir} < \hat{a}_{ir} \leq a_{ir}^{H}$ and $e_{ir} \geq \hat{e}_{ir}$ $\forall a \in A'$, $\forall e \in A - A'$, $r \in R$, i.e., some real attribute values of 3PL i on transportation request r are worse than its bid values, but is not greater than the maximum acceptable attribute values.

In this case, the utility of 3PL i on transportation request r $U_{ir}(\mathbf{b}_{\mathbf{ir}},\hat{\mathbf{b}}_{\mathbf{ir}}) = \eta_{ir}(\mathbf{b}_{\mathbf{ir}},\hat{\mathbf{b}}_{\mathbf{ir}}) - \hat{c}_{ir} = -\sum_{a \in A'} p(\hat{a}_{ir}) < 0$.

Therefore, if 3PL i does not bid truthfully, and is the winner on transportation request r, the utility $U_{ir}(\mathbf{b}_{\mathbf{ir}},\hat{\mathbf{b}}_{\mathbf{ir}})$ is negative, i.e., 3PL i cannot get benefit from transportation request r, still can bring loss to oneself. From the above arguments, we know that in this case $\mathbf{b}_{\mathbf{ir}} = \hat{\mathbf{b}}_{\mathbf{ir}}$ is the dominant strategy.

Case 3. $\hat{a}_{ir} > a_{ir}^{H}$ $\exists a \in A$, $r \in R$, i.e., some real attribute values of 3PL i on transportation request r are greater than the maximum acceptable attribute values.

In this case, the utility of 3PL i on transportation request r $U_{ir}(\mathbf{b}_{\mathbf{ir}},\hat{\mathbf{b}}_{\mathbf{ir}}) = \eta_{ir}(\mathbf{b}_{\mathbf{ir}},\hat{\mathbf{b}}_{\mathbf{ir}}) - \hat{c}_{ij} = -\sum_{a \in A''} p(\hat{a}_{ir}) - \hat{c}_{ir} < 0$.

Therefore, if 3PL i does not bid truthfully, and is the winner on transportation request r, the utility $U_{ir}(\mathbf{b}_{\mathbf{ir}},\hat{\mathbf{b}}_{\mathbf{ir}})$ is also negative. From the above arguments, we know that in this case $\mathbf{b}_{\mathbf{ir}} = \hat{\mathbf{b}}_{\mathbf{ir}}$ is the dominant strategy.

Case 4. 3PL i lies about transportation capacity.

In this case, even if 3PL i gets transportation request r, if it fails to complete the transportation request r, 3PL i will receive a large penalty P, i.e., $U_{ir}(\mathbf{b_{ir}}, \hat{\mathbf{b}}_{\mathbf{ir}}) = -P < 0$ so it will not lie about the transportation capacity.

To sum up, truthful bidding is a dominant strategy for 3PLs, so the EES-MMRA mechanism meets IC.

Property 2. The EES-MMRA mechanism meets individual rationality (IR), i.e., all the players have non-negative utility.

Proof. From **Property 1,** we know that the EES-MMRA mechanism meets IC. When all the 3PLs bid truthfully, the payment to each winner $\eta_{ir}(\mathbf{b_{ir}}, \hat{\mathbf{b}}_{\mathbf{ir}}) = \hat{c}_{ir} + C(I_0 \mid I_{r-i}, \mathbf{b_{-ir}}) - C(I_0 \mid I, \mathbf{b})$, thus the utility of each winner $U_{ir}(\mathbf{b_{ir}}, \hat{\mathbf{b}}_{\mathbf{ir}}) = \eta_{ir}(\mathbf{b_{ir}}, \hat{\mathbf{b}}_{\mathbf{ir}}) - \hat{c}_{ir} = C(I_0 \mid I_{r-i}, \mathbf{b_{-ir}}) - C(I_0 \mid I, \mathbf{b}) \geq 0$. And the non-winning 3PLs do not undertake the transportation task, so they do not get benefits and not generate costs, thus their utility values are also non-negative. In addition, according to the model P1, the 4PL will purchase transportation services from 3PLs on the premise that all attributes are not larger than the maximum acceptable values. As such, we know that the EES-MMRA mechanism meets IR.

Property 3. The EES-MMRA mechanism meets allocation efficiency (AE).

Proof. In EES-MMRA mechanism, we consider the influence of non-price attributes on cost, therefore, when defining the allocative efficiency of auction, the cost should integrate the non-price attribute costs (Zhang et al., 2019). And the objective of allocation model P1 in our proposed mechanism is to minimize the total cost of integrating non-price attribute costs based on 4PL satisfaction. As such, the EES-MMRA mechanism meets AE.

Property 4. The EES-MMRA mechanism meets budget balance (BB).

Proof. From **Property 1,** In the process of EES-MMRA, the participants include a 4PL which is the auctioneer and a set of 3PLs, and there is not the third-party. After the winning 3PLs perform the transportation services, the 4PL will pay payments to the winners according to the payment rule and their real transportation performances. If the real transportation performances are not worse than their bids, the 4PL will pay the payments (including the winners' contributions and real costs) to the winners, otherwise, the winners may get some penalty, which will be paid to the 4PL. And the utility of the 4PL is nonnegative in the auction, otherwise, the trade will fail. From the above arguments, the EES-MMRA mechanism meets BB.

5. Numerical analysis

In this section, we design a numerical example for the 4PL transportation service procurement auction. Also, we conduct the sensitivity analysis and comparison analysis to illustrate the effectiveness of the proposed auction mechanism.

5.1. Numerical example

Suppose there are five transportation requests ($R = \{r_1, r_2, ..., r_5\}$) generated from customers' demands, and these transportation requests are all from JIT systems. The 4PL wants to allocate these transportation requests to the appropriate 3PLs through the EES-MMRA. First, the 4PL announce these transportation requests in its logistics system. Then, ten 3PLs ($I = \{i_1, i_2, ..., i_{10}\}$) submit their bids on transportation requests which they are interested, and their total transportation capacities, as shown in Table 1. In addition, the reference point and maximum acceptable value of each attribute for each transportation request are provided in Table 1.

Table 1
3PLs' bids on transportation requests and the corresponding information of transportation requests

R/I	r_1			r_2			r_3			r_4			r_5			Transportation capacity
A	c	t	q	c	t	q	c	t	q	c	t	q	c	t	q	
i_1	2	3	6	2	4	4							4	4	7	30
i_2				1.9	4	7	3	5	4	4.2	4.5	5				30
i_3	2	3	5	1.8	4	8				4	5	5	4.5	3.8	7	40
i_4	2.1	3.5	5				3	4.5	8							50
i_5				2	3.5	6				4	5	5				50
i_6	2	3	5				3.4	5	8	4	5	5	4	3.5	8	40
i_7	2.1	2.8	5				3	5	7							30
i_8				2.2	4	5				3.8	5	5	4	4.5	6	20
i_9	1.9	3.5	5				3	5	7	4	6	5				40
i_{10}				2.3	4	4	3.2	5	4				3.5	5	5	30
Reference point	2	3	5	2	4	5	3	5	5	4	5	5	4	5	5	---
Maximum acceptable value	3	4	10	3	5	10	5	6	10	6	6	10	6	6	10	

Demand	10	20	15	20	10	

In section 4.3, we have demonstrated that our proposed EES-MMRA mechanism meets IC, i.e., all 3PLs will bid truthfully. Let $\alpha=0.88$, $\beta=0.88$, $\theta=2.25$, $w_t=0.5$, $w_q=0.5$, $\kappa^t=0.1$, $\kappa^q=0.2$. In the process of request allocation, first, by Eqs. (1)-(2), we obtain the 4PL ex-ante satisfactions of non-price attributes on the 3PLs' bids, as shown in Table 2. And then, by Eqs. (3)-(6), we can calculate the non-price attribute costs considering the 4PL ex-ante satisfaction and the revised costs, which are shown in Table 3. Next, we apply the model P1 to obtain the efficient allocation of transportation requests (see Table 4). And according to our proposed payment rule, the payments which the winners get can be calculated, which are shown in Table 4.

Table 2
The 4PL ex-ante satisfactions of non-price attributes on the 3PLs' bids

R/I	r_1		r_2		r_3		r_4		r_5	
	t	q	t	q	t	q	t	q	t	q
i_1	0.00	-2.25	0.00	1.00					-2.25	-4.14
i_2			0.00	-4.14	0.00	1.00	-1.22	0.00		
i_3	0.00	0.00	0.00	-5.92			0.00	0.00	-2.64	-4.14
i_4	-1.22	0.00			-1.22	-5.92				
i_5			-1.22	-2.25			0.00	0.00		
i_6	0.00	0.00			0.00	-5.92	0.00	0.00	-3.21	-5.92
i_7	-0.55	0.00			0.00	-4.14				
i_8			0.00	0.00			0.00	0.00	-1.22	-2.25
i_9	-1.22	0.00			0.00	-4.14	-2.25	0.00		
i_{10}			0.00	1.00	0.00	1.00			0.00	0.00

Table 3
The non-price attribute costs considering 4PL ex-ante satisfaction and the ex-ante revised costs

R/I	r_1		r_2		r_3		r_4		r_5	
	$\mu(t_{ir},q_{ir})$	$\tilde{c}_{ir}$	$\mu(t_{ir},q_{ir})$	$\tilde{c}_{ir}$	$\mu(t_{ir},q_{ir})$	$\tilde{c}_{ir}$	$\mu(t_{ir},q_{ir})$	$\tilde{c}_{ir}$	$\mu(t_{ir},q_{ir})$	$\tilde{c}_{ir}$
i_1	-0.23	2.23	0.10	1.90					-0.53	4.53
i_2			-0.41	2.31	0.10	2.90	-0.06	4.26		
i_3	0.00	2.00	-0.59	2.39			0.00	4.00	-0.55	5.05
i_4	-0.06	2.16			-0.65	3.65				
i_5			-0.29	2.29			0.00	4.00		
i_6	0.00	2.00			-0.59	3.99	0.00	4.00	-0.75	4.75
i_7	-0.03	2.13			-0.41	3.41				
i_8			0.00	2.20			0.00	3.80	-0.29	4.29
i_9	-0.06	1.96			-0.41	3.41	-0.11	4.11		
i_{10}			0.10	2.20	0.10	3.10			0.00	3.50

Table 4
The allocation and payment on transportation requests

I/R		i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}
Winners	r_1									√	
	r_2	√									
	r_3		√								
	r_4								√		
	r_5										√
Payment		2.30	3.20	-	-	-	-	-	4.00	1.94	4.49

5.2. Sensitivity analysis

In this section, we conduct a sensitivity analysis to investigate the effectiveness of the proposed EES-MMRA mechanism. In sensitivity analysis, we investigate the influences of the non-price attribute weight, risk attitude coefficients and loss aversion coefficient. Then, in the comparison analysis, we discuss the auction results under EES-MMRA mechanism and P-VCG mechanism.

(1) The influence of the non-price attribute weights on the auction results

In this subsection, we consider three different cases of the non-price attribute weights.

Case1 $\mathbf{w} = (0.9, 0.1)^T$, in this case, the 4PL pays more attention to attribute t .

Case2 $\mathbf{w} = (0.5, 0.5)^T$, in this case, the 4PL pays equal attention to attribute t and attribute q .

Case3 $\mathbf{w} = (0.1, 0.9)^T$, in this case, the 4PL pays more attention to attribute q .

Then, based on the example in section 5.1, we run the model P1 under different values of $\mathbf{w}$, and obtain the allocation of transportation requests, which is shown in Table 5. Furthermore, the total cost and the total payments of the 4PL are calculated under different $\mathbf{w}$ values, which are shown in Table 5.

From Table 5, we observe that: under different $\mathbf{w}$ values, the results of transportation request allocation may be different. Even though case 2 has the same allocation result as case 3, the total costs of the auction and the total payments of the 4PL are both different. This implies that the non-price attribute weight $\mathbf{w}$ has a greater influence on the allocation result and the total payment of the 4PL.

Table 5
The allocation of transportation requests under different $\mathbf{w}$

R	r_1	r_2	r_3	r_4	r_5	Total cost	Total payment
Case1	i_6	i_3	i_2	i_8	i_{10}	14.06	15.94
Case2	i_9	i_1	i_2	i_8	i_{10}	14.20	15.93
Case3	i_9	i_1	i_2	i_8	i_{10}	13.85	16.11

(2) The influence of risk attitude coefficients (α and β) on the auction results

In this subsection, first we set $\alpha = \beta \in \{0.01, 0.08, 0.28, 0.48, 0.68, 0.88, 0.98, 0.99\}$, and fix other parameters. Then, based on the example in section 5.1, we calculate the 4PL ex-ante satisfaction and run the model P1 to obtain the allocation of transportation requests, which is shown in Table 6. Furthermore, the total costs and the total payments of the 4PL are calculated under different cases, which are shown in Table 6 and Fig. 5.

Table 6 shows that the allocation results change as the parameters α and β change. When the values of α and β increase to 0.28, transportation request r_1 is no longer allocated to 3PL i_6, but to 3PL i_9. This implies that risk attitude coefficients α and β have a greater influence on the allocation results.

In addition, From Table 6 and Fig. 5, we observe that: the total costs and total payments change as the parameters α and β change. When $\alpha = \beta \in \{0.01, 0.08\}$, the total costs are same, but the total payments are different. And with the values of α and β increasing, the total costs decrease and the total payments increase approximately. This implies that risk attitude coefficients α and β have the greater influence on the total costs and the total payments of the 4PL.

Table 6
The allocation of transportation requests under different α and β

α	β	r_1	r_2	r_3	r_4	r_5	Total cost	Total payment
0.01	0.01	i_6	i_1	i_2	i_8	i_{10}	14.100	15.666
0.08	0.08	i_6	i_1	i_2	i_8	i_{10}	14.100	15.700
0.28	0.28	i_9	i_1	i_2	i_8	i_{10}	14.093	15.697
0.48	0.48	i_9	i_1	i_2	i_8	i_{10}	14.081	15.825
0.68	0.68	i_9	i_1	i_2	i_8	i_{10}	14.070	15.904
0.88	0.88	i_9	i_1	i_2	i_8	i_{10}	14.061	15.926
0.99	0.99	i_9	i_1	i_2	i_8	i_{10}	14.057	15.923

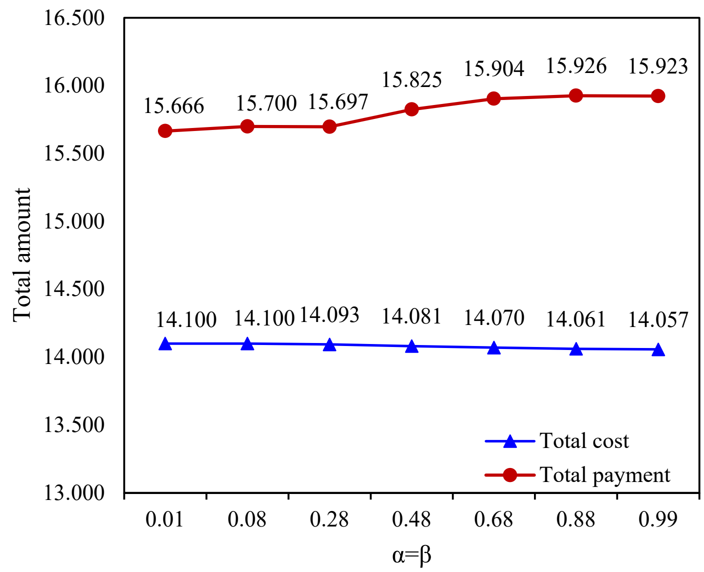

Fig. 5. The total costs and total payments under different α and β

(3) The influence of loss aversion coefficient θ on the auction results

In this subsection, first we set $\theta \in \{0.05, 0.5, 1, 1.5, 2.25, 10, 30, 50\}$, and fix other parameters. Then, based on the example in section 5.1, we calculate the 4PL ex-ante satisfactions and run the model P1 to obtain the allocation of transportation requests, which is shown in Table 7. Furthermore, the total cost and the total payments of the 4PL are calculated under different cases, which are also shown in Table 7 and Fig. 6.

Table 7 shows that when the value of θ is small (i.e., $\theta \le 0.05$) transportation request r_2 is allocated to 3PL i_3. When the value of θ increases (i.e., $0.05 < \theta \le 2.25$), transportation request r_2 is no longer allocated to 3PL i_3, but to 3PL i_2. And when the value of θ increases further (i.e., $\theta > 2.25$), transportation request r_1 is no longer allocated to 3PL i_9, but to 3PL i_6. This implies that loss aversion coefficient θ has the greater influence on the allocation results.

In addition, From Table 7 and Fig. 6, we observe that: with the value of θ increasing, the total costs and the total payments increase and when θ is large enough (i.e., $\theta \ge 10$), the total costs remain unchanged, but the total payments increase significantly. This implies that loss aversion coefficient θ has the greater influence on the total costs and total payments of the 4PL.

Table 7
The allocation on transportation requests under different θ

θ	r_1	r_2	r_3	r_4	r_5	Total cost	Total payment
0.05	i_9	i_3	i_2	i_8	i_{10}	13.915	15.206
0.5	i_9	i_1	i_2	i_8	i_{10}	14.014	15.327
1	i_9	i_1	i_2	i_8	i_{10}	14.027	15.570
1.5	i_9	i_1	i_2	i_8	i_{10}	14.041	15.801
2.25	i_9	i_1	i_2	i_8	i_{10}	14.061	15.925
10	i_6	i_1	i_2	i_8	i_{10}	14.100	16.972
30	i_6	i_1	i_2	i_8	i_{10}	14.100	19.515
50	i_6	i_1	i_2	i_8	i_{10}	14.100	22.058

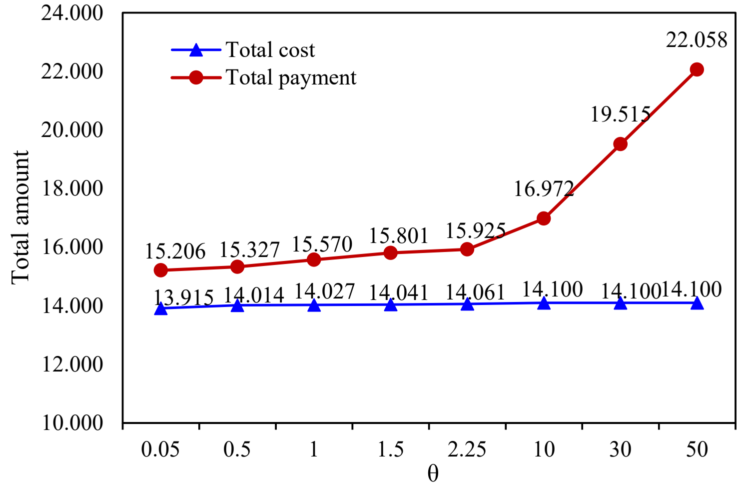

Fig. 6. The total costs and total payments under different θ

5.3. Comparison analysis

Vickrey–Clark–Groves (P-VCG) auction is a price-only auction. To illustrate the validity and applicability of the proposed EES-MMRA mechanism, we compare EES-MMRA mechanism and P-VCG mechanism. The model for winner determination and request allocation in the P-VCG mechanism is described in detail in Appendix A. First, based on the example in section 5.1, we run the allocation models of EES-MMRA mechanism and P-VCG mechanism respectively, and obtain the results of transportation requests allocation, which are shown in Table 8. Then, the total costs and the total payments of the 4PL are calculated under EES-MMRA mechanism and P-VCG mechanism respectively, which are also shown in Table 8.

Table 8
The comparison between EES-MMRA mechanism and P-VCG mechanism

Transportation request	EES-MMRA				P-VCG			
	winner	cost	time	quality	winner	cost	time	quality
r_1	i_9	1.9	3	5	i_9	1.9	3	5
r_2	i_1	2	4	4	i_3	1.8	4	8
r_3	i_2	3	5	4	i_7	3	5	7
r_4	i_8	3.8	5	5	i_8	3.8	5	5
r_5	i_{10}	3.5	5	5	i_{10}	3.5	5	5
Non-price attribute cost of winners	-0.140				1.060			
Total cost	14.061				14.000			
Total payment	15.926				14.900			

From Table 8, we observe:

(i) The request allocation results of the two mechanisms are different. In EES-MMRA mechanism, transportation requests r_2 and r_3 are assigned to 3PL i_1 and 3PL i_2 respectively. However, In P-VCG mechanism, transportation requests r_2 and r_3 are assigned to 3PLs i_3 and 3PL i_7 respectively. And in EES-MMRA mechanism, the non-price attribute values of winners are superior. For example, the damage rate of goods of winner on transportation request r_2 is 8 in P-VCG, which is worse than EES-MMRA mechanism. In addition, the allocations of other transportation requests are same in the two mechanisms because the bids of 3PL i_9, 3PL i_8, and 3PL i_{10} on transportation requests r_1, r_4, r_5 have the absolute advantage over the bids of other 3PLs.

(ii) Although the total cost in the EES-MMRA mechanism is a little bigger than that of P-VCG, the non-price attribute cost of the winner in the EES-MMRA mechanism is smaller than that of P-VCG. And the total cost of winning in the EES-MMRA mechanism includes non-price attribute cost. If non-price attribute cost is included in the total cost of the VCG mechanism, the final total cost is 15.060, which is higher than the total cost of the EES-MMRA mechanism.

(iii) In EES-MMRA mechanism, the total payment to winning 3PLs with better non-price attribute values is higher than that of P-VCG mechanism, which can incentivize 3PLs to improve their non-price attribute performances and facilitate the establishment of a good long-term relationship between 3PLs and the 4PL.

6. Conclusions

In this paper, we design an efficient multi-attribute multi-item simultaneous auction mechanism for the risk-averse 4PL to purchase transportation services. The main contribution of this paper is summarized below.

(i) Transportation service performance is related to price and non-price attributes. This paper designs a novel EES-MMRA mechanism. Theoretical analysis verified that the proposed mechanism meets IC, IR, BB and AE.

(ii) A winner determination and request allocation rule is developed, in which the 4PL ex-ante satisfaction with loss-averse behavior is particularly considered. And in order to achieve efficient allocation of transportation requests, a 0-1 programming model is established, whose objective is to minimize the total cost including the bidding cost and the non-price attribute cost incurred by the 4PL ex-ante satisfaction.

(iii) A payment rule that considers the 4PL ex-post satisfaction with loss-averse behavior is proposed. If 3PLs' real transportation service performances are not inferior to their bids in the auction process, the 3PLs will be paid based on their contributions; otherwise 3PLs will be penalized based on the 4PL's satisfaction. The payment rule encourages 3PLs to bid truthfully in the auction.

(iv) A numerical example is developed to demonstrate the effectiveness and applicability of our proposed mechanism. The result shows that the total cost and total payment will be affected by the non-price attribute weight, risk attitude coefficients and loss aversion coefficient. Comparison analysis shows that the proposed mechanism performs better than the known P-VCG mechanism and is helpful for the 4PL to establish a long-term cooperative relationship with 3PLs. Although the total cost of the proposed mechanism is slightly higher than that of P-VCG, the proposed mechanism generates a smaller non-price attribute cost of winning 3PLs by comparing it with the P-VCG.

In the future, many topics are interesting to be investigated. This paper assumes that the transportation requests are independent. In some transportation services, transportation requests can be correlated. For example, although different transportation requests are atomic and different, their routings may be complementary. In this case, it is interesting to study multi-attribute combinatorial auctions with heterogeneous multiple items for 4PL transportation service procurement. Also, this paper assumes that the transportation demand is deterministic. Yet in some practice, transportation demand may be uncertain. Hence, it is interesting to introduce demand uncertainty to transportation service procurement auctions.

Acknowledgements

This work is supported by the National Key R&D Program of China Grant No. 2021YFB3300900; the NSFC Key Supported Project of the Major Research Plan Grant No. 92267206; the NSFC Grant No. 62032013; the Fundamental Research Funds for State Key Laboratory of Synthetical Automation for Process Industries Grant No. 2013ZCX11; the 111 Project 2.0 (No. B08015).

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Appendix A

The model for winner determination and request allocation in the P-VCG mechanism is as follows.

Let y_{ir} $(i \in I, r \in R)$ be a binary variable, that denotes the allocation on transportation request r. Based on our research problem, the allocation model P2 of P-VCG auction is developed as follows:

$$\min \sum_{i \in I} \sum_{r \in R} c_{ir} y_{ir} \tag{A.1}$$

s.t.

$$\sum_{r\in R} d_r y_{ir} \le l_i \qquad i\in I \tag{A.2}$$

$$0 \le c_{ir} y_{ir} \le c_r^H \qquad i\in I;\ r\in R \tag{A.3}$$

$$0 \le t_{ir} y_{ir} \le t_r^H \qquad i\in I;\ r\in R \tag{A.4}$$

$$0 \le q_{ir} y_{ir} \le q_r^{\mathrm{H}} \qquad i\in I;\ r\in R \tag{A.5}$$

$$y_{ir} = 0 \qquad i\in I;\ r\in R \setminus R_i \tag{A.6}$$

$$\sum_{i\in I} y_{ir} = 1 \qquad r\in R \tag{A.7}$$

$$y_{ir} \in \{0,1\} \qquad i\in I;\ r\in R \tag{A.8}$$

where the objective of P2 is to minimize the bid cost. Constraints (A.2) ensure that the total demand for transport requests assigned to 3PL i is not greater than upper limit of 3PL i 's total transportation capacity. Constraints (A.3)-(A.5) guarantee that the winner 3PL i 's bid attribute values on transportation request r are not greater than the maximum acceptable attribute values. Constraint (A.6) means that if 3PL i does not submit the bid on transportation request r , its corresponding allocation $y_{ir} = 0$. Constraints (A.7) and (A.8) ensure that a transportation request can only be assigned to one 3PL.