Crowdshipping platform as an intermediary: Auction-based mechanism design for order allocation and payment schemes

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1 INTRODUCTION

The fast-growing e-commerce has brought about an explosive increase in parcel delivery volume. In this context, crowdshipping has emerged as a novel service paradigm to move parcels by utlizing the latent capacity of traveling "crowd" from enormous traveling trips in the transportation system. To ensure the sustainability of crowdshipping platforms, the crucial challenge lies in matching orders to crowd carriers so that the payments are differentiated, the platform gains nonnegative profits and system efficiency is achieved. However, heterogeneity among individual crowd carriers exists and their preferences are not readily available. This motivates us to devise auction mechanisms for order allocation and payment of the crowdshipping platform.

In the crowdshipping system, crowd carriers report their trip information (e.g., origin, destination, and available routes) to the platform and are recommended for some orders for each route. Then travelers select their intended orders and submit route-based bids based on the detour costs. The platform takes carriers' strategic behavior into account and applies the classic Vickrey-Clarke-Groves (VCG) payment scheme to ensure incentive compatibility, individual rationality, and system efficiency (Krishna, 2009). For the sake of computational efficiency, we design an approximately efficient mechanism which retains most of the economic properties with theoretical guarantee. The profit gained by the platform can be lower bounded in both mechanisms. Extensive numerical experiments are conducted to test the performance of the proposed mechanisms and generate policy implications and managerial insights.

This work is among the first to investigate the order allocation and payment schemes in a crowdshipping system through the lens of mechanism design and auction theory. The crowdshipping platform is designed as an intermediary sitting between orders and travelers, which seeks the services provided by either the crowd carrier or the outsourced dedicated carrier. The auction mechanisms and results will be elaborated on in the subsequent sections.

2 AUCTION MECHANISMS

Consider an environment where a collection of distinct orders $J = \{1, \dots, |J|\}$ are to be delivered. We index each order in the set J by the letter j and the corresponding fulfillment fee of third-party logistics (3PL) by r_j. A central platform has already collected the information and the service fare f_j of these orders from customers. There is a set of heterogeneous crowd carriers $I = \{1, \dots, |I|\}$ participating in the crowdshipping system. These crowd carriers have their own trip purposes, but intend to fulfill some delivery tasks of the orders en route for additional incomes. The crowdshipping platform serves as an intermediary, sitting between the delivery demand and suppliers. In other words, it seeks the delivery services by either the crowd carriers or dedicated couriers from 3PL. Given the high degree of heterogeneity among the crowd carriers, the platform adopts a sealed-bid auction to recruit occasional carriers from the crowd, as a substitute or supplementary to dedicated couriers.

Bidding for tens of thousands of individual orders in the wholesale market is impractical for crowd carriers. The available routes connecting the origin-destination (OD) pairs of crowd carriers are much more manageable and are what closely relates to crowd carriers' trip information, which motivates the use of route-based bids. Bidding on the orders associated with the routes also vastly simplifies the bidding process of travelers and facilitates the management of the auctioneer. Given crowd carriers may wish to carry multiple tasks during their trip, we allow crowd carriers to submit package bids (i.e., bundles). The framework and decision makings involved in the crowdshipping system are illustrated in Fig. 1.

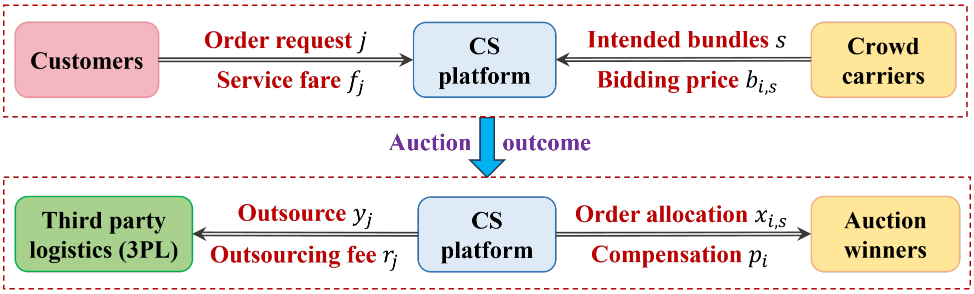

Figure 1 – *Auction setting in the crowdshipping system.*

2.1 The Winner Determination Problem (WDP)

As mentioned earlier, the crowd carriers can submit multiple route-based bids for the intended bundles in the sealed-bid auction. In other words, they are allowed to bid on alternative routes and the package bids on bundles of orders for each route. This constitutes a combinatorial procurement auction where the platform (also the auctioneer) seeks crowdshipping service and allocates orders to crowd carriers (also the bidders) (Cramton *et al.*, 2006). The optimal order allocation problem can be formulated as an integer program IP (1):

$$\min_{x_{i,s},y_j} \quad \sum_{i\in I}\sum_{s\in S_i} b_{i,s}x_{i,s} + \sum_{j\in J} r_j y_j \tag{1a}$$

$$\text{s.t.} \quad \sum_{s\in S_i} x_{i,s} \le 1 \qquad \forall i \in I \tag{1b}$$

$$\sum_{i\in I}\sum_{s\ni j, s\in S_i} x_{i,s} + y_j = 1 \qquad \forall j \in J \tag{1c}$$

$$x_{i,s} \in \{0,1\} \qquad \forall i \in I, s \in S_i \tag{1d}$$

$$y_j \in \{0,1\} \qquad \forall j \in J \tag{1e}$$

The above optimization problem is also referred to as the winner determination problem (WDP) for the combinatorial procurement auction in the crowdshipping system. The objective function (1a) is to minimize the total cost for the delivery of the tasks. Constraint (1b) restricts that each crowd carrier is allocated at most one bundle. Constraint (1c) ensures that the orders are either served by the crowd carriers or by the dedicated couriers from 3PL. The binary variable $x_{i,s}$ in (1d) represents the matching status between crowd carrier i and his intended bundle s. The binary variable y_j in (1e) indicates whether order j is delivered by 3PL or not (at the cost of r_j). Constraints (1c), (1d) and (1e) together also make sure that each order is served by at most one crowd carrier.

2.2 The Vickrey-Clarke-Groves Mechanism

Denote the bidding prices and allocation result of crowd carrier i as $\mathbf{b}_i = (b_{i,s})_{s\in S_i}$ and $\mathbf{x}_i = (x_{i,s})_{s\in S_i}$ respectively, both of which are column vectors. Let the bidding prices of all crowd carriers constitute vector $\mathbf{b} = (\mathbf{b}_i)_{i\in I}$, representing the profile of all bidding vectors of the crowd carriers. The assigned result to each crowd carrier constitute a row vector $\mathbf{x} = (\mathbf{x}_i)_{i\in I}$. Similarly, let $\mathbf{y} = (y_j)_{j\in J}$ be a row vector indicating the outsourcing result of orders.

We start with the application of celebrated VCG mechanism to WDP (1), which is the unique mechanism achieving both allocative efficiency (AE) and strategyproofness (SP) in an environment of quasi-linear utility. Denote the optimal value of WDP (1) with and without crowd carrier i as π and π^{-i}, respectively. The VCG mechanism is shown in Algorithm 1.

Algorithm 1 The applied VCG mechanism

Input: The bidding price vector $\mathbf{b}$ and the outsourcing fee r_j of order j for using 3PL.
Output: The allocation result $(\mathbf{x}^*, \mathbf{y}^*)$ and the payment result $\mathbf{p}^*$.

1: Solve WDP (1) for the minimizer $(\mathbf{x}^*, \mathbf{y}^*)$ and the optimal value π. ▷ Allocation problem
2: **for** every winner $i \in \hat{I}$ **do** ▷ $\hat{I}$ is the winner set
3: Solve WDP (1) without crowd carrier i and calculate the optimal value π^{-i}.
4: Set the payment for crowd carrier i as $p_i^* = \pi^{-i} - \pi + \mathbf{b}_i^T \mathbf{x}_i^*$. ▷ Pricing problem
5: **end for**

2.3 An Approximately Efficient Mechanism

Given that the VCG mechanism requires multiple computations of the optimal solution to the WDP, which we have established as NP-hard in fact, it becomes computationally intractable for large-scale instances. To this end, we leverage the information from duality to design an approximately efficient algorithm that is implementable in real-world systems, where we sacrifice the optimality for the tractability while maintaining as many economic properties as possible. Let Lagrangian multipliers λ_i and μ_j associated with constraint (1b) and (1c) respectively. Then the dual problem (2) is written as follows:

$$\max_{\lambda_i,\mu_j} \quad \sum_{j\in J} \mu_j - \sum_{i\in I} \lambda_i \tag{2a}$$

$$\text{s.t.} \quad b_{i,s} + \lambda_i - \sum_{j\in s} \mu_j \geq 0 \qquad \forall i \in I, s \in S_i \tag{2b}$$

$$r_j - \mu_j \geq 0 \qquad \forall j \in J \tag{2c}$$

$$\lambda_i \geq 0 \qquad \forall i \in I \tag{2d}$$

For the dual problem, obviously in (2) $\lambda_i = 0$ and $\mu_j = r_j$ is what we want for maximization, but the optimal condition may not always be obtained due to the following two constraints: $\lambda_i \geq \max\left\{\sum_{j\in s} \mu_j - b_{i,s}, 0\right\}$ and $\mu_j \leq r_j$. However, for some special cases we can get the sufficient conditions, that is if $\sum_{j\in s} r_j - b_{i,s} \leq 0, \forall i \in I, s \in S_i$, then both conditions can be easily derived. Interestingly, the physical meaning of the left-hand side can be interpreted as the reduced cost in each bundle. And thus, this inequality means there is no reduced cost in any bundle. On the other hand, if $\exists i \in I, s \in S_i$ such that $\sum_{j\in s} r_j - b_{i,s} > 0$ in the optimal solution of the dual $\lambda_i > 0$. By primal-dual complementary slackness, we obtain $\sum_{s\in S_i} x_{i,s} = 1$.

The intuition is quite straightforward: if there is some room for improvement by crowd carrier i, he should be assigned a (fractional) order. Although the parcels are indivisible, inspired by such primal dual analysis, we can do it in a greedy way which yields a sub-optimal solution. To guarantee the desirable economic properties, we integrate the second-best pricing scheme into the greedy allocation based on the reduced cost of crowd carriers, which yields Algorithm 2.

Algorithm 2 A greedy allocation rule with the second-best payment scheme

Input: The bids $b_{i,s}$ and the outsourcing fee r_j of order j for using 3PL

Output: The allocation result $x_{i,s}, y_j$, and the payment result p_i.

1: $x_{i,s} \leftarrow 0$, $y_j \leftarrow 1$, $p_i \leftarrow 0$, $\lambda_i \leftarrow \max_{s \in S_i} \left\{ \sum_{j \in s} r_j - b_{i,s}, 0 \right\}$ ▷ Initialization
2: **while** $J \neq \varnothing$ and $I \neq \varnothing$ **do**
3: Find the bidder with the highest reduced cost i^* and the corresponding bundle s_{i^*}.
4: Pay i^* based on second largest reduced cost, $p_{i^*} \leftarrow b_{i^*,s_{i^*}} + \lambda_{i^*} - \lambda_{i'}$ ▷ i' is the 2nd
5: Update the order set J and crowd carrier set I.
6: **end while**

3 RESULTS

The VCG mechanism is stretegyproof, individual rational and budget balanced. The Greedy mechanism is approximately-strategyproof while maintaining other economic properties. Moreover, the Greedy mechanism can be implemented in polynomial time and provides a guarantee for the objective function of WDP (1). We omit theoretical proofs here due to the limited space.

We use the real-world data to construct the bids based on the road network of Atlanta, US (Behrend & Meisel, 2018). We only present the results of the benchmark case in Table 1, where there are 100 crowd carriers and 100 orders. Each crowd carrier can submit at most 5 bundles and each bundle contains at most 3 orders. We observe that the Greedy mechanism approximates the VCG mechanism well in terms of the evaluation metrics. We also conduct extensive experiments to test the bidding restriction strategies at different problem scales.

Table 1 – *The results of the benchmark (100 simulations)*

Evaluation metric	VCG	Greedy	Note
Matching rate	0.478 (0.022)	0.398 (0.023)	Matching outcome
Service rate (by crowd carriers)	0.998 (0.005)	0.885 (0.029)	
Total cost	735.409 (42.327)	1250.208 (132.507)	
Total payment	1115.146 (174.867)	815.930 (41.960)	Pricing outcome
Total profit	4371.064 (209.325)	4095.500 (155.345)	
Computation time	19.102 (10.488)	0.009 (0.004)	-

4 CONCLUSION

In this paper, we examine a crowdshipping system where an online platform recruiting crowd carriers as a supplementary to traditional delivery services operated by 3PL. We seek incentive mechanisms through the lens of auction design to support the centralized decision making with the decentralized revealed information. Both theoretical and numerical analysis indicate that the heterogeneity among crowd carriers can be handled well by the proposed mechanisms.

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