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RESEARCH ARTICLE

Novel Double Auction Mechanisms for Agricultural Supply Chain Trading

YANG ZHANG[1] **AND HUIBING CHENG**[2]
[1]School of Management, Jinan University, Guangzhou 510632, China
[2]School Transportation and Logistics, Guangzhou Railway Polytechnic, Guangzhou, Guangdong 510430, China

Corresponding author: Huibing Cheng (chbgzrp2022@163.com)

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ABSTRACT Due to the deteriorated and obsolete nature, fresh produces generate a large amount of carbon emission, which has reduced the quality of modern life. This makes it important for agricultural supply chain trading (ASCT) to achieve efficient trading time and more social welfare based on efficient auctions. This paper is among the first contributions that incorporate bilateral bidding into auction mechanism design for produce trading problem. Two double auction mechanism are proposed to realize the optimal resource allocation and pricing of produce. This paper aims to realize efficient allocation and dynamic pricing in produce trading. We first consider a produce market with m growers and n sellers, and develop the multiunit nonreduction mechanism (MNR) and multi-unit trade reduction (MTR) mechanism in the market. According to the supply and demand relationship in the produce market, we consider two market scenarios of supply and demand oversupply, and overdemand, and formulated corresponding auction allocation and pricing rules. The two novel MUDA mechanisms have been constructed to allocate fresh produce with more reasonable prices in bilateral trade markets. Furthermore, a numerical study and analysis were considered to verify the effectiveness and efficiency of the two agricultural trading mechanisms. Numerical study results show that the proposed MTR mechanism can achieve efficient resource allocation.

INDEX TERMS Agricultural supply chain trading, multiunit double auction, produce bilateral exchange, produce carbon emission.

I. INTRODUCTION

Fresh products (such as produce, meats and seafood, etc.) are a necessity of life, and, as such, play a pivotal role in human evolution. Firs, fresh produce, meat and seafood has a high yield. China, for instance, produced a total of 749.12 million tons of vegetables, 286.92 million tons of fruit, 77.48 million tons of meat and 65.49 million tons of seafood in 2020. On the other hand, more than 150 types of vegetables have circulated in food markets. The abundant output and wide variety of fresh products always require fast circulation in supply chain to gain additional market value. Similar to classic perishable products (such as computer, iPhone, hotels, gifts, toys, concert tickets, etc.), fresh products have long delivery times and a finite shelf-life. Yet fresh products, since they are particularly perishable, also generate a lot of circulation loss, spoilage and there are not salvage value after the sale period [1]. For example, approximately 200 million tons of fruits and vegetables are lost during circulation. The mechanism of agricultural supply chains has an enormous impact on both economic development and living standard.

The production and management of agricultural supply chain is essential for the environment protection, especially in carbon emission. For example, global agricultural land releases more than 14% of global anthropogenic greenhouse gas emissions. The food supply chain emits up to 26% of greenhouse gas emissions, which is the second largest industry in terms of greenhouse gas emissions after the energy and construction industries. In the composition of Chinese greenhouse gas emissions, agricultural activities ranked third after energy activities and industrial production activities, accounting for 6.7% of the country's total greenhouse gas emissions. What's more, refrigeration transportation constitutes a major source of energy consumption and carbon emissions

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in fresh produce trading [2]. Optimal allocation of resources, energy conservation and green technology innovation make the low-carbon policy play an important intermediary role in promoting carbon emission efficiency [3]. For produce trading problem, auction mechanism can realize optimal allocation of resources to reduce the carbon emission.

In general, agricultural supply chain trading (ASCT) involves exchange and delivery of commodities, support services and the exchange of information in fresh produce trading. It carries the same advantages with usual supply chain trading such as matching demand and supply, facilitating goods exchange and providing a supporting service, and usually comprises sellers, buyers and a market intermediary [4]. Supply chain trading is only based on price and does not incorporate product characteristics such as long delivery times, unbalance nature in supply and demand, and short shelf-lives. Therefore, more non-monetary attributes should be considered as part of ASCT such as quality, amount, delivery time, and source of production. Pasternack first considers the pricing decision faced by a producer of a commodity with a short shelf or demand life [5]. Meanwhile, the agricultural supply chain selects suitable mechanisms to lower transaction costs only, neglecting transaction time [6]. A novel comprehensive agricultural supply chain trading mechanism is imperative to promoting both living standard and economic development.

Auction is defined as ''a market institution with an explicit set of rules determining resource allocation and prices based on bids of market participants'' [7] Auction mechanisms make two contributions to product markets: they eliminate haggling and provide for efficient allocation. To date, auction mechanisms for ASCT are mainly open-cry auctions, involving English and Dutch auctions [8], [9], [10], [11] where bidders can observe their competitors' bids. However, sealed-bid auctions will come to dominate the stable long-time markets since e-commerce is the one of the critical drivers of the circulation in trading [12]. In most relevant literature, four essential goals are proposed when designing auction mechanisms: (1) incentive compatibility (IC) – truthful bidding is a weak dominant strategy for each bidder; (2) allocation efficiency (AE) – final allocation of output can maximize the sum of participants' value; (3) ex-post individually rational (IR) – all participants obtain nonnegative utility; therefore, potential customers and providers are willing to bid; (4) ex-post budget-balanced (BB) – the auctioneer has nonnegative payoff; hence, the auctioneer is willing to hold the auction with no outside subsidies [13]. A stable and efficient auction that realizes maximum social welfare is imperative to ensure the imperishable and stability of produce markets.

From a practical standpoint, online auctions can improve transactional efficiency, reduce transaction costs via specific schemes for self-interested participants, and overcome geographical separation. The benefits of online auctions will encourage growers from all over the country to compete with others and gain their desired produce orders. Meanwhile, procurers can obtain products at a lower price to realize more utility. E-commerce has further development in recent such as the accuracy of the community navigation map unfortunately, limited studies have devoted attention to online auctions for ASCT. Furthermore, a lot of study on practical mechanisms for ASCT merely pay attention to English or Dutch auctions. It is known that effective auctions such as VCG [14] auctions are utilized to procure transportation services. Such online auction mechanisms are practically more attractive in two-sided exchange than one-sided exchange.

However, one-side VCG auction mechanism is unable to achieve rapid supply and demand matching. A bilateral trading mechanism such as double auction is more suitable to realize rapid matching, avoid to compute the NP-hard problem, and attract potential market's participants. Moreover, the third-party bilateral trading service is provided by a central platform (e.g., e-marketplace, onsite market), which allows procurers and growers to share their demands and supply goods, to facilitate the transactions between procurers and growers [15]. Because of the deteriorated and obsolete nature of products, fresh produce supply chain generates a large number of carbon emissions via refrigerated transportation, which receives more attention in carbon emission reduction of food [2]. Thus, double auction mechanism can reduce the decay of produces to lessen the time of refrigeration, which is helpful to achieve low carbon for agriculture supply chain. The application of double auction for produce trading will respond to the policy of ''Green Mountains and Clear Water'', which implies that such mechanism is beneficial for energy conservation and environment protection [16]. Last but not least, double auction can decrease disorderly agricultural production by matching capacities from growers and needs of procurers, which results in the reduction of greenhouse gas emissions from agricultural land.

For all we know, this paper is the first to research how to extend double auction mechanisms to address produce trading problems in bilateral markets. Hence, this study attempts to address the following questions: (1) How to collect superfluous products from growers and demand from procurers in the ASCT to generate a two-sided market; (2) How to realize produce pricing dynamically based on the supply and demand in bilateral market; and (3) How to allocate limited products provided by growers to limited procurement task offered by procurers? To solve the first problem, an e-commerce platform is created to support the process of collecting and plays the role of market institution. Consequently, we introduce two different MUDA mechanisms to achieve dynamic pricing: the multiunit nonreduction (MNR) mechanism and the multiunit trade reduction (MTR) mechanism, which can be proved by their properties. To solve the final problem, different allocation and pricing rules are proposed under the MNR and MTR mechanisms. Finally, the MTR mechanism can realize IC, BB, IR, and AsE (asymptotic efficiency) which provide support for sustaining a stable fresh product market.

The primary contributions of this research are highlighted as follows: (1) To the best of our knowledge, this work is the first to introduce the double auction mechanisms to realize the maximum value of ASCT. The proposed mechanism can effectively promote the profit of produce providers and the utility of customers and supplement the blank of bilateral auction application research (2) Some key findings have been obtained by comparing the performance of MNR mechanism with that of MTR mechanism. Such findings provide insightful views for produce providers and customers and verify the effectiveness and applicability of the proposed approach.

The remainder of this article is constructed as follows. In Section II, the literature related to the fresh product supply chain, double auction mechanisms and auction based ASCT are investigated. Section III describes the model of product trading. In Section IV, to design the MUDA mechanism, we propose the multiunit nonreduction mechanism (MNR) and multiunit trade reduction (MTR) mechanisms in the bilateral market, respectively. To evaluate the efficiencies of the mechanisms, numerical analyses are conducted, and managerial implications are discussed in Section V. Finally, our conclusions and some directions for future research are summarized in Section VI.

II. LITERATURE REVIEW

In this section, we briefly review related topics: 1) fresh produce supply chain; 2) double auction; and 3) Auction-based ASCT. After our review of the literature, we identify some research gaps.

A. FRESH PRODUCE SUPPLY CHAIN

In the first category, the question of a fresh produce supply chain has been widely studied, such as, with regard to the design of supply chain network, member cooperation in supply chain, and reviews of relevant literature. Blackburn and Scudder use the example of sweet corn and melons to investigate design strategies of supply chain [17]. They find a hybrid sensitive model to minimize loss in the supply chain. Soto-Silva note that the supply chain has the nature of enormous unbalance between supply and demand in the food and agribusiness sector [18]. They review scientific models adopted in the agricultural supply chain and conclude by discussing several such as the deficiency of integral methods for the design of agricultural supply chain. Cai propose a contract between producers and distributors, and a contract between producers and third platform logistics (3PL) providers to integrate the supply chain [19].

Wu takes the risk preference of the third-party logistics into consideration and proposed two model mechanisms to integrate the decentralized channel, which finally realize cooperation for entire channel [20]. Ma proposed the cooperation mechanism in a three-grades agricultural supply chain and improves sales dramatically and boost the profit of each supply chain member [21]. Ahumada and Villalobos review the contributions in the production management and allocation planning for fresh produce and diagnose some future requirements for modeling the produce supply chain [22]. Borodin proposed a configurable overview about the application of operations research methodologies for dealing with uncertainties according to fresh produce supply chain. They aim to investigate the present art, gaps in actual research, and further loads on the article [23]. In recent, green agricultural supply chain has received much attention. Wang consider refrigerated transportation services among agricultural supply chain and develop a carbon trading mechanism, which provides strategies to pricing fresh produce [1]. Bortolini propose a three-objective allocation decision maker where operation cost, carbon emission cost and delivery time are incorporated to model, which apply the system to handle the allocation of produces [24].

The above works mainly explores the fresh produce sales flow from upstream suppliers to retailers. However, we may improve circulation efficiency via an efficient allocation and pricing scheme for fresh produce.

B. DOUBLE AUCTION MECHANISMS

The last theme concentrates on a multi-attribute auction. In recent studies about auctions, double auctions have attracted much attention. Not like one-sided auctions, double auctions can allow sellers to increase their bids as buyers increase their own bids. In double auctions, many auction mechanisms which realize truthful are proposed to solve resource distribution problems and those mechanisms are then categorized into multi-stage methods and trade reduction scheme. Commodities in the multiunit trade reduction mechanism are fractionized into distinct markets and each market's least profitable trade pair is sacrificed but the pair's bid price serves as the trade price for the remaining efficient pairs in the same market. A mechanism proposed by [25] deals with a simple trading situation where customers and providers can make a single unit trading with the same commodity. Based on McAfee's work, Huang extended the mechanism into a multiunit trading situation [26]. Babaioff and Walsh develop a known single-minded trade reduction (KSM-TR) for a bilateral market where each customer needs to buy some commodities while each seller provides the only one commodity [27]. Babaioff further found trade-reduction mechanism in distributed markets [28]. To improve further total net, Chu and Shen first find a multi-stage scheme in which applying the price from each buyer as the bid price minus the minimum shadow price, and the trading price of each winning seller is the asking price plus the maximum shadow price [13]. Chu and Shen further develop modified buyer competition mechanisms to pricing. Nevertheless, the above two multistage approaches are assumed to have a single output restriction. Thus, the property of budget balance could not be guaranteed if a single output restriction is directly slacked to a multiunit setting [29]. To deal with the potential situation, Chu further provides a padding approach that intentionally finds imbalances between demand and supply via a phantom buyer, leading to higher efficiency, higher trade prices and lower trade prices [30]. There has also been some application-oriented research, such as logistics procurement services provided by e-marketplaces, truckload carrier procurement services [12], [15] and multi-attribute MUDAs for produce supply chains [31]. Wang first provide an optimization mechanism to investigate the strategy in mixed traffic conditions [32]. Although MUDA mechanisms have been widely utilized in many life-fields, only limited studies apply them to solving fresh product trading problems.

C. AUCTION-BASED ASCT

The latter focus on auctions has been utilized in practice for fresh product allocation and pricing. Cramton point out that the most fundamental economics questions, which are asked and answered by auctions, are who win the goods with certain prices [33]. In Europe, there exists Dutch auctions for over a century to exchange flowers [9]. The produce markets are mainly dependent on some on-site auctions, such as traditional Dutch auctions [6], [9], [11], dual Dutch auctions [8], and Japanese Dutch auctions [10]. McCabe et al. prove that multiunit Dutch auctions, used for produce, fish, or cut flowers, have the same theoretical properties as the corresponding single-unit Dutch clock [11]. Kambil and van Heck propose a novel trading mechanism driven by information technology as a tool for determining price and organizing transactions to partly replace the traditional Dutch auction [6]. Crawford and Kuo studied a dual Dutch auction for aquatic products, where auction with bundling [8]. Kitahara and Ogawa point out that a Japanese Dutch auction has ''Mari''-stages. To begin with, the price drops continuously until a buyer stops the clock. Then, the ''Mari'' signal appears briefly (usually for a few seconds) when other buyers are able to compete for the products at the same price [10]. Kambil and van Heck discussed the disadvantages of conventional Dutch auctions. First, rapid growth in the flower industry increases the complexity of logistics service and limited space needs to be expanded in the auctions. Second, it is difficult to attend several auctions to bid simultaneously. Third, growers cannot understand the truthful preferences of customers since manufacturing process are independent with the sale of their produce [6]. To overcome the limits of on-site space and time, online auctions for produce are studied [34], [35]. Miyashita proposes an online MUDA mechanism for produce according to their time-urgency in order to achieve efficient and fair allocations among participants [35]. Huang and Song adopt an agent-based optimization scheme to discover online auction plan to adjust inventory in fresh produce supply chain [34]. The above literature pays little attention to efficient and truthful auction mechanisms. Such auction mechanisms for ASCT can introduce participants to reporting truthfully and maximizing social welfare, which implies that there is potential market in ASCT to be explored.

It can be observed from the literature described above that although those models can improve circulation efficiency and obtain more social welfare, they cannot achieve maximum social welfare and truthful information revelation for ASCT. However, previous research has established the foundation for our work on auction mechanisms for produce trading problems. We attempt to conclude some of the research gaps from the review of existing literature. Most fresh produce supply chain research considers improved circulation efficiency of flow and profit allocation among members. However, there are a few studies on auction mechanisms to achieve allocative efficiency and maximum social welfare. Additionally, many fields, such as transportation procurement and supply chain, apply MUDA mechanisms to improve social welfare, but few studies in the literature solve produce trading problems in bilateral markets via efficient auction mechanisms. Our paper attempts to utilize MUDA mechanism for ASCT in a bilateral market. Finally, fresh produce is diversified and cannot be directly sold in other fields of markets. Thus, our paper separates multiple two-sides markets based on the types of produce involved.

III. MODEL OF PRODUCE TRADING SYSTEMS

Number equations consecutively with equation numbers in Based on the carbon footprint analysis for the life-cycle of agricultural products, the carbon emissions in the entire process of production, circulation and sales of agricultural products are decomposed into carbon emissions of production, carbon emissions of refrigeration logistics and storage, carbon emissions of sales and carbon emissions of decay [36]. The sum of these four parts constitutes the total carbon emissions per unit of agricultural products, which increases with the output of agricultural products increasing. Among them, the carbon emissions of refrigeration logistics and storage increase with the use of refrigeration logistics increasing, decrease with the usage efficiency of refrigeration logistics increasing. Carbon emissions from decay decrease with the use and the usage efficiency of refrigeration logistics increasing. A suitable trading mechanism have a large amount of impact on carbon emissions in the life cycle of produces. The trading mechanisms matching rapidly not only can reduce refrigeration service time and decay but also alleviate disorderly production and vendition pressure.

There are a group of growers who provide different kinds of fresh produce and that produce is used to meet the demands of individuals, especially in developed regions (e.g., Shanghai). At any point in time, some growers, known as providers, have excess production (e.g., cut flowers, seafood, fruits, teas), while some individuals, corporations, and supermarkets need fresh produce, and they are known as procurers. Superfluous yielding capacity of produce is visualized and encapsulated into commodities so that they can be bargained via e-commerce platforms. Such e-commerce platform, called auctioneer, is the market maker who plays a critical role in collecting demand and supply together and executing the designed auction mechanism to make market clear.

In fresh produce trading (FPT), each type of produce can be classified into various level commodities based on quality, weight, origin of the brand etc., as shown in Fig. 1. When procurers demand fresh produce, they can submit their need for

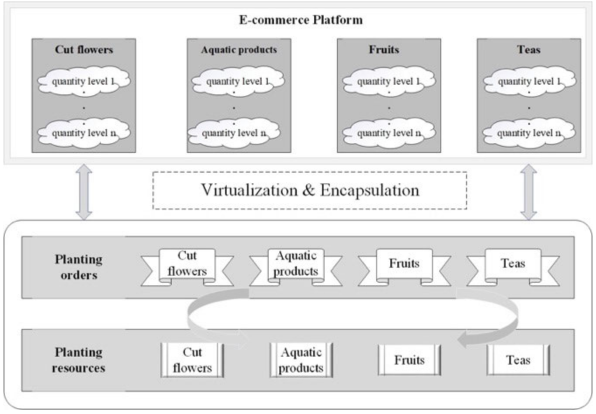


FIGURE 1. FPT in the e-commerce platform.

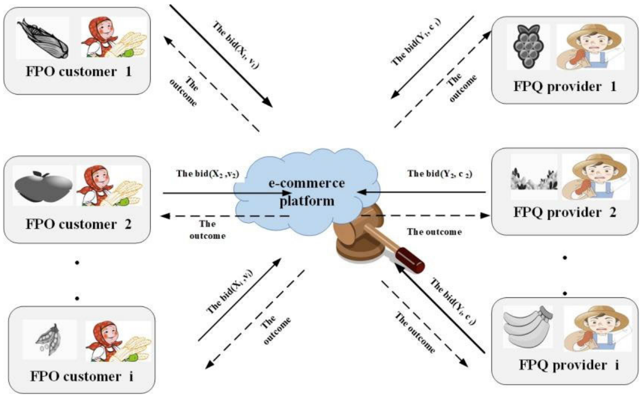


FIGURE 2. Auction-based FPT in bilateral market.

a corresponding type of produce. Meanwhile, when growers have superfluous produce yielding capacity, they can submit the type of produce they have, the level of commodity and auctioned quantity. Therefore, growers and procurers conduct transactions at one level commodity of the same produce. We propose that transactions in different produce markets are unrelated bilateral markets and mutually independent. So, ''one-unit item'' is defined as a standard measurement of produce purchased. For the sake of explaining conveniently, we mainly consider one type of produce allocation and others following the same method.

The growers and procurers of produce trade by participating in auctions via e-commerce platforms, as shown in Fig. 2. Each procurer can offer a fresh produce order (FTO), while fresh produce quantity (FPQ) is provided by each grower. The term ''bid'' and ''item'' denote a participant's declaration and one unit commodity, respectively. Let I be the set of procurers and J be the set of growers. A produce procurer is defined as ''she'' and a produce provider as ''he.'' There is a produce market with m procurers and n providers. In such market, each procurer i $(i \in I)$ wants to purchase X_i unit items and each grower j $(j \in J)$ has superfluous Y_j unit items to sell. We propose that both X_i and Y_j are common knowledge and participants are allowed to split their volumes. Let v_i and c_j denote the valuation of procurer i and the cost of grower j for per unit item, respectively. Such valuation and cost are reservation values, which are supposed to be private information for each grower and procurer. Similarly, let v_i and c_j be the bid price of procurer $i$and grower $j$for each unit item, respectively.

It is assumed that each procurer and grower is *a* self-interested participant who attempts to get her/his own maximal utility. Since participants' utilities are derived from valuation and trading price, we make an important assumption that they have quasi-linear utility. That is, if a participant engages in transactions, her or his utility is equal to the difference between the participant's reservation value and the amount of money transferred; otherwise, utility is zero. The monetary payoff of the auctioneer (i.e., e-commerce platform) is the difference between the total payments from procurers and the total revenues received by growers. Meanwhile, social welfare is the sum of each participant's utility and the auctioneer's payoff.

Our aim in this paper is to propose fresh produce MUDA mechanisms, which can achieve IC, IR, BB, and AsE. Note that AsE represents asymptotic efficiency, which shows that market inefficiency of the mechanism approaches zero as the number of participants increases. Therefore, AE can be achieved if the number of auction participants has been large enough.

A. MODEL DESCRIPTION

In this section, we define a market for single type of produce with m procurers and n growers. Let q_{ij} be the quantity procurer i procures from grower j and p_{ij} be the exchange price. Note that v_i and c_j are procurer i's bidding price with her reservation value, and grower j's bidding price with his cost, respectively. Therefore, procurer i's utility is : $u_i = \sum_j (v_i - p_{ij})q_{ij}$, and grower j's utility is $u_j = \sum_i (p_{ij} - c_j)q_{ij}$. If each participant in auction report truthful price, the maximum social welfare $V(I, J)$, the sum of all participants' utilities and the platform's payoff are obtained by:

$$V(I, J) = \max \sum_{i}^{m} \sum_{j}^{n} q_{ij}(v_i - c_j) \tag{1}$$

$$\text{s.t.} \sum_{j=1}^{J} q_{ij} \le X_i, \quad i \in I \tag{2}$$

$$\sum_{i=1}^{I} q_{ij} \le Y_j, \quad j \in J \tag{3}$$

$$q_{ij} \ge 0 \quad \forall i, j. \tag{4}$$

Constraints (2) and (3) indicate that a procurer cannot buy more than her demands, and a grower will not sell more than what he owns, respectively. The auction process of trading is thus:

Step 1: E-commerce platform, regarded as auctioneer, organizes the auction, sends information about the beginning of the auction to both procurers and growers, and formulates the rules including winner determination rule and payment rule.

Step 2: Procurer i submits her bid $(X_i, \hat{v}_i)$ and grower j submits his bid.

Step 3: The e-commerce platform operators inform participants about bidding confirmation and stop the auction.

Step 4: According to the formulated auction mechanism, the auctioneer announces the winner and the final price and inform both procurers and growers about the final result, including winners and the corresponding trade price.

Step 5: The winning procurers obtain the allocated produce provided by relevant growers and give related payment to auctioneers based on the result.

Step 6: The winning growers receive the money from the auctioneers and provide relevant produce according to the allocation result and payment rule.

Note that social welfare is determined by both procurers' and growers' reservation value and trade prices will impact each participant's utility rather than the total social net profit. In other words, the total social net profit consists of growers' utility, procurers' utility, and auctioneers' payoff, and what the trade prices affect becomes allocated as profit among them. We use the following example to explain this further. There are five procurers with reservation values $(10, 9, 7, 6, 2)$ and five growers with reservation values $(1, 3, 4, 5, 9)$. Each participant reports her/his truthful private information (i.e., reservation value) and plans to trade a one-unit commodity. In this example, there are four pairs to realize positive total social net profit. The first four procurers with bids $(10, 9, 7, 6)$ and growers with bids $(1, 3, 4, 5)$ are selected. We assume that the final price p_{ij} is (6+5)/2=5.5 for all winners including procurers and growers, so those procurers gain their utility (4.5, 3.5, 1.5, 0.5) and growers obtain their utility (4.5, 2.5, 1.5, 0.5). Social welfare is 19.

We propose that the price between the procurer with the maximal price and the grower with the minimal price is $p_{11} = (10 + 1)/2 = 5.5$. Similarly, $p_{22} = (9 + 3)/2 = 6$, and $p_{33} = (7 + 4)/2 = 5.5$, $p_{ij} = (6 + 5)/2 = 5.5$. At present, the winning procurers obtain their utility (4.5, 3, 1.5, 0.5) and the winning growers obtain their utility is (4.5, 3, 1.5, 0.5). Hence, there exists participants to be motivated to misreport their reservation value to gain more money from the produce trade. For instance, if the procurer with value 6 changes her bid price to 5.5, while the others' bid prices remain unchanged, the utility of this procurer increases to 0.75. The procurer has increased utility via misreporting behavior, but it has no influence on the social welfare. In another instance, the procurer who has truthful value 6 bids 5 as her price, and the grower who has truthful value 5 bids 6 as his price, meanwhile the others remain unchanged. In this instance, there are three trading pairs. Assuming that the trade price $p_{ij} = (7 + 4)/2 = 5.5$ for all winners, the winning procurers gain utility 4.5, 3.5, and 1.5, and the winning growers gain utility 4.5, 2.5, and 1.5. Thus, the social welfare is 18. In conclusion, the performance mechanism worsens because of participant's misreporting behavior such that social welfare decreases about 5.26% from 19 to 18, and the final trading volume decreases about 25% from 4 to 3. In many cases, the centralized methods are unavailable since both procurers and growers own their private information, and their bidding strategy can bring trading system loss. Thus, the design of MUDA will be sophisticated enough to handle the IC problem by inducing both the participants' private information.

IV. DESIGN OF MUDA AUCTION MECHANISM

In our schemes, we develop a truthful and efficient MUDA mechanism for produce trading systems. In a market with m procurers and n growers, both procurers and growers can obtain more benefit by adjusting discriminate trade prices. In order to encourage the participants to submit their bids as reservation values, we apply the Vickrey-like auction both in bilateral market. First, we sort the bid prices of all procurers and growers, respectively. The results are presented in the following equations:

$$\hat{v}_1 \geq \hat{v}_2 \geq \cdots \geq \hat{v}_m \tag{5}$$

$$\hat{c}_1 \leq \hat{c}_2 \leq \cdots \leq \hat{c}_n \tag{6}$$

After sorting all participant bid prices, the quantity point when market is cleared $Q^* = min\{\sum_{i=1}^{K} X_i, \sum_{j=1}^{L} Y_j\}$ where total demand and supply are balanced, which leads to $\hat{v}_k \geq \hat{c}_l$ and $\hat{v}_{k+1} < \hat{c}_{l+1}$. We find two market clearing situations from the above. For case I, the total demand and supply and their bids' order are given by, respectively:

$$\sum_{j=1}^{L} Y_j \geq \sum_{i=1}^{K} X_i \geq \sum_{j=1}^{L-1} Y_j \tag{7}$$

$$\hat{v}_K \geq \hat{c}_L \geq \hat{v}_{K+1} \tag{8}$$

For case II, the total demand and supply and their bids must follow the equations, respectively:

$$\sum_{i=1}^{K} X_i \geq \sum_{j=1}^{L} Y_j \geq \sum_{i=1}^{K-1} X_i \tag{9}$$

$$\hat{c}_{L+1} \geq \hat{v}_K \geq \hat{c}_L \tag{10}$$

A. MULTIUNIT NONREDUCTION MECHANISM

When total supply and demand are balanced, we can find the critical quantity point Q^* from (7) and (8) or (9) and (10). According to the MNR mechanism, K is the highest bid price procurers make trades with, L is the lowest bid price of growers, with procurers paying $\hat{v}_K$ and growers receiving $\hat{c}_L$. Additionally, this assumes that the total trade quantity of MNR mechanism is Q^*. To achieve market clearance, there are two cases of relationships between demand and supply: over-supply and over-demand. The over-supply case and the over-demand case are shown as (11) and (12), respectively.

$$\sum_{j=1}^{L} Y_j \geq \sum_{i=1}^{K} X_i \tag{11}$$

$$\sum_{i=1}^{K} X_i \geq \sum_{j=1}^{L} Y_j \tag{12}$$

To allocate produce in each case, the winner determination problem can be solved by well-designed allocation rules. If equation (11) holds, all procurers with $i \leq K$ win their demand quantity X_i based on the indiscriminate price $\hat{v}_K$, and all growers with $j \leq L$ win based on the indiscriminate price $\hat{c}_L$. To figure out the final trade quantity $q_{j'}$ of grower j when all demand volume X_i are finally met, the auctioneer announces rule 1 to rank all trading growers ($j \leq L$). A perturbation technique is adopted to break the tie if some growers' have an equal number of supplies. Then, let $r_{j'}$ be the ranking of grower j'. Note that grower j' may or may not be equal to grower j. Then, all winning growers' rankings are shown as following in strongly ascending order: $r_{1'} < r_{2'} < \cdots < r_{L'}$. According to Rule 1, each grower j' sells at least a "basic" volume $\bar{q}_{j'} = \text{fix}\,(\frac{Y_{j'} \sum_{i=1}^{K} X_i}{\sum_{j'=1'}^{L'} Y_{j'}})$, where $\bar{q}_{j'} \leq Y_{j'}$. Let the remaining demand be $\text{RD} = \sum_{i=1}^{K} X_i - \sum_{j=1}^{L} \bar{q}_j$. The final trade volume $q_{j'}$ of grower j' is given by:

$$q_{j'} = \begin{cases} min\left\{Y_{j'}, \bar{q}_{j'} + \left[\text{RD} - \sum\limits_{a'=(j+1)'}^{L'} (q_{a'} - \bar{q}_{a'})\right]\right\}, \\ \quad 1' \leq j' \leq (L-1)' \\ min\left\{Y_{L'}, \bar{q}_{L'} + RD\right\}, \\ \quad j' = L' \end{cases} \tag{13}$$

where $q_{j'}$ is an integer, and $\bar{q}_{j'} \leq q_{j'} \leq Y_{j'}$.

The rule 1 is summarized as follow:

1. All the procurers with $i \leq K$ win their demand quantity X_i based on the indiscriminate price $\hat{v}_K$, and all growers with $j \leq L$ win based on the indiscriminate price $\hat{c}_L$.
2. All winning growers' rankings are shown as following in strongly ascending order: $r_{1'} < r_{2'} < \cdots < r_{L'}$.
3. each grower j' sells at least a "basic" volume $\bar{q}_{j'} = \text{fix}\,(\frac{Y_{j'} \sum_{i=1}^{K} X_i}{\sum_{j'=1'}^{L'} Y_{j'}})$, where $\bar{q}_{j'} \leq Y_{j'}$. Let the remaining demand be $\text{RD} = \sum_{i=1}^{K} X_i - \sum_{j=1}^{L} \bar{q}_j$. The final trade volume $q_{j'}$ of grower j' is given by equation (13).

If equation (12) holds, each grower with $j \leq L$ sells production volume Y_j based on the indiscriminate price $\hat{c}_L$ and each procurer with $i \leq K$ procures according to the indiscriminate price $\hat{v}_K$. Therefore, Rule 2 is proposed to determine the trading volume $q_{i'}$ of procurer i when the entire supply volume Y_i is finally exchanged. The auctioneer ranks all selected procurers ($i \leq K$) with descending order based on their demand quantities. Let $r_{i'}$ be the grade of the procurer i'. In fact, the procurer i' is not equal to the procurer i. Therefore, all the selected procurers' rankings are organized with strongly ascending order: $r_{1'} < r_{2'} < \cdots < r_{K'}$. According to Rule 2, each procurer i' procures $\bar{q}_{i'} = \text{fix}(\frac{X_{i'} \sum_{j=1}^{L} Y_j}{\sum_{i'=1'}^{K'} X_{i'}})$, where $\bar{q}_{i'} \leq X_{i'}$ and $\sum_{i'=1'}^{K'} X_{i'} = \sum_{i=1}^{K} X_i$. The remaining supply (RS) is $\sum_{j=1}^{L} Y_j - \sum_{i=1}^{K} \bar{q}_i$. Let $q_{i'}$ be the volume procured by procurer i'. Therefore, $q_{i'}$ is given by:

$$q_{i'} = \begin{cases} min\left\{X_{i'}, \bar{q}_{i'} + \left[\text{RS} - \sum\limits_{b'=(i+1)'}^{K'} (q_{b'} - \bar{q}_{b'})\right]\right\}, \\ \quad 1' \leq i' \leq (K-1)' \\ min\left\{X_{K'}, \bar{q}_{K'} + RS\right\}, \quad i' = K' \end{cases} \tag{14}$$

where $q_{i'}$ is an integer, and $\bar{q}_{i'} \leq q_{i'} \leq X_{i'}$.

The rule 2 is summarized as follow:

1. each grower with $j \leq L$ sells production volume Y_j based on the indiscriminate price $\hat{c}_L$ and each procurer with $i \leq K$ procures according to the indiscriminate price $\hat{v}_K$.
2. all the selected procurers' rankings are organized with strongly ascending order: $r_{1'} < r_{2'} < \cdots < r_{K'}$.
3. each procurer i' procures $\bar{q}_{i'} = \text{fix}(\frac{X_{i'} \sum_{j=1}^{L} Y_j}{\sum_{i'=1'}^{K'} X_{i'}})$, where $\bar{q}_{i'} \leq X_{i'}$ and $\sum_{i'=1'}^{K'} X_{i'} = \sum_{i=1}^{K} X_i$. The remaining supply (RS) is $\sum_{j=1}^{L} Y_j - \sum_{i=1}^{K} \bar{q}_i$. Let $q_{i'}$ be the volume procured by procurer i'. Therefore, $q_{i'}$ is given by equation (14).

The trading volume is $Q^* = min\{\sum_{i=1}^{K} X_i, \sum_{j=1}^{L} Y_j\}$. Therefore, the e-commerce platform operators (i.e., auctioneers) take the total trade surplus, shown as:

$$U_{eo}^{MNR} = (\hat{v}_K - \hat{c}_L) * \min\{\sum_{i=1}^{K} X_i, \sum_{j=1}^{L} Y_j\} \tag{15}$$

Additionally, each procurer's utility and each grower's utility are given by:

$$U_{v_i}^{MNR} = (\hat{v}_K - \hat{c}_L) * \min\{X_i, q_i\}, \quad i \in \{1, 2, \ldots, K\} \tag{16}$$

$$U_{c_j}^{MNR} = (\hat{v}_K - \hat{c}_L) * \min\{Y_j, q_j\}, \quad j \in \{1, 2, \ldots, L\} \tag{17}$$

From the mechanism is summarized, the above mechanism is given as follows:

1. Gather sealed bid from all participants, including volumes and prices.
2. Rank procurers' bids as $\hat{v}_1 \geq \hat{v}_2 \geq \cdots \geq \hat{v}_m$, and growers' bids as $\hat{c}_1 \leq \hat{c}_2 \leq \cdots \leq \hat{c}_n$.
3. Clear the market at the point $Q^* = \min\{\sum_{i=1}^{K} X_i, \sum_{j=1}^{L} Y_j\}$ where total supply and total demand are equal, which leads to $\hat{v}_k \geq \hat{c}_l$ and $\hat{v}_{k+1} < \hat{c}_{l+1}$.
4. Remove all participants who are excluded from auctions, that is, procurers with indices $i \leq K$ and growers with indices $j \geq L$.
5. If equation (11) holds, use Rule 1; otherwise, use Rule 2.

The best approach to understanding the MNR mechanism is to take an instance (see Table 1). In this instance, K = L = 4, $\hat{v}_k = 9$, $\hat{c}_L = 6$. Since $\sum_{j=1}^{L} Y_j = 20 > \sum_{i=1}^{K} X_i = 18$, inequality (11) holds and trade volume is 18. According to Rule 1, we can drive each grower's quantity: $\bar{q}_{1'} = \text{fix}(\frac{8*18}{20}) = 7$(forgrower2), $\bar{q}_{2'} = \text{fix}(\frac{7*18}{20}) = 6$(forgrower4), $\bar{q}_{3'} = \text{fix}(\frac{3*18}{20}) = 2$(forgrower3),

TABLE 1. An example of MNR mechanism.

Produce market	
Procurers: $(X_i, \hat{v}_i)$	Growers: $(Y_j, \hat{c}_j; r_{j\prime})$
(7, 12)	(2, 3; $r_{4\prime}$)
(4, 11)	(8, 4; $r_{1\prime}$)
(6, 10)	(3, 5; $r_{3\prime}$)
(1, **9**)	(7, **6**; $r_{2\prime}$)
(5, 5)	(3, 10)
(6, 3)	(5, 11)

$\bar{q}_{4'} = \text{fix}(\frac{2*18}{20}) = 1(\text{forgrower}1)$. This remaining demand is derived by $\text{RD} = \sum_{i=1}^{K} X_i - \sum_{j=1}^{L} \bar{q}_j = 2$. Then, we find the volume from the winning grower with the lowest ranking (i.e., grower 1): $q_{4'} = \min\{Y_{4'}, \bar{q}_{L'} + RD\} = 2$. Similarly, $q_{3'} = \min\{Y_{3'}, 2+1\} = 3$, $q_{2'} = \min Y_{2'}, 6+0 = 6$, $q_{1'} = \min\{Y_{1'}, 7+0\} = 7$.

In such mechanism, both procurers and growers submit bid prices. Assumed that procurer i with reservation value v_i reports her private information, that is, a bid price equal to v_i. If $v_K = v_i$, procurer i has no profit. Since no procurer can ensure that her bid price is higher than the K_{th} bid price, each procurer submits the bid with price lower than her reservation value. Similarly, the grower submits bid with price higher than his reservation value. As mentioned previously, both procurers and growers are self-interested participants. As such, they are eager for maximizing their utility by increasing or decreasing their bid prices submitted based on reservation values. Thus, such mechanism is not incentive compatible, which implies that participants submit their bids not as reservation values. However, participants must deal with a simple trade-off when considering others' bidding strategies. For instance, procurers increase the bid price and growers decrease the bid price, respectively. It is essential to find symmetric equilibrium strategies for balancing the payoff from winning.

It is assumed that demand quantity X_i of procurer i is an independent random sample, and the quantity Y_j from grower j is an independent random sample. Additionally, it is assumed that private values of m procurers are selected independently from a continuously differentiable distribution $F(v)$ with continuous density $f(v)$ and support on the compact interval $\left[v_-, v^+\right]$ with the mean v, and reservation values of the n growers are selected independently from a distribution $G(c)$ with continuous density $g(c)$ and support on the compact interval $\left[c_-, c^+\right]$ with the mean c. We also assume that density functions f and g have nonnegative values.

Theorem 1: In the MNR mechanism, for each produce procurer $i(1 \le i \le m)$ and each grower $j(1 \le j \le n)$, the symmetric equilibrium strategies $\beta^p(v_i)$ and $\beta^g(c_j)$ are given by:

$$\beta^p(v_i) = \int_{v_-}^{v^+} v \frac{\sum_{a=K}^{m} \binom{m}{a} \{F(v)\}^{m-a}\{1-F(v)\}^a}{\sum_{a=K}^{m} \binom{m}{a} \{F(v_i)\}^{m-a}\{1-F(v_i)\}^a} dv \tag{18}$$

$$\beta^g(c_j) = \int_{c_j}^{c^+} c \frac{\sum_{b=L}^{n} \binom{n}{b} \{1-G(c)\}^{n-b}\{G(c)\}^b}{\sum_{b=L}^{n} \binom{n}{b} \{1-G(c_j)\}^{n-b}\{G(c_j)\}^b} dc \tag{19}$$

where $\sum_{a=K}^{m} \binom{m}{a} \{F(v)\}^{m-a}\{1-F(v)\}^a$ denotes the density of the K_{th} highest order statistic T_K^m selected from $F(v)$; $\sum_{b=L}^{n} \binom{n}{b} \{1-G(c)\}^{n-b}\{G(c)\}^b$ is the density of distribution of the L_{th} lowest order statistic T_L^n drawn from the distribution $g(c)$.

Proof: Based on the work of [37], for each procurer i, the symmetric equilibrium strategy is given by:

$$\beta^p(v_i) = E_{m,v}[\mathrm{T}_K^m | \mathrm{T}_K^m < v_i] \tag{20}$$

where $1 \le K \le m$ and T_K^m is the $\mathrm{K_{th}}$ highest order statistic of m procurers selected from the distribution $F(v)$. The probability that a procurer with v_i belongs those winners given the number m is given by:

$$\begin{aligned} Pr\left(\mathrm{T}_K^m \le v_i \,|\, m\right) &= \sum_{a=K}^{m} \Pr(v_i = v_a among\ m\ procurers) \\ &= \sum_{a=K}^{m} \binom{m}{a} \{F(v)\}^{m-a}\{1-F(v)\}^a \end{aligned} \tag{21}$$

According to equations (20) and (21), we can get:

$$\begin{aligned} \beta^p(v_i) &= E_{m,v}[\mathrm{T}_K^m | \mathrm{T}_K^m < v_i] \\ &= \frac{E_{m,v}[\mathrm{T}_K^m, \mathrm{T}_K^m < v_i]}{Pr(\mathrm{T}_K^m \le v_i)} \\ &= \frac{\int_{v_-}^{v_i} v \sum_{a=K}^{m} \binom{m}{a} \{F(v)\}^{m-a}\{1-F(v)\}^a dv}{Pr(\mathrm{T}_K^m \le v_i)} \end{aligned} \tag{22}$$

where $Pr(\mathrm{T}_K^m \le v_i) = \sum_{a=K}^{m} \binom{m}{a} \{F(v_i)\}^{m-a}\{1-F(v_i)\}^a$.

For each produce grower, the symmetric equilibrium strategy can likewise be proven using the same method.

The theorem shows that all participants have equilibrium strategies. To apply symmetric equilibrium strategies, m, n, K, and L may be announced. Because all elements of the model other than the private information are regarded as common knowledge for both growers and procurers. But the K and L are not determined until stopping the auction. Therefore, we can estimate K and L via exponential smoothing on the basis of historical data. The K_t and L_t are defined to be the number of selected procurers and selected growers in the t_{th} auction, respectively. The $\hat{K}_t$ and $\hat{L}_t$ represent the estimated number of selected procurers and growers in the t_{th} auction, respectively. Given α_K and α_L in the $(t+1)_{th}$ auction, respectively, K and L are given by:

$$\hat{K}_{t+1} = \alpha_K K_t + (1-\alpha_K)\hat{K}_t \tag{23}$$

$$\hat{L}_{t+1} = \alpha_L L_t + (1-\alpha_L)\hat{L}_t \tag{24}$$

Theorem 2: In the MNR mechanism, the system, including m procurers, n growers and auctioneer, can achieve individual rationality and weekly balanced budgets.

Proof: In our mechanism, all winning procurers, including the one who satisfies $i = K$, submit their payment, which is less than their valuation since the sealed bid price of procurer K is lower than valuation that ensures her utility is positive due to equilibrium strategies. Meanwhile, all winning growers including the one who satisfies $j = L$ also gain the money, which is higher than their bid price. Therefore, the MNR mechanism can realize individually rational.

In previous double auctions, strong BB is defined to require that total payments from procurers must be equal to total payments received by growers and the auctioneer should not lose or gain in terms of payoff. It is regarded as a weekly balanced budget when total payments received by growers are less than total payments from procurers. Since we have $\hat{v}_K \geq \hat{c}_L$ in the MNR mechanism, we can derive that $(\hat{v}_K - \hat{c}_L)Q^* \geq 0$, which implies that the auctioneer gains a nonnegative payoff. Thus, the system achieves a weekly balanced budget.

Lemma 1:

$$\frac{1}{\varphi(m+1)} \leq E[v_i - v_{i+1}] \leq \frac{1}{\omega(m+1)},\ i \in \{1, 2, \cdots m-1\} \tag{25}$$

$$\frac{1}{\delta(n+1)} \leq E[c_{j+1} - c_j] \leq \frac{1}{\gamma(n+1)},\ i \in \{1, 2, \cdots n-1\} \tag{26}$$

where $\varphi = max\{f(v) : v_- \leq v \leq v^+\}$, $\omega = \min\{f(v) : v_- \leq v \leq v^+\}$, $\delta = max\{g(c) : c_- \leq c \leq c^+\}$, $\gamma = min\{g(c) : c_- \leq c \leq c^+\}$, $\omega < \varphi$, and $\gamma < \delta$ and they are nonnegative constants.

Proof: If the case for growers $E[c_{j+1} - c_j]$ is proven, the case for procurers is similar.

The joint distribution of c_{j+1} and c_j is:

$$\begin{aligned} & g_{j,j+1}(x, y) \\ & = n(n-j)\, C_{n-1}^{j-1} G(x)^{j-1} g(x)\, g(y)\, (1 - G(y))^{n-j-1}\, dxdy, \end{aligned}$$

where $C_{n-1}^{j-1} = \frac{(n-1)!}{(j-1)!(n-j)!}$. Thus, the expectation can be given directly by:

$$\begin{aligned} & E\left[c_{j+1} - c_j\right] \\ & = n(n-j)C_{n-1}^{j-1} \\ & \quad \times \int_{c_-}^{c^+} \int_{c_-}^{y} (y-x)G(x)^{j-1} g(x) g(y)(1-G(y))^{n-j-1} dxdy \\ & = n(n-j)C_{n-1}^{j-1} \int_{c_-}^{c^+} g(y)(1 \\ & \quad - G(y))^{n-j-1} \left[\frac{(y-x)G(x)^j}{j} \Bigg|_{c_-}^{y} + \int_{c_-}^{y} \frac{G(x)^j}{j} dx \right] dy \\ & = n(n-j)C_{n-1}^{j-1} \int_{c_-}^{c^+} \frac{g(y)(1-G(y))^{n-j-1}}{j} \left[\int_{c_-}^{y} G(x)^j dx \right] dy \end{aligned}$$

we regard as $\int_{c_-}^{y} G(x)^j dx$ as $I(y)$. Then, the above integral equation can be rewritten as:

$$\begin{aligned} & \int_{c_-}^{c^+} \frac{g(y)(1-G(y))^{n-j-1} I(y)}{j} dy \\ & = \frac{-I(y)(1-G(y))^{n-j}}{j(n-j)} \Bigg|_{c_-}^{c^+} \\ & \quad + \int_{c_-}^{c^+} \frac{(1-G(y))^{n-j}}{j(n-j)} dI(y) \\ & = \int_{c_-}^{c^+} \frac{G(y)^j (1-G(y))^{n-j}}{j(n-j)} dy. \end{aligned}$$

Thus, we can have:

$$E\left[c_{j+1} - c_j\right] = C_n^j \int_{c_-}^{c^+} G(y)^j \left(1 - G(y)\right)^{n-j} dy$$

By integral transformation $u = G(y)$, the $E\left[c_{j+1} - c_j\right]$ can be rewritten as:

$$E\left[c_{j+1} - c_j\right] = C_n^j \int_0^1 g^{-1}(u)\, u^j \left(1 - u\right)^{n-j} du,$$

where $g^{-1}(u) = \frac{dG^{-1}(u)}{du}$ is the derivative of the inverse distribution function $G^{-1}(u)$ and is $g^{-1}(u) = \frac{1}{g(y)}$. Because $g(y)$ is continuous on a closed interval $[c_-, c^+]$, there is a maximum value of $\delta = \max\{g(y) : c_- \leq y \leq c^+\}$. Thus, we have:

$$\frac{1}{\delta} \leq g^{-1}(u) \leq \frac{1}{\gamma}.$$

Noting that:

$$\int_0^1 u^j (1-u)^{n-j} du = \frac{j!\,(n-j)!}{(n+1)!}$$

We have:

$$\frac{1}{\delta(n+1)} \leq E[c_{j+1} - c_j] \leq \frac{1}{\gamma(n+1)}$$

and the case for procurers is similar.

In our mechanism, the sum of efficiency loss $\varpi^{MNR}(K, L)$ is termed as Δ^{MNR}, which denotes the sacrificed trade value. Thus, if equation (11) holds, the loss is bounded by $\Delta^{MNR} \leq (v_1 - \hat{v}_K)X_K$; otherwise, the loss is bounded by $\Delta^{MNR} \leq (\hat{c}_L - c_1)Y_L$.

Maximum social welfare can be expressed as:

$$\begin{aligned} s^{MNR}(K, L) = {} & (\hat{v}_K - \hat{c}_L) * min\{\sum_{i=1}^{K} X_i, \sum_{j=1}^{L} Y_j\} \\ & + \sum_{i=1}^{K} (v_i - \hat{v}_K)X_i + \sum_{j=1}^{L} (\hat{c}_L - c_j)Y_j \end{aligned} \tag{27}$$

where $(\hat{v}_K - \hat{c}_L) * min\{\sum_{i=1}^{K} X_i, \sum_{j=1}^{L} Y_j\}$ is the auctioneer's payoff, $\sum_{i=1}^{K} (v_i - \hat{v}_K)X_i$ is procurers' utility, and $\sum_{j=1}^{L} (\hat{c}_L - c_j)Y_j$ is growers' utility.

Given K and L, the "inefficiency ratio" for the mechanism in market ir^{MNR} is given by:

$$ir^{MNR}(K, L) = \frac{E[\varpi^{MNR}(K, L)]}{E[s^{MNR}(K, L)]} \tag{28}$$

Based on lemma 1, theorem 3 is derived as follows:

Theorem 3: Assume that $0 < E[X], E[Y] < \infty$. Then, using the MNR mechanism, $ir^{MNR}(K,L) \le O(max\frac{1}{K+1},\frac{1}{L+1})$, where O is a constant.

Proof: If equation (12) holds and $Q^* = \sum_{i=1}^{K} X_i$, via Lemma 1, $\varpi^{MNR}(K,L)$ can be rewritten as:

$$E\left[\varpi^{MNR}(K,L)\right] \le E\left[\left(\hat{c}_L - c_1\right)Y_L\right]$$
$$= E\left[\left(\hat{c}_L - c_1\right)\right]E[Y] \le \frac{LE[Y]}{\gamma(n+1)}.$$

Similarly, $s^{MNR}(K,L)$ can be expressed as:

$$E\left[s^{MNR}(K,L)\right]$$
$$= E\left[(\hat{v}_K - \hat{c}_L)\sum_{i=1}^{K}X_i + \sum_{i=1}^{K}(v_i - \hat{v}_K)X_i + \sum_{j=1}^{L}\left(\hat{c}_L - c_j\right)Y_j\right]$$
$$\ge KE[X]E[(\hat{v}_K - \hat{c}_L)] + \frac{E\left[X_1 + (X_1+X_2) + \cdots + \sum_{i=1}^{K}X_i\right]}{\varphi(m+1)}$$
$$+ \frac{E\left[Y_1 + (Y_1+Y_2) + \cdots + \sum_{j=1}^{L}Y_j\right]}{\delta(n+1)}$$
$$= KE[X]E[(\hat{v}_K - \hat{c}_L)] + \frac{K(K+1)E[X]}{2\varphi(m+1)}$$
$$+ \frac{L(L+1)E[Y]}{2\delta(n+1)}.$$

Thus,

$$ir^{MNR}(K,L) = \frac{E\left[\varpi^{MNR}(K,L)\right]}{E\left[s^{MNR}(K,L)\right]} \le \frac{1}{L+1}\frac{2\delta}{\gamma}.$$

Also, if equation (11) holds and $Q^* = \sum_{j=1}^{L} X_j$, we have:

$$ir^{MNR}(K,L) = \frac{E\left[\varpi^{MNR}(K,L)\right]}{E\left[s^{MNR}(K,L)\right]} \le \frac{\frac{KE[X]}{\omega(m+1)}}{\frac{K(K+1)E[X]}{2\varphi(m+1)}}$$
$$= \frac{1}{K+1}\frac{2\varphi}{\omega}.$$

Theorem 3 implies that in our mechanism, if the participants competing in auctions have large enough, the inefficiency ratio converges to zero. However, the theorem does not answer the question of why when increasing the number of participants, the inefficiency ratio also converges to zero. Therefore, when K and L increase to infinity, the efficiency loss converges to zero. To derive market efficiency with m and n, the expected ratio of market inefficiency is defined as:

$$IR(m,n) = \sum_{K=1}^{m}\sum_{L=1}^{n} P(K,L)\, ir^{MNR}(K,L),$$

where $P(K,L)$ refers to the probability that K procurers trade with L growers successfully given that there are m procurers and n growers. Therefore, we need to prove $IR(\infty,\infty) = \lim_{m,n\to\infty} IR(m,n) \to 0$.

Theorem 4: The MNR mechanism is AsE in the case that $ir^{MNR}(K,L) \to 0$ when K and L increase to infinity as m and n go to infinity.

Proof: It is assumed that $\lim_{m,n\to\infty} P(K=\infty, L=\infty) \to 1$ in the MNR mechanism, which denotes the probability that K procurers and L growers go to infinity if m procurers and n growers increase to infinity, respectively. Let $P(K=m_0, L=n_0)$ be the probability that $K \le m_0$ *and* $L \le n_0$. Thus, we have:

$$IR(\infty,\infty) = \sum_{K=1}^{\infty}\sum_{L=1}^{\infty} P(K,L)\, ir^{MNR}(K,L)$$
$$= \sum_{K=1}^{m_0-2}\sum_{L=1}^{n_0-2} P(K,L)\, ir^{MNR}(K,L)$$
$$+ \sum_{K=m_0}^{\infty}\sum_{L=1}^{n_0-2} P(K,L)\, ir^{MNR}(K,L)$$
$$+ \sum_{K=1}^{m_0-2}\sum_{L=n_0}^{\infty} P(K,L)\, ir^{MNR}(K,L)$$
$$+ \sum_{K=m_0}^{\infty}\sum_{L=n_0}^{\infty} P(K,L)\, ir^{MNR}(K,L).$$

Based on Theorem 4, $ir^{MNR}(K,L) \le 1$, $IR(\infty,\infty)$ can be rewritten as follows:

$$IR(\infty,\infty)$$
$$\le P(K \le m_0 - 2, L \le n_0 - 2)$$
$$+ P(K \ge m_0 - 1, L \le n_0 - 2)$$
$$+ P(K \le m_0 - 2, L \ge n_0 - 1)$$
$$+ O\max\left(\frac{1}{m_0}, \frac{1}{n_0}\right)P(K \ge m_0 - 1, L \ge n_0 - 1).$$

Given any $\varepsilon > 0$, there is $O\max(\frac{1}{m_0}, \frac{1}{n_0}) \le \frac{\varepsilon}{2}$ with finite m_0 and n_0 as m and n increase to infinity. Hence, the fourth term in the RHS of the above inequality is bounded by $\frac{\varepsilon}{2}$ since $P(K \ge m_0 - 1, L \ge n_0 - 1) \le 1$.

Hence, we can deduce that if the number of both winning procurers and growers increases to infinity, the inefficiency ratio of market becomes zero. The MNR mechanism can achieve maximum social welfare and is AsE.

B. MULTIUNIT TRADE REDUCTION MECHANISM

In this paper, we develop the MTR mechanism to handle the problem of incentive compatibility. When the point Q^* is determined by (7), (8) or (9) and (10), the auctioneer lets the $K-1$ highest bid price procurers trade with the $L-1$ lowest bid price growers, with procurers paying $\hat{v}_K$ and growers receiving $\hat{c}_L$. Let Q' denote the sum of trade volume in the MTR mechanism, given by $Q' = \min\{\sum_{i=1}^{K-1} X_i, \sum_{j=1}^{L-1} Y_j\}$. The relationships between supply and demand should be checked to clear the market. Also, there are two cases: over-supply and over-demand, which are given by equation (29) and equation (30), respectively:

$$\sum_{j=1}^{L-1} Y_j \geq \sum_{i=1}^{K-1} X_i \tag{29}$$

$$\sum_{i=1}^{K-1} X_i \geq \sum_{j=1}^{L-1} Y_j \tag{30}$$

In conclusion, if equation (29) holds, then the MTR mechanism follows Rule 3.

Rule 3:

1. All procurers with indices $i \leq K-1$ win their demand quantity X_i at indiscriminate price $\hat{v}_K$
2. All growers with indices $j \leq L-1$ trade at price $\hat{c}_L$. The auctioneer ranks all winning growers who satisfy indices $j < L$ based on the quantity of their supplies, that is, the larger supply quantity one grower owns, the higher ranking for the grower.
3. Let $r_{j'}$ denote the ranking of the grower j'. In ascending order, all winning growers' rankings are given by: $r_{1'} \leq r_{2'} \leq \cdots \leq r_{(L-1)'}$.
4. Each grower j' sells at least a "basic" quantity $\bar{q}_{j'} =$ fix $(\frac{Y_{j'} \sum_{i=1}^{K-1} X_i}{\sum_{j'=1'}^{(L-1)'} Y_{j'}})$. The remaining demand is given by $RD = \sum_{i=1}^{K-1} X_i - \sum_{j=1}^{L-1} \bar{q}_j$, which is distributed among all winning growers based on their supply volumes and rankings. Let $q_{j'}$ be the "final" allocated quantity of grower j'. Then, $q_{j'}$ is given by:

$$q_{j'} = \begin{cases} min\left\{Y_{j'}, \bar{q}_{j'} + \left[RD - \sum\limits_{a'=(j+1)'}^{(L-1)'} (q_{a'} - \bar{q}_{a'})\right]\right\}, \\ \quad 1' \leq j' \leq (L-2)' \\ min\left\{Y_{(L-1)'}, \bar{q}_{(L-1)'} + RD\right\}, \\ \quad j' = (L-1)' \end{cases}$$

where $q_{j'}$ is an integer and satisfies the inequation $\bar{q}_{j'} \leq q_{j'} \leq Y_{j'}$.

If equation (30) holds, then the MTR mechanism follows Rule 4.

1. All growers with indices $j \leq L-1$ win their supply quantity Y_j at indiscriminate price $\hat{c}_L$.
2. All procurers with indices $i \leq K-1$ trade at price $\hat{v}_K$. The auctioneer ranks all winning procurers who satisfy indices $i \leq K-1$ based on the quantity of their demands, that is, the more demand a procurer has, the higher her ranking.
3. Let $r_{i'}$ denote the ranking of procurer i'. In ascending order, all winning procurers' rankings are given by $r_{1'} \leq r_{2'} \leq \cdots \leq r_{(K-1)'}$.
4. Each procurer i' sells at least a "basic" quantity $\bar{q}_{i'} =$ fix$(\frac{X_{i'} \sum_{j=1}^{L-1} Y_j}{\sum_{i'=1'}^{(K-1)'} X_{i'}})$. The remaining supply is given by $RS = \sum_{j=1}^{L-1} Y_j - \sum_{i=1}^{K-1} \bar{q}_i$, which is distributed among all winning growers based on their supply volumes and rankings. Let $q_{i'}$ be the "final" allocated quantity of grower i'. Then, $q_{i'}$ is given by:
5.

$$q_{i'} = \begin{cases} min\left\{X_{i'}, \bar{q}_{i'} + \left[RS - \sum\limits_{b'=(i+1)'}^{(K-1)'} (q_{b'} - \bar{q}_{b'})\right]\right\}, \\ \quad 1' \leq i' \leq (K-2)' \\ min\left\{X_{(K-1)'}, \bar{q}_{(K-1)'} + RS\right\}, \\ \quad i' = (K-1)' \end{cases}$$

where $q_{i'}$ is an integer and satisfies the inequation $\bar{q}_{i'} \leq q_{i'} \leq X_{i'}$

Since the total trade volume is $Q' = \min\{\sum_{i=1}^{K-1} X_i, \sum_{j=1}^{L-1} Y_j\}$, the auctioneer takes the total trade surplus given by:

$$\begin{aligned} U_i^{MTR} &= (\hat{v}_K - \hat{v}_i) * min\{X_i, q_i\}, \quad i \in \{1, 2, \ldots, K-1\} \\ U_j^{MTR} &= (\hat{c}_j - \hat{c}_L) * min\{Y_j, q_j\}, \quad j \in \{1, 2, \ldots, L-1\} \\ U_{eo}^{MTR} &= (\hat{v}_K - \hat{c}_L) * min\{\sum_{i=1}^{K-1} X_i, \sum_{j=1}^{L-1} Y_j\} \end{aligned} \tag{31}$$

Then, each procurer and grower's utilities are given as follows:

When following Rule 3, the total utility of procurers is $\sum_{i=1}^{K-1} (v_i - v_K) X_i$ and the total utility of growers is $\sum_{j=1'}^{(L-1)'} (c_L - c_j) q_j$. When following Rule 4, the total utility of procurers is $\sum_{i=1'}^{(K-1)'} (v_i - v_K) q_i$, and that of growers is $\sum_{j=1}^{L-1} (c_L - c_j) Y_j$.

Like the MNR mechanism, the perturbation technique is introduced to break the tie and determine a final solution. Hence, the above mechanism is summarized as follows:

1. Gather all sealed bids from participants.
2. Rank procurers' bid prices as $\hat{v}_1 \geq \hat{v}_2 \geq \cdots \geq \hat{v}_m$, and growers' bid prices as $\hat{c}_1 \leq \hat{c}_2 \leq \cdots \leq \hat{c}_n$.
3. Clear the produce market at the point Q^* where $\hat{v}_K \geq \hat{c}_L$ and $\hat{v}_{K+1} < \hat{c}_{L+1}$.
4. Remove all participants who excluded from auction (i.e., procurers with indices $i \geq K$ and growers with indices $j \geq L$).
5. Follow Rule 3 if equation (29) holds; otherwise, follow Rule 4.

The best approach to understand the MNR mechanism is to take a simple instance (see Table 1). In this example, K = L =4, $\hat{v}_k = 9$, $\hat{c}_L = 6$. Since $\sum_{j=1}^{L-1} Y_j = 13 < \sum_{i=1}^{K-1} X_i = 17$, inequality (30) holds, and the trade quantity is 13. According to rule 2, we can drive each procurer's basic volume: $\bar{q}_{1'} =$ fix$(\frac{7*13}{17}) = 5$(for procurer 1), $\bar{q}_{2'} =$ fix $\left(\frac{6*13}{17}\right) = 4$ (for procurer 3) , $\bar{q}_{3'} =$ fix$(\frac{4*13}{17}) = 3$(for procurer 2). This remaining demand is derived by $RS = \sum_{j=1}^{L-1} Y_j - \sum_{i=1}^{K-1} \bar{q}_i = 1$. Then, we calculate the volume obtained by the winning procurer with the lowest ranking (i.e., procurer 2): $\mathrm{q}_{3'} = \mathrm{min}\{\mathrm{X}_{3'}, \bar{q}_{3'} + \mathrm{RS}\} = 4$. Similarly, $q_{2'} = min\{X_{2'}, 4+0 = 4\}$, $q_{1'} = min\{X_{1'}, 5+0 = 5\}$.

TABLE 2. An example of MTR mechanism.

Produce market	
Procurers:$(X_i, \hat{v}_i; r_{i\prime})$	Growers: $(Y_j, \hat{c}_j)$
$(7, 12; r_{1\prime})$	(2, 3)
$(4, 11; r_{3\prime})$	(8, 4)
$(6, 10; r_{2\prime})$	(3, 5)
(1, **9**)	(7, **6**)
(5, 7)	(3, 8)
(6, 3)	(5, 10)

Theorem 5: In the MNR mechanism, we can realize IC, weekly BB, and IR.

If procurer K among m procurers and grower L among n growers make successful trades, the total efficiency loss, including two parts, is termed as:

$$\varpi^{MTR}(K, L) = \left(v_i - c_j\right)\left(Q^* - Q'\right) + \Delta^{MTR} \tag{32}$$

where $\left(v_i - c_j\right)\left(Q^* - Q'\right)$ denotes the auctioneer's efficiency loss, and Δ^{MTR} is the sacrificed trade value in the MTR mechanism. Since MTR requires sacrificing a trade volume pair, if equation (30) holds, the efficiency loss is bounded by $\Delta^{MTR} \leq (v_1 - v_K)Y_L$; otherwise, the efficiency loss is bounded by $\Delta^{MTR} \leq (c_L - c_1)X_K$.

Maximum social welfare can be expressed as:

$$\begin{aligned} s^{MTR}(K, L) = (v_K - c_L) * min\{\sum_{i=1}^{K} X_i\}, \sum_{j=1}^{L} Y_j \\ + \sum_{i=1}^{K} (v_i - v_K)X_i \\ + \sum_{j=1}^{L} (c_L - c_j)Y_j \end{aligned} \tag{33}$$

where $(v_K - c_L) * min\{\sum_{i=1}^{K} X_i\}, \sum_{j=1}^{L} Y_j$ is the auctioneer's payoff, $\sum_{i=1}^{K} (v_i - v_K)X_i$ is procurers' utility, and $\sum_{j=1}^{L} (c_L - c_j)Y_j$ is growers' utilities.

Given K and L, the market "inefficiency ratio" for the MTR mechanism ir^{MTR} is written as:

$$ir^{MTR}(K, L) = \frac{E[\varpi^{MTR}(K, L)]}{E[s^{MTR}(K, L)]} \tag{34}$$

Theorem 6: In the MTR mechanism, $ir^{MTR}(K, L) \leq \Omega\left(max\left\{\frac{1}{K}, \frac{1}{L}\right\}\right)$, where Ω is a constant.

The proof process is like that of Theorem 3. In case I, if equation (29) holds, then

$$ir^{MTR}(K, L) \leq \max\left\{\frac{1}{K}, \frac{1}{L}\frac{2\delta E[X]}{\gamma E[Y]}\right\}.$$

In case I, if equation (30) holds, then:

$$ir^{MTR}(K, L) \leq \max\left\{\frac{1}{K}\frac{E[Y]}{E[X]}, \frac{1}{K}\frac{2\varphi E[Y]}{\omega E[X]}\right\} = \frac{1}{K}\frac{2\varphi E[Y]}{\omega E[X]}.$$

In case II, if equation (29) holds, then:

$$ir^{MTR}(K, L) \leq \max\left\{\frac{1}{L}\frac{E[X]}{E[Y]}, \frac{1}{L}\frac{2\delta E[X]}{\gamma E[Y]}\right\} = \frac{1}{L}\frac{2\delta E[X]}{\gamma E[Y]}.$$

In case II, if equation (30) holds, then:

$$ir^{MTR}(K, L) \leq \max\left\{\frac{1}{L}, \frac{1}{K}\frac{2\varphi E[Y]}{\omega E[X]}\right\}.$$

Thus, we have inequation $ir^{MTR}(K, L) \leq \Omega\left(max\left\{\frac{1}{K}, \frac{1}{L}\right\}\right)$.

Like Theorem 3, Theorem 6 dose not solve the problem of whether market efficiency increases as the number of participants rises. Hence, market efficiency requires further discussion.

Theorem 7: The MTR mechanism is AsE in the case where $ir^{MNR}(K, L) \to 0$ when K and L go to infinity as m and n converge to infinity.

The proof of AsE for the MTR mechanism is similar with that of the MNR mechanism. Hence, we find that when the inefficiency ratio converges to zero, the trading system can realize maximum social welfare.

V. IMPLEMENTATION AND EXPERIMENTS

A. NUMERICAL ANALYSIS

Our experiments use cut flowers as an example of a produce trading system. The winner determination problem with cut flowers is solved by applying MNR and MTR mechanisms. In e-commerce platforms, operators are regarded as auctioneers. In the trading system, plenty of produce procurers compete for cut flowers provided by many growers who plant flowers for cutting. It is assumed that all cut flowers can meet procurers' quality and other nonmonetary attribute requirements. When the auction begins, both procurers and growers submit their bids to e-commerce platforms according to the formulated auction mechanism. After auction stops, the auctioneer clears the produce trading markets according to the auction mechanism.

For the sake of simplicity, we propose that the number of both procurers and growers taking part in auctions is no more than 150. Both the procurers' value $v_i (i = 1, 2, \ldots, m)$ and growers' value $c_j (j = 1, 2, \ldots, n)$ follow a continuous distribution in intervals [100,150] and [90,140], respectively. Meanwhile, X_i and Y_j also follow the distribution in intervals [4, 10] and [8, 14], respectively. A pair of m procurers and growers is expressed as (m, n). For our experiments, we test eight groups of indicators: 1) K and L; 2) total trade quantity; 3) auctioneer payoff; 4) procurer utility; 5) grower utility; 6) social welfare achieved; 7) maximum social welfare; and 8) allocation efficiency. All solutions are obtained from 5000 randomly generated scenarios and average values are reported.

Performance of the MNR mechanism is compared with the MTR mechanism when selecting the pairs (30,30), (70,70), and (100,100) presented in TABLE 3. In the MNR mechanism, to guarantee the participants' positive utility in an auction, each procurer's bid price must be lower than valuation, and each grower's bid price must be higher than valuation.

TABLE 3. Comparison of the MNR and MTR mechanism.

Various range	K/L	Total trade quantity	Auctioneer' payoff	Procurers/growers' utility	Realized social welfare	Maximal social welfare	Allocative efficiency
30 procurers and 30 growers							
MTR	21.41/15.64	146.11	266.68	2513.80/1694.33	4474.81	4579.17	97.72%
[1, 10]	19.62/13.96	126.57	223.83	2161.38/1463.72	3848.94	4657.48	82.64%
[10, 20]	12.56/7.73	34.75	61.24	561.21/374.85	997.22	4593.39	21.71%
[20, 30]	5.47/2.83	5.79	9.49	85.37/57.54	152.41	4646.82	3.28%
70 procurers and 70 growers							
MTR	49.24/35.31	345.94	296.10	6232.08/4660.20	11188.38	11285.43	99.14%
[1, 10]	46.91/32.38	296.32	256.11	5397.83/4036.40	9689.35	11302.17	85.73%
[10, 20]	32.64/19.21	82.27	76.73	1582.54/1176.72	2841.02	11291.83	25.16%
[20, 30]	16.78/5.74	15.64	25.93	546.24/415.64	987.81	11315.23	8.73%
100 procurers and 100 growers							
MTR	70.23/50.30	517.81	326.67	9317.63/6762.56	16406.86	16500.91	99.43%
[1, 10]	66.81/45.37	426.73	289.94	8325.51/6023.11	14638.56	16418.31	89.16%
[10, 20]	45.70/27.28	118.49	108.68	2985.42/2152.13	5246.23	16523.58	31.75%
[20, 30]	22.59/9.04	23.78	44.76	1283.33/915.85	2243.94	16487.49	13.61%

TABLE 4. Impact of the number of procurers and growers.

(m, n)	K/L	Total trade quantity	Auctioneer' payoff	Procurers/growers' utility	Realized social welfare	Maximal social welfare	Allocative efficiency
(10,10)	6.67/5.15	66.79	247.62	1165.83/874.40	2287.85	2354.72	97.16%
(30,30)	21.41/15.64	146.11	266.68	2513.80/1694.33	4474.81	4579.17	97.72%
(50,50)	32.41/25.53	243.75	276.49	4755.73/3017.04	8049.26	8156.10	98.69%
(70,70)	49.24/35.31	345.94	296.10	6232.08/4660.20	11188.38	11285.43	99.14%
(100,100)	70.23/50.30	517.81	326.67	9317.63/6762.56	16406.86	16500.91	99.43%

TABLE 5. Impact of the number of growers.

(m, n)	K/L	Total trade quantity	Auctioneer' payoff	Procurers/growers' utility	Realized social welfare	Maximal social welfare	Allocative efficiency
(50,10)	10.87/7.15	114.85	307.62	1093.43/2407.91	3808.96	3874.43	98.31%
(50,30)	22.33/17.62	163.71	288.68	3113.51/2874.63	6276.82	6370.46	98.53%
(50,50)	32.41/25.53	243.75	276.49	4755.73/3017.04	8049.26	8156.10	98.69%
(50,70)	38.34/31.10	328.72	286.10	5972.48/2952.18	9210.76	9300.04	99.04%
(50,100)	41.13/35.30	359.37	295.67	7017.83/2592.16	9905.66	9982.52	99.23%

Note that [a, b] represents the MNR mechanism in which procurers' bid prices are obtained by lowering their valuation following continuous uniform distribution in the interval [a, b] and growers' bid prices are obtained by increasing their valuation following continuous uniform distribution in the interval [a, b]; First, we can take different value for [a, b], such as [1, 10], [10, 20], [20, 30]. shows that in the experiment involving 30 procurers and 30 growers, performance of the MNR mechanism decreases from 82.64% to 21.71% to 3.28% in eight groups of indicators with interval increasing from [1, 10] to [10, 20], and to [20, 30].. As the value for [a, b] increases, the performance of MNR mechanism is getting worse in each experiment. Hence, the more complex the bid strategy, the more trading loss. The allocative efficiencies of MNR mechanism are increasing in the interval [1, 10], [10, 20] and [20, 30] with the number of growers and procurers increasing. As the number of participants increases, the impact of the range interval becomes smaller. We have an inference that when the number of participants is small, it is suitable to announce MTR mechanism and when the number is bigger enough, MNR mechanism should be announced since the process is simpler. Therefore, the MNR mechanism is equal to the MTR mechanism when the number of participants approaches infinity. The more participants e-commerce platform attracts, the simpler the implemented mechanism is. To alleviate repeated experiments, the experiments considered and analyzed only the MTR mechanism.

As shown in TABLE 4, all indicators monotonically increase according to the increase in the number of procurers and growers, such that K rises from 6.67 to 70.23 and L rises from 5.15 to 50.30. The increment of L's increase is smaller than that of K because the expected number of X_i is smaller than that of Y_j. Hence, more procurers are successful trading in double auctions. Maximal social welfare, platform payoff, growers' utility, procurers' utility, total trade volume, and AE increase monotonically as the number of growers and procurers increases. Therefore, when the number of participants approaches infinity, the inefficiency ratio approaches zero and each participant's utility is the biggest. Moreover, TABLE 4 presents that AE increases as the participants increases; that is, the ratio converges to one and the inefficiency ratio converges to zero, which proves Theorem 7. The more people participate in the auction platform, the more profitable the platform will be.

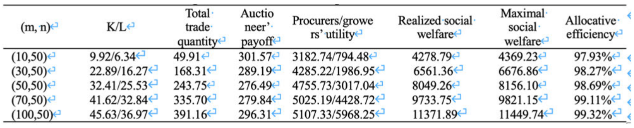
TABLE 5 displays the impact of the number of growers when setting the number of procurers at 50. As the number of growers increases, not all indicators monotonically increase like in the preceding TABLE 4. The payoff of e-commerce platform (i.e., auctioneer) decreases from 307.62 to 276.49 when the number of growers increases from 10 to 50, and finally increases to 295.47 when the number of growers rises to 100. The difference between price v_K and c_L is decreasing gradually, which leads to the payoff of auctioneers reducing according to equation (31); the reason for auctioneer's payoff increasing after going to nadir is that when the number of growers increasing largely enough, the difference of trade price will not decrease sharply, but the total trade quantity Q will rise constantly, which leads to a payoff increment for auctioneer. The auctioneer's payoff decreases since the trade price of growers c_L is close to the trade price of procurers v_K. Thus, the difference between price v_K and c_L is decreasing gradually, which leads to the payoff of auctioneers reducing according to equation (31); the reason for auctioneer's payoff increasing after going to nadir is that when the number of growers increasing largely enough, the difference of trade price will not decrease sharply, but the total trade quantity Q' will rise constantly, which leads to a payoff increment for auctioneer. In comparison, growers' utility decrease from 3,017.04 to 2,407.91. The number of winning growers increases from 7.15 to 17.62 when the number of growers participated in the double auction go up from 10 to 30, leading to an increase of growers' utility. Moreover, as the number of growers involved in the bilateral market increases to 100, the oversupply of produce is created, which introduces a reduction of the trade price of growers. Hence, the utility of growers has decreased. Although the utility of growers has decreased, allocative efficiency has increased. Reduction of the trade price of growers leads to more trade volume and the increase of allocative efficiency. When the auctioneer attracts more growers to participant, the realized social welfare will be more.

Similarly, in TABLE 6, the payoff of auctioneers and the utility of growers do not monotonically increase, and others monotonically increase, given the same reason as the above analysis for Table 5. Compared with TABLE 5, the impact of the number of procurers has more significant impacts on the produce market. For example, as the number of procurers increases, K increases from 9.92 to 45.63 and L increases from 6.34 to 36.97, which implies that more participants win. since procurers' value that follow a continuous distribution in intervals [100,150] is more than [90,140] that growers' value follow, the impact of the number of procurers has more significant impacts on the produce market. Moreover, the total trade quantity increases from 49.91 to 391.16 in TABLE 6, while the volume increases from 114.85 to 359.37 in TABLE 5. This change of data proves the impact of the number of procurers has more significant impacts on trade quantity, which is the reason that the continuous distribution the procurers' value follow is more than that of growers.

TABLE 7 illustrates the impact of value range, considering the pair (50,50). Note that [20, 100]/ [10, 90] represents that both the value of procurers and the value of growers follows a continuous uniform distribution. When the value ranges of both procurers and growers are narrowed, K, L, total trade quantity, and AE monotonically increase. The reason for increases in all indicators is that narrowing the value ranges accepts more procurers and growers to satisfy (7) and (8), or (9) and (10) when the number of both procurers and growers is constant. When the value ranges of both procurers and growers are same, the trade can obtain maximal trade quantity and AE. Besides, maximum social welfare, auctioneer's payoff, and the utility of procurers and growers monotonically decrease. Maximum social welfare is monotonically decreased since the value of $(v_K - c_L)$, $(v_i - v_K)$, and $(c_L - c_j)$ decreases when the value ranges narrow, even if total trade quantity increases. The auctioneer should attract the people whose value for produce are same.

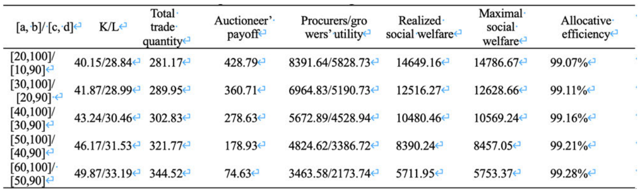
Finally, an exponential smoothing approach is adapted to estimate K and L according to equation (23) and (24). For analysis of the α_K and α_L, we take this experiment of 100 procurers and 100 growers. Then, we suppose that in MNR mechanism, procurers' bid prices are determinized by lowering their valuation and growers' bid prices are determined by increasing continuous uniform distribution in the interval [1, 10]. Suppose that $\hat{K}_t$ and $\hat{L}_t$ is equal to that of MTR mechanism. As shown in TABLE 8, the exponential smoothing improves K and L. As the value of α_K and α_L increases, the allocative efficiency slightly reduces. According to equation (23) and (24), we have a conclusion that the real data have more impact on allocative efficiency. Moreover, the influence of α_K is bigger than that of α_L. It may be because the costs of growers and values of procurers follow different continuous distribution in intervals and the continuous distribution the procurers' value follow is more than that of growers.

TABLE 6. Impact of the number of procurers.



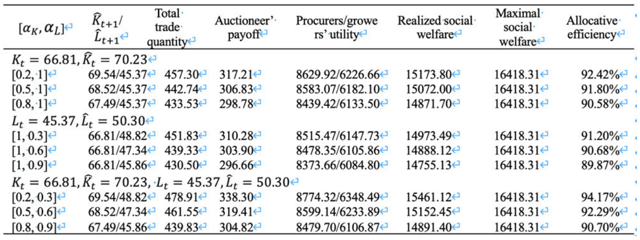
(m, n)	K/L	Total trade quantity	Auctioneer' payoff	Procurers/growers' utility	Realized social welfare	Maximal social welfare	Allocative efficiency
(10,50)	9.92/6.34	49.91	301.57	3182.74/794.48	4278.79	4369.23	97.93%
(30,50)	22.89/16.27	168.31	289.19	4285.22/1986.95	6561.36	6676.86	98.27%
(50,50)	32.41/25.53	243.75	276.49	4755.73/3017.04	8049.26	8156.10	98.69%
(70,50)	41.62/32.84	335.70	279.84	5025.19/4428.72	9733.75	9821.15	99.11%
(100,50)	45.63/36.97	391.16	296.31	5107.33/5968.25	11371.89	11449.74	99.32%

TABLE 7. Impact of the value range.



[a, b]/ [c, d]	K/L	Total trade quantity	Auctioneer' payoff	Procurers/growers' utility	Realized social welfare	Maximal social welfare	Allocative efficiency
[20,100]/ [10,90]	40.15/28.84	281.17	428.79	8391.64/5828.73	14649.16	14786.67	99.07%
[30,100]/ [20,90]	41.87/28.99	289.95	360.71	6964.83/5190.73	12516.27	12628.66	99.11%
[40,100]/ [30,90]	43.24/30.46	302.83	278.63	5672.89/4528.94	10480.46	10569.24	99.16%
[50,100]/ [40,90]	46.17/31.53	321.77	178.93	4824.62/3386.72	8390.24	8457.05	99.21%
[60,100]/ [50,90]	49.87/33.19	344.52	74.63	3463.58/2173.74	5711.95	5753.37	99.28%

TABLE 8. Impact of the α_K and α_L.



$[\alpha_K, \alpha_L]$	$\hat{K}_{t+1}$/ $\hat{L}_{t+1}$	Total trade quantity	Auctioneer' payoff	Procurers/growers' utility	Realized social welfare	Maximal social welfare	Allocative efficiency
$K_t = 66.81, \hat{K}_t = 70.23$							
[0.2, 1]	69.54/45.37	457.30	317.21	8629.92/6226.66	15173.80	16418.31	92.42%
[0.5, 1]	68.52/45.37	442.74	306.83	8583.07/6182.10	15072.00	16418.31	91.80%
[0.8, 1]	67.49/45.37	433.53	298.78	8439.42/6133.50	14871.70	16418.31	90.58%
$L_t = 45.37, \hat{L}_t = 50.30$							
[1, 0.3]	66.81/48.82	451.83	310.28	8515.47/6147.73	14973.49	16418.31	91.20%
[1, 0.6]	66.81/47.34	439.33	303.90	8478.35/6105.86	14888.12	16418.31	90.68%
[1, 0.9]	66.81/45.86	430.50	296.66	8373.66/6084.80	14755.13	16418.31	89.87%
$K_t = 66.81, \hat{K}_t = 70.23, L_t = 45.37, \hat{L}_t = 50.30$							
[0.2, 0.3]	69.54/48.82	478.91	338.30	8774.32/6348.49	15461.12	16418.31	94.17%
[0.5, 0.6]	68.52/47.34	461.55	319.41	8599.14/6233.89	15152.45	16418.31	92.29%
[0.8, 0.9]	67.49/45.86	439.83	304.82	8479.70/6106.87	14891.40	16418.31	90.70%

B. MANAGERIAL IMPLICATIONS

There are some results can be summarized into managerial implications for procurers, growers and auctioneers.

First, MUDA mechanisms determine dynamic prices for produce in order to gain more utility for trading systems. Moreover, AE can achieve more than 99%, which implies that social welfare can be further maximized. The result of the MTR mechanism can encourage participants to take part in produce auctions. Hence, superfluous capability can be collected and fully utilized and the carbon emission of production can be reduced significantly.

Second, compared to cases in which supply and demand are balanced, over-supply or over-demand may improve the payoff of the e-commerce platform, as well as increase the utility of minority participants. Obviously, in MUDA mechanisms, an imbalance between supply and demand is created to effectively improve the utilities of e-commerce platform and some participants. Thus, this situation will harm the utilities of the most participants and further prevent them from participating auctions.

Finally, the overlap between value range of procurers and growers greatly influences those indicators. The larger the overlap, the more social welfare, auctioneer's payoff, and utility of procurers and growers can be realized. On the contrary, the smaller the overlap, the larger total trade quantity can be realized. Although some indicators do not increase, more participants should be involved, which can improve the social welfare.

VI. CONCLUSION

To promote the development of the produce market and reduce the carbon emission of agricultural supply chain, agricultural supply chain trading has widely received people's attention. Motivated by the carbon reduction policies, high trading cost, long trading time and complicate bidding strategies in bilateral produce market, this paper proposes two MUDA mechanisms to deal with produce trading problems in bilateral markets where growers can share superfluous produce. First, we analyze the necessity and profits from applying MUDA mechanisms in produce trading markets based on challenges faced by previous methods when existing imbalances between demand and supply. Second, we introduce two MUDA mechanisms to solve produce trading problems by an e-commerce platform. Such two mechanisms effectively distribute any kinds of produce as long as ''one unit'' is defined. Bid strategies for both procurers and growers are provided by the above properties. Last but not least, with the number of participants increasing, the two MUDA mechanisms finally generate the same outcome from a quantitative perspective. Finally, we verify the effectiveness and robustness of the two mechanisms by numerical study. Our paper's contributions are mainly two-points: (1) To the best of our knowledge, this work is the first to introduce two MUDA mechanisms to realize the maximum value of ASCT. The proposed mechanism can effectively promote the profit of produce providers and the utility of customers and supplement the blank of bilateral auction application research. Our study provides one single viewing for others to research ASCT. (2) Some key findings have been obtained by comparing the performance of MNR mechanism with that of MTR mechanism. Such findings provide insightful views for produce providers and customers and verify the effectiveness and applicability of the proposed approach. The proposed mechanisms can effectively reduce the carbon emission, trading cost and time and provide one better approach to trade for growers and procurers.

This paper serves as effort to design mechanisms for produce trading systems. Since produce trading systems are complex in real-trading application, our approach has some limitations. Future works should overcome our limitations and are extended in several directions. First, this paper only considers one single attribute, that is price, for bilateral produce markets. But with the development of economic and living, the nonmoney attributes of produce get more focus. It is challenging for produce trading how to incorporate more non-price attributes into considerations in MUDA mechanisms. Thus, considering the multi-attribute double auction of produce will be an issue worthy of further exploration in the future. Second, the proposed approaches are assumed that all the participant only take once auction and make all trading demand. However, in reality, many participants will submit bids in multiple rounds and they may adjust their bidding strategies via previous auction outcomes. For example, procurers may intentionally modify their cost functions by learning previous auction results for more benefit. A more complex mechanism is required to apply a case when learning from previous auction outcomes. Hence, Multi-rounds double auction mechanism will be an interesting research topic to consider bidder's behavior. Third, our mechanisms only can reduce the transaction cost and time, not consider the transportation cost. Since growers are distributed all over the country, production logistics play an indispensable role in the produce market. For example, if growers are located in different cities, produce trading could generate significant logistics costs that then impact participants' utilities. Thus, in future research, incorporating the transportation cost between growers and procurers into our model makes the model more realistic. Finally, the proposed approach has assumed there is one type of produce to exchange. When all produce is integrated by an e-commerce platform, growers and procurers may need more than one type of produce at the same time. Therefore, a combination MUDA mechanism should be designed to solve mixture trading problems types for produce.

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YANG ZHANG received the B.Eng. degree in industrial engineering from the Hubei University of Automotive Technology, Shiyan, China, in 2019. He is currently pursuing the master's degree with the Department of Management Science and Engineering, Jinan University, Guangzhou, China.

His research interests include produce allocation and auction theory.

HUIBING CHENG received the Ph.D. degree from Management School, Jinan University, Guangdong, China. He is currently an Associate Professor with the Department of Transportation and Logistics, Guangzhou Railway Polytechnic, Guangdong. He has published several journal articles, such as *Transportation Research Part E: Logistics and Transportation Review*, *Applied Mathematical Modelling*, *Transportmetrica A: Transport Science*, *Computers and Industrial Engineering*, and *Sustainability*. His major research interests include ferry service operations, market design, and game theory.

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