Achieving Economic and Environmental Sustainability in Urban Consolidation Center with Bi-criteria Auction

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Abstract

Consolidation lies at the heart of the last-mile logistics problem. Urban Consolidation Centers (UCCs) have been setup to facilitate such consolidation all over the world. To our knowledge, most—if not all—of the UCCs operate on volume-based fixed-rate charges. To achieve environmental sustainability while ensuring economic sustainability in urban logistics, we propose in this paper a bi-criteria auction mechanism for the automated assignment of last-mile delivery orders to transport resources. We formulate and solve the winner determination problem of the auction as a bi-objective programming model. We then present a systematic way to generate the Pareto frontier to characterize the trade-off between achieving economic and environmental sustainability in urban logistics. Finally, we demonstrate that our proposed bi-criteria auction produces solutions that significantly dominate those obtained from fixed-rate mechanisms. Our sensitivity analysis on the willingness of carriers to participate in the UCC operation reveals that higher willingness is favorable towards achieving greater good for all, if UCC is designed to be non-profit and self-sustaining.

Note to Practitioners

One of the main issues with last-mile logistics is the low utilization of delivery trucks, resulting in unnecessarily large number of trucks carrying out the last-mile delivery. This creates congestion, worsens air pollution, and drives up the cost of the individual carriers. Consolidation of orders can reduce the total number of trucks used to perform the last-mile delivery. This can considerably improve the environmental sustainability around the delivery area and reduce the cost of the individual carrier. Without proper mechanism, however, such consolidation is often not economically sustainable, requiring the government to continually inject subsidy. To address the issue, we propose in this paper a bi-criteria auction that considers both the economic and the environmental sustainability aspects when performing winner determination. We then present a systematic way to characterize the trade-off between the two objectives. Finally, we show that our proposal leads to the solutions that dominate those obtained from the commonly-used fixed-rate mechanisms.

I. Introduction

Urban or last-mile logistics involves the movement of freight in urban cities. Consolidation and coordination lie at the heart to solve the last-mile logistics problems [1], since they are capable of increasing truck utilization and reducing total distance traveled. This in turn brings about greater cost-effectiveness with fewer man-hours and less fuel consumption; and more environmental-friendliness with less air pollution and congestion in urban areas [2], [3].

Urban Consolidation Centers (UCCs) [4] (or City Distribution Centers) are facilities that enable consolidation and coordination of last-mile deliveries in a number of cities around the world. Inbound freight from different carriers arrive at the UCC are first sorted according to their destinations. Orders are then consolidated based on destinations so as to achieve efficient and coordinated deliveries within cities. UCCs can be generally divided into two categories: as *facility providers* or *service providers*.

When a UCC serves as a facility provider, it provides cross-docking functionality for the participating carriers. The cost savings obtained are finally shared among the carriers. As a result, higher truck utilization is attained, fewer trucks are required, and lower total delivery cost is incurred. The wait time incurred by

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carriers assigned to carry out the consolidated last-mile deliveries is compensated by the savings attained by those carriers that no longer need to enter the city center. A fair allocation of the savings need to be agreed among the participating carriers in order to ensure participation. The Tenjin Joint Distribution System in Fukuoka, Japan is an example of this type of UCCs.

In another context, a UCC may serve as a service provider with its own fleet of vehicles. These UCCs carry out last-mile deliveries on behalf of the participating carriers at a fee. Occasionally, the UCCs may be government initiatives or pilot runs and provide the last-mile delivery service free-of-charge. Participating carriers simply drop off their loads at the UCCs and pay to get the loads delivered into the city center. The examples of these UCCs are La Petite Reine in Paris, France, the Westfield Consolidation Centre in London, U.K., and the Binnenstadservice in Nijmegen, the Netherlands. By using the UCCs' service, the participating carriers no longer need to enter the city center. Retaining the use of large trucks for the economies of scale outside the city center thus becomes possible in the case of government's restrictions on the allowed types of vehicles within the city center.

In this paper, we are concerned with UCCs that serve as a service provider. To our knowledge, most—if not all—existing UCCs operate on volume-based fixed-rate charges. That is, UCCs set various rates per unit volume for using its service to deliver to different areas in the city center. Participating carriers submit their requests for consolidation and are charged according to rates set by the UCCs. In economic terms, the carriers are price takers.

One challenge in operating UCCs as a service is economic sustainability. To maintain profitability, a UCC should adopt a market-based approach by charging deliveries according to rates determined by market demands rather than fixed rates. However, determining the optimal rates to charge carriers is however not straightforward, since the potential cost savings perceived by different carriers vary and are not normally known to the UCC. Setting the rates too low, the UCCs could miss the opportunity to maximize the profit. On the other hand, the UCCs could lose potential customers by setting them too high, which eventually leads to reduced profit.

Auctions have been used for thousands of years as market mechanisms. Today, auctions account for an enormous amount of economic activity: governments use auctions to sell treasury bills, radio frequency spectrums, and other assets such as firms to be privatized. Similarly, firms select their suppliers through procurement auctions. For end consumers, houses, cars, antiques, artwork, agricultural produce are commonly sold through auctions. Internet auction web-sites such as Ebay are used to sell almost anything. Auctions are simple but effective price discovery mechanisms to extract buyers' or sellers' valuations, especially when there is uncertainty about the value of an object or service.

Motivated by this, [5] proposed a profit-maximizing auction mechanism for the UCCs. Their proposed mechanism are based on operational costs which comprise *delivery* and *storage* costs. The delivery cost is the cost of operating a truck to a zone in the city center. The storage cost, on the other hand, is the cost of storing a unit volume of delivery order overnight in the UCCs' warehouse. With these costs known, their proposed mechanism ensures budget balance on the resulting allocation.

While maximizing the UCC's profit ensures economic sustainability, it should be noted that the establishments of UCC, especially under government pilot runs, are aimed at achieving environmental sustainability. Inspired by this, we propose in this paper a bi-criteria auction for the UCCs to achieve both economic and environmental sustainability.

In this paper, our goal is neither to design simultaneous auction mechanisms with desirable properties (such as incentive compatibility), nor to investigate if the auction mechanisms in place have such properties, nor to characterize equilibrium strategies of carriers in such auctions. Rather, we are interested in demonstrating the viability of auctions which produce the twin outcome of economic and environmental sustainability.

Our contributions can be summarized as follows.

1) We identify three determining factors from the UCC operation that contribute to the environmental sustainability.
2) We formulate the winner determination problem of the bi-criteria auction as a bi-objective program.

3) We present an iterative algorithm to systematically populate the Pareto frontier of the bi-criteria auction.
4) We study the efficacy of the proposed bi-criteria auction computationally and assess the effects of the carriers' willingness to share their cost savings to the success of the proposed auction scheme.

The remaining of this paper is organized as follows. Section II presents brief literature review on logistics and multi-attribute auctions. Section III establishes the UCC problem addressed in this paper. Section IV details the proposed bi-criteria auction as a plausible solution to the problem. Section V assesses the efficacy of the proposed solution. Finally, Section VI concludes this paper and presents future research directions.

II. Literature Review

Auctions have been commonly used as mechanisms for resource allocation in transportation and logistics - particularly, in the context of global logistics. Suppliers submit ad-hoc delivery demands and their budgets to get these demands served. Carriers submit their spare capacities in their truck fleet and the cost of using these spare capacities in the reverse auction. In some platforms, we see bipartite auctions where both carriers and suppliers function as bidders [6]. Combining different service providers to fulfill transportation demands can be modelled as set partition problems [7] or lane covering problems [8], [9]. Several efficient methods for procurement scheduling can be found in [10], which studied the liner shipping problem. [11] characterized auctions held by distributors and e-commerce companies for carriers to bid on contracts as combinatorial reversed procurement auction. In such a contract auction, shippers as the auctioneer need to estimate their future demands to procure service of carriers. These demands are commonly uncertain, making the decision process a stochastic problem. [12] studied this uncertainty in winner determination stage of auctioneer. When a shipper does not have a complete distribution of its demands, auctioneer has to consider the worst-case scenario analysis which can be done by solving a robust optimization problem [13]. In the context of the last-mile logistics, [5] recently proposed a profit-maximizing auction mechanism to address the economic sustainability of the UCC.

Many auctions concentrate only on the interests of the auctioneers while ignoring those of the bidders. It is observed when price is the sole priority of the auctioneers. This could potentially damage the long-term relationships between the bidders and the auctioneers [14]. As a response, auctions mechanisms that take non-price attributes such as quality as well as delivery and payment terms explicitly into consideration have been proposed [15]. The $A + B$ auction—also known as cost/time auction—is a commonly-encountered two-attribute sealed-bid auction for procurement [16], [17], [18], [19], [20]. The A part of the equation is the bidder's cost and the B part is the estimated time, requiring each bidder to express additional quantity besides price when joining the auction. A utility/scoring function then assigns each bid a score, based on which the bids can then be ranked and the winners may thus be determined. Commonly-used scoring functions are additive or quasi-linear [21], [22], [23], [24], [25], [26]. Separately, [27] presented a bi-objective winner determination problem for a combinatorial auction in transportation procurement. The two objectives include minimizing the total procurement costs and maximizing the service-quality level.

III. Problem Statement

In this paper, we consider the setting of last-mile deliveries in a city with Z delivery zones $\mathbb{Z} = \{1, \ldots, Z\}$. We assume a delivery operation incurs a cost of δ per unit distance traveled. Additionally, the city authority imposes a tax on the carbon emission as much as ε per unit emission produced. We employ the activity-based method outlined in [28] for computing the carbon footprint for heavy goods vehicles. When traveling empty, a truck produces γ_0 emission. Depending on its utilization, a truck produces $\gamma_0 + \vartheta\Delta\gamma$ emission where $\vartheta \in [0, 1]$ denotes the utilization of the truck. For simplicity of the model presentation, we assume trucks to be homogeneous and the emission profile of all trucks to be identical. Since it is difficult to track the utilization of a truck, when a carrier performs last-mile deliveries to the city on its own, we assume that the authority imposes a carbon tax based on *full* utilization of the truck. Hence, to a carrier, the total cost of performing the last-mile deliveries to zones $\mathcal{Z} \subseteq \mathbb{Z}$ is $\Gamma(\mathcal{Z}) = [\delta + \varepsilon(\gamma_0 + \Delta\gamma)]d(\mathcal{Z})$, where $d(\mathcal{Z})$ represents the shortest total distance required to satisfy all demands in $\mathcal{Z}$ from the carrier's depot (if multiple trucks are required, $d(\mathcal{Z})$ should be the total distance traveled by all trucks).

We assume that the UCC is located at the outskirt of the city, and for simplicity, inbound freight into the UCC incurs no additional inbound travel cost. By not delivering its order to a zone on its own, a carrier j who requests the UCC to deliver its order to zone z derives a benefit ς_{jz}. In this paper, this benefit is conservatively quantified as the lower bound of its marginal cost savings over all possible combinations of the remaining zones to which the carrier must deliver. That is,

$$\varsigma_{jz} = \min_{\mathfrak{z} \subseteq \mathcal{Z} \setminus \{z\}} \left[\Gamma(\mathfrak{z} \cup \{z\}) - \Gamma(\mathfrak{z})\right]. \tag{1}$$

As the use of UCC can cause some inconveniences for individual carriers, we define a parameter $\omega \in [0, 1]$ to quantify the *perceived benefit* (which discounts the computed benefit in (1)). In other words, a carrier j will utilize UCC's service for zone z only if $\omega\varsigma_{jz}$ is higher than the payment requested by the UCC.

We assume that the UCC adopts a zone-based consolidation, i.e., each truck delivers only to a particular zone during each trip. This allows the authority to easily track and audit the utilization of UCC trucks, and carbon tax can thus be accurately charged according to the utilization level. This is in contrast to the full-load carbon tax charged for individual carrier's own deliveries.

As argued earlier in the introduction, to more effectively allocate limited UCC capacity to tasks that are more valuable, a more flexible and effective approach is to use *auction markets* to solicit carrier's desire in utilizing UCC services. In order to use the UCC service for a delivery order i, a carrier has to submit a bid in the following format:

$$b_i = [a_i, \ell_i, v_i, z_i, p_i], \tag{2}$$

where a_i and ℓ_i are arrival and deadline periods respectively (the planning horizon is assumed to be T time periods), v_i is the order volume, z_i is the destination zone, and p_i is the highest price the carrier is willing to pay for the order. In this work, p_i is essentially the perceived benefit $\omega\varsigma_{jz_i}$ where j denotes the carrier who owns order i and submits bid b_i. We assume that orders cannot be divided and has to be satisfied by a single truck. All bids are assumed to be submitted sealed, and the auction is single-round. The case where the objective of the auction market is to maximize UCC's profit has been studied in [5]. A major contribution as stated earlier is the extension of this market framework to also consider environmental factor beyond just profits.

An alternative to the auction market will be to charge carriers with fixed prices. In this paper, a zone-based rate r_z, which represents per unit volume to deliver to zone z, will be charged. For simplicity, we can assume that for each order i satisfying $\omega\varsigma_{c_i z_i} \geq v_i r_{z_i}$ (c_i is the carrier owning order i), a proxy bid will be placed, with $p_i = v_i r_{z_i}$. In both allocation schemes described above, the same winner determination problem (which determines what orders to satisfy, given the capacity constraint) will be formulated and solved.

IV. Formulation and Solution Approach

Our UCC winner determination problem aims to maximize either the economic or environmental objective by assigning bids to trucks, while observing fleet and truck capacity constraints. Let $\mathcal{B} = \{b_1, \ldots, b_N\}$ be the set of all bids, number of time periods be T, number of UCC trucks be K, and the capacity of each truck be Q.

We introduce three groups of binary decision variables: 1) x_{ik}^t indicates if order i is assigned to truck k in period t; 2) y_{kz}^t indicates if truck k is activated to serve zone z in period t; and 3) c_j represents the need for carrier j to arrange for its own order deliveries.[1] Let $\mathcal{B}_j$ denote the set of bids put up by carrier j.

[1]In most case, this is caused by insufficient capacity or low bid prices; however, certain orders might require private trucks and the use of UCC will thus be impossible.

In terms of objective functions, the economic function, denoted f_1, is a function of the net profit derived from bid prices of the auction minus operational costs. The environmental function is composed of a number of factors, and in this paper, we consider the total number of trucks (carrier trucks plus UCC trucks) that eventually carry the last-mile deliveries, the number of orders consolidated, and the total consolidated volume. Let f_2, f_3, and f_4 respectively denote these quantities.

Let $\mathbf{X} = \{x_{ik}^t\}$, $\mathbf{Y} = \{y_{kz}^t\}$, and $\mathbf{C} = \{c_j\}$. Let $d(z)$ denote the distance traveled from the UCC to zone z and back to the UCC and $\hbar$ denote the holding cost coefficient (i.e. the rate for storing an order of unit volume of good for one period in the UCC). We have,

$$f_1(\mathbf{X},\mathbf{Y}) = \sum_{i,k,t} p_i x_{ik}^t - \sum_{i,k,t} \left\{ \hbar v_i [t - a_i] + \varepsilon \Delta\gamma \frac{v_i}{Q} d(z_i) \right\} x_{ik}^t - \sum_{k,z,t} \{[\delta + \varepsilon\gamma_0] d(z)\} \, y_{kz}^t \tag{3}$$

$$f_2(\mathbf{Y},\mathbf{C}) = \sum_{k,z,t} y_{kz}^t + \sum_j c_j \tag{4}$$

$$f_3(\mathbf{X}) = \sum_{i,k,t} x_{ik}^t \tag{5}$$

$$f_4(\mathbf{X}) = \sum_{i,k,t} v_i x_{ik}^t \tag{6}$$

The net profit f_1 is the total payment received by the UCC (first term) minus the total operational cost, which is made up of the cost for consolidating order i into truck k at period t (second term) and the cost for sending truck k to zone z at period t (third term). The function f_2 is simply the number of trucks activated by the UCC over the period $[1, T]$ plus the number of carrier trucks which deliver some orders to the city on their own. The other two functions f_3 and f_4 are self-explanatory.

Now to quantify the environmental function, we need to combine its three influential factors f_2 to f_4. In practice, the ultimate goal of consolidation is to minimize the number of trucks f_2, since ultimately, carbon emission is associated with number of trucks used. Secondly, the number of orders consolidated also plays a role in reducing carbon emission, since orders that are otherwise not consolidated will be delivered by carriers' trucks which will likely be less-than-truckload. Hence, in this paper, we propose a weighted sum of these factors $N f_2(\mathbf{Y},\mathbf{C}) - f_3(\mathbf{X}) - \frac{1}{V} f_4(\mathbf{X})$ where the weights are defined as $N = |\mathcal{B}|$ and $V = \sum_i v_i$.

Finally, we discuss the constraints associated with our model. In order to account for the utilization of the carriers' own trucks in the model (see equation (4) which counts the total number of trucks used eventually), we need an indicator variable to specify if a carrier intends to still visit the city when all its bidded orders are accepted for delivery by the UCC. We denote this as $\mathbb{I}_j$, where $\mathbb{I}_j = 1$ if carrier j still intends to visit the city, and 0 otherwise. And for simplicity, we assume that each carrier owns a single truck in the formulation, although this can be readily relaxed by distinguishing the carrier index from their truck indices.

Hence, the constraints are defined as follows.

$$x_{ik}^t = 0 \qquad \forall i \forall k \forall t \notin [a_i, \ell_i] \tag{7}$$

$$\sum_{k,t} x_{ik}^t \leq 1 \qquad \forall i \tag{8}$$

$$\sum_{z} y_{kz}^t \leq 1 \qquad \forall k \forall t \tag{9}$$

$$x_{ik}^t \leq y_{kz_i}^t \qquad \forall i \forall k \forall t \tag{10}$$

$$c_j \geq \mathbb{I}_j \qquad \forall j \tag{11}$$

$$1 - \sum_{k,t} x_{ik}^t \leq c_j \qquad \forall j, \forall i \in \mathcal{B}_j \tag{12}$$

$$\mathbb{I}_j + |\mathcal{B}_j| - \sum_{i \in \mathcal{B}_j, k, t} x_{ik}^t \geq c_j \qquad \forall j \tag{13}$$

$$\sum_i v_i x_{ik}^t \leq Q \qquad \forall k \forall t \tag{14}$$

Constraint (7) eliminates impossible consolidation. Constraint (8) ensures the UCC only consolidates an order at most once. Constraint (9) enforces single zone consolidation. Constraint (10) relates consolidation of an order with activation of a truck. Constraints (11)–(13) govern the deactivation of a carrier. A truck is said to be deactivated if the associated carrier no longer need to enter the city (by having all its orders delivered by the UCC). Note that when $\mathbb{I}_j = 1$, these constraints requires $c_j = 1$, thereby disallowing the deactivation. Finally, (14) is the capacity constraint.

We now propose our method to solve the bi-objective winner determination problem (BO-WDP). First, we solve the following problem that maximizes the environmental sustainability. That is,

$$\underset{\mathbf{X},\mathbf{Y},\mathbf{C}}{\arg\min} \left[N f_2(\mathbf{Y}, \mathbf{C}) - f_3(\mathbf{X}) - \frac{1}{V} f_4(\mathbf{X}) \right] \tag{15}$$

subject to (7)–(14) and

$$\sum_{k,z,t} y_{kz}^t \leq M \tag{16}$$

$$f_1(\mathbf{X}, \mathbf{Y}) \geq P \tag{17}$$

Then, we assign $\mathbf{X}' = \mathbf{X}$ and $\mathbf{Y}' = \mathbf{Y}$ and next, we solve the following problem that maximizes economic sustainability.

$$\underset{\mathbf{X},\mathbf{Y}}{\arg\max} f_1(\mathbf{X}, \mathbf{Y}) \tag{18}$$

subject to (7)–(14), (16), and

$$f_2(\mathbf{Y}, \mathbf{C}) = f_2(\mathbf{Y}', \mathbf{C}) \tag{19}$$

$$f_3(\mathbf{X}) = f_3(\mathbf{X}') \tag{20}$$

$$f_4(\mathbf{X}) = f_4(\mathbf{X}') \tag{21}$$

By appropriately setting different M and P values and repeating the above, Algorithm 1 outlines the procedure to systematically obtain the approximate Pareto frontier to BO-WDP.

Algorithm 1

```
set P = -∞
set M = KT
solve [X, Y, C] = BO-WDP(M, P)
while not infeasible do
    add [X, Y, C] to Pareto set F
    set P = f_1(X, Y)
    set M = ∑_{k,z,t} y^t_{kz} - 1
    solve [X, Y, C] = BO-WDP(M, P)
end while
return F
```

We note that it is theoretically possible to obtain the other approximate Pareto frontier by reversing the direction in Algorithm 1 and exchanging the precedence of the optimization criteria with appropriate changes to constraints (16)–(17). However, we consciously avoid such approach since the very reason the UCC is established is to minimize the negative impacts of the last-mile deliveries on the environment. Thus, given a threshold on the number of trucks the UCC can dispatch over the period $[1, T]$, the consolidation plan that achieves the highest environmental sustainability must first be identified and if multiple plans are available, only then the one that produces the greatest consolidation profit will have to be singled out.

V. Numerical Experiment

In this section, we present a numerical study that illustrates the advantages of using market mechanism over fixed-charge scheme when both economic and environmental considerations are important.

A. Experimental Setup

We consider a city with 5 zones (Z) and a planning horizon of 5 time periods (T). The UCC of the city owns a fleet of 5 trucks (K), each with capacity of 100 volume units (Q), and serves 25 carriers (C). The discount factor for computing perceived benefit (ω) is set to $3/4$. The holding cost ($\hbar$) at the UCC is 0.05 per unit volume per time period. The base emission (γ_0) is set to 0.712, while emission per unit distance traveled ($\Delta\gamma$) is set to 0.333. The cost associated with per unit distance traveled (δ) is 1, while the carbon tax rate (ε) is 0.1 per unit emission.

For each carrier, the number of orders (m) follows a discrete uniform distribution $U[1, Z]$, with orders serving distinct zones (each zone with equal probability being chosen). An order is characterized by (a_i, d_i, v_i), where the deadline d_i follows a discrete uniform distribution $U[1, T]$, the arrival time a_i follows a discrete uniform distribution $U[1, d_i]$, and the volume v_i follows a discrete uniform distribution $U[Q/(5m) + 1, Q/(m + 1)]$ (intuitively speaking, total order volume from a carrier can fill from 20% to 100% of a truck).

B. Pareto Frontier

The performance of UCC operations with respect to the number of activated trucks are measured using a number of metrics and plotted in Figure 1 (to be explained in the next paragraph). Truck allocation plans at the UCC are generated by executing Algorithm 1. As our market cleaning algorithm is bi-objective, a Pareto frontier is necessary to illustrate the trade-off between economic and environmental considerations. One such Pareto frontier is plotted in Figure 2.

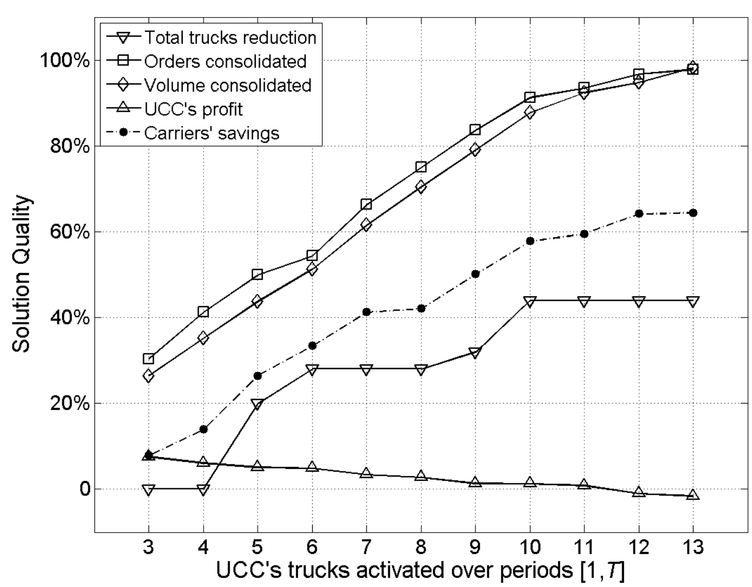

Figure 1. Comparison of Algorithm 1's performance with increasing number of activated trucks.

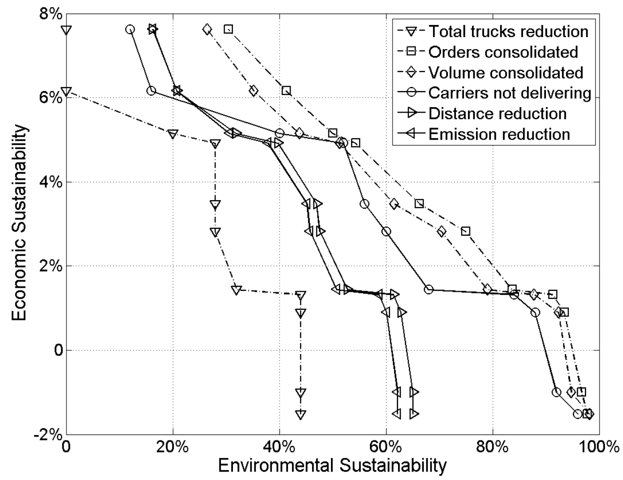

Figure 2. Pareto frontier of the auction mechanism.

The impact of UCC are measured by two groups of conflicting metrics: economic one and environmental ones. The economic metric is measured by *UCC's profit*, and it shows how viable it is to operate a UCC (a negative UCC profit implies that subsidies are needed). To allow performance comparison across different scenarios, we normalize UCC profit over total cost of operation without UCC. On the other hand, environmental sustainability is multifaceted and we use the following metrics to provide a more complete view on UCC's environmental impact.

- Total trucks reduction: Without UCC, all carriers will need to utilize their own trucks to make deliveries. With UCC, number of activated trucks is optimized as $f_2(\cdot)$. Therefore, reduction in number of trucks is simply $C - f_2(\cdot)$.
- Orders consolidated: essentially $f_3(\cdot)$.
- Volume consolidated: essentially $f_4(\cdot)$.
- Carriers not delivering: essentially $\sum_j (1 - c_j)$, indicating number of carriers whose orders are fully served by UCC.
- Distance and emission reductions: The decrease in distance/emission after the introduction of UCC.
- Carrier's savings: for a carrier, its saving due to UCC is computed by finding the difference between: 1) (variable) costs paid to delivery all orders on its own (which include distance and emission charges), and 2) total costs with UCC in operation, which include both amount paid to UCC and costs for making its own deliveries.

Note that all above metrics are normalized to ensure comparability. Normalizations are done over the original system-wide values without UCC (i.e., all carriers have to make deliveries on their own).

As expected, environmental sustainability can be improved by increasing UCC fleet size; in our scenario, when 13 trucks are deployed, almost all orders can be served by the UCC (97.83% of orders and 98.23% of total volume can be respectively served). On the other hand, we can see that smaller fleet size is actually better for the UCC operator in terms of profits earned, as profits continue to fall as UCC fleet size expands. If we choose to maximize only UCC profits, only 3 trucks would be deployed, resulting in highest profit, yet only serving 30.43% of orders and 26.50% of total volume.

The conflict between economic and environmental objectives is what motivates us to introduce the Pareto frontier. By having a Pareto frontier, such as the one plotted in Figure 2, we can present to the decision maker a wide selection of potential policies, with trade-offs clearly illustrated. It then depends completely on individual decision makers to balance these two conflicting goals. Although not explicitly pointed out, all points in Figure 2 are produced by executing Algorithm 1, which places decreasing limits on the UCC fleet size in successive iteration.

C. Auction versus Fixed-rate Mechanism

As discussed earlier, fixed-rate mechanisms (i.e., zone-specific rate r_z is used in place of p_i) are most commonly used among existing UCC operations. We are thus interested in quantifying the potential benefits of using auction market in place of fixed-rate mechanism.

To explore wider ranges of pricing schemes, we introduce a pricing coefficient $\vartheta \in (0, 1]$, and compute r_z as follows:

$$r_z = \frac{1}{\vartheta Q}[\delta + \varepsilon(\gamma_0 + \vartheta\Delta\gamma)]d(z). \tag{22}$$

Intuitively speaking, ϑ represents the anticipated utilization level of UCC trucks (in other words, ϑ can be seen as a measure on how optimistic/pessimistic the UCC is). The unit-volume rate is then designed to ensure that collected revenues from carriers are sufficient to cover costs associated with deployed trucks (higher ϑ implies more optimistic expectation, and will result in lower rate).

Besides this difference in determining price, the decision rules for individual carriers are exactly the same: a carrier j will only *outsource* the delivery of its order to UCC if perceived benefits are greater than charged price. In other words, only for order i such that $\omega\varsigma_{jz_i} \geq v_i r_{z_i}$.

To see the impact of ϑ in carrier participation, we try to set ϑ to 1/2, 3/4, 5/6, and observe the percentages of orders *outsourced* (i.e., submitted as bids to the UCC) to be 15.22%, 33.70%, and 39.13% respectively. On the other hand, as carriers are free to name their prices in the auction market, the participation is always 100% (of course, not all submitted bids are accepted).

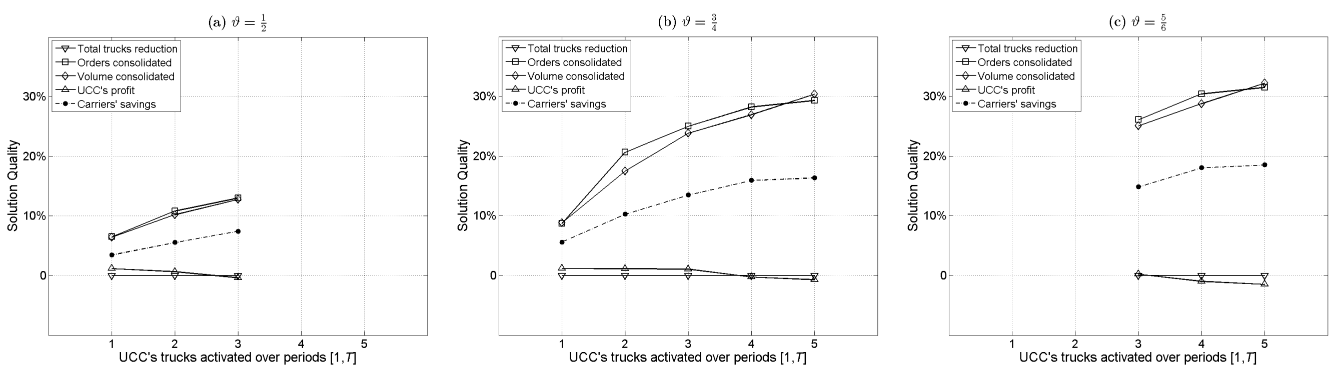

Figure 3. Fixed-rate mechanism with different ϑ: Comparison of Algorithm 1's performance with increasing number of activated trucks.

We try to visualize the performance of fixed-rate mechanism as in Figures 1 and 2. In Figure 3, we plot the performance of the mechanism over increasing fleet size, under different ϑ. Although UCC still can make a profit in most cases, it's much lower than the auction mechanism. Also, all metrics related to environmental sustainability also deteriorate significantly. This is mainly due to the fact that the participation ratio is much lower and as a result, almost all carriers still need to dispatch their own trucks, resulting in zero reduction in truck deployment. Although almost all carrier trucks still need to be deployed, we still manage to see some non-trivial carrier savings (although they are much lower than what's possible with auction markets). This is mostly due to the fact that carriers can outsource orders to the UCC if those destinations would induce significant detours.

The trade-offs between economic and environmental sustainability are illustrated in Figure 4. The resulting plots are consistent with our previous findings, which show that UCC profit (economic sustainability suffers the most drops, while environmental benefits are also negatively impacted).

In both Figures 3 and 4, we can see that value of ϑ can greatly affect the effectiveness of UCC. Of all the values $(1/2, 3/4, 5/6)$, setting ϑ to $3/4$ seems to be the best choice as it balances both economic and environmental considerations. Setting ϑ any lower, UCC will activate less trucks, thus significantly reduce the environmental benefits. Setting ϑ higher will bring in higher environmental benefits, however, almost all fleet size (except for the fleet size 3) will incur losses.

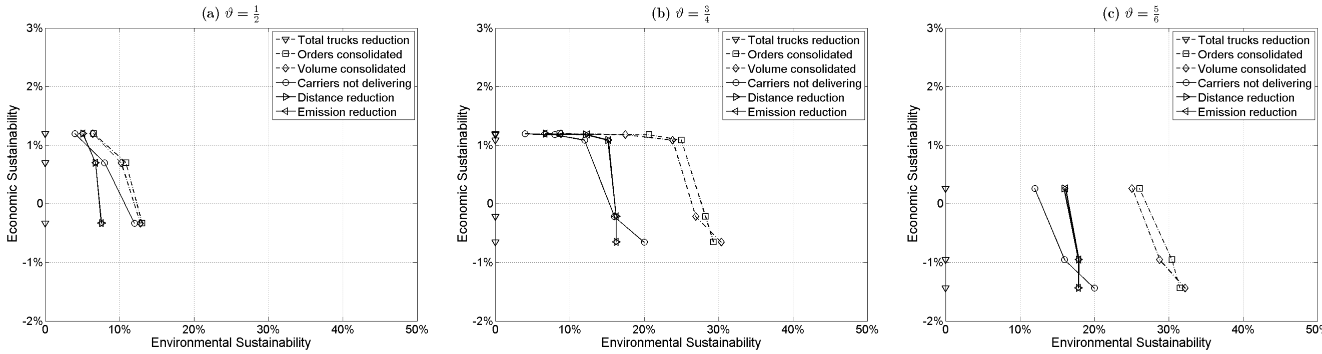

Figure 4. Pareto frontier of the fixed-rate mechanism, with different ϑ.

These observations highlight one of the major weakness of fixed-rate mechanism: the difficulty in setting the *right* price. As fixed rates are not carrier-specific, and depend on carrier's orders, it's not straightforward how to optimally set the *right* price centrally. Auction mechanism, on the other hand, allows all carriers to participate and name their own prices, thus significantly increases market participation, making it much easily to identify a match, and allow carrier-specific pricing by construction.

D. Sensitivity Analysis

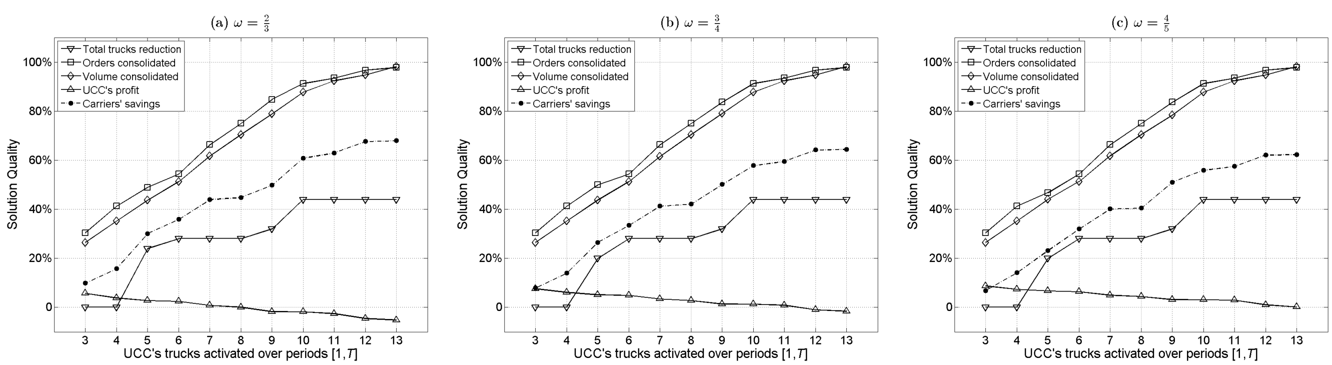

Figure 5. Comparison of Algorithm 1's performance for the auction mechanism, with different ω.

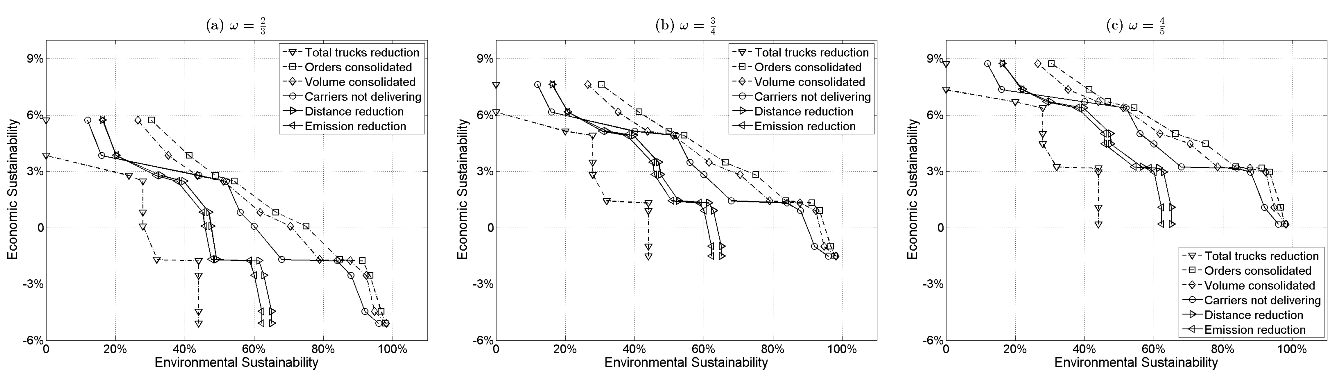

Figure 6. Pareto frontier of the auction mechanism, with different ω.

Finally, for the auction mechanism, we want to explore the impact of discount parameter (ω used in computing perceived benefit) on UCC operations. In earlier section, ω is set to be 3/4; in this section, we rerun the numerical experiments by setting ω to 2/3 and 4/5 respectively (illustrating the impact of decreasing and increasing ω). Two classes of similar figures are plotted as Figures 5 and 6.

Intuitively speaking, the higher the value of ω, the higher the perceived benefit. As a result, by setting ω high (low), carriers would be more (less) likely to utilize UCC services, which would directly impact UCC's profits as well. This can be clearly seen in Figure 5. Carrier's saving, on the other hand, moves in the opposite direction of ω: i.e., as ω increases (decreases), carrier's saving should decreases (increases). In other words, if carriers are more open to using UCC, they will end up saving less.

However, the above observation is only valid if UCC is designed to only *maximize* its own profit. If UCC is instructed to instead pursue environmental objective without losing money, the conclusion is actually reversed. When ω is set to 2/3, the UCC can dispatch up to 8 trucks profitably, saving up to 44.8% of carrier costs. When ω is set to 3/4, the UCC can dispatch up to 11 trucks profitably, saving up to 59.5% of carrier costs. Finally, when ω is set to 4/5, the UCC can dispatch up to 13 trucks profitably, saving up to 62.3% of carrier costs. In other words, if a UCC is operated in a self-sustaining and non-profit way (not maximizing for profit, yet not losing money either), encouraging carrier participation can actually improve both carrier savings and environmental sustainability.

VI. Conclusion

In this paper, we propose a bi-criteria auction for operating a UCC that aims to achieve both economic and environmental sustainability. We first define means in quantifying environmental sustainability. We then develop a bi-objective optimization model as the winner determination problem for the auction. Finally, we present a procedure to systematically construct the Pareto frontier for this model by solving the bi-objective optimization problem multiple times while incrementally adjusting the fleet size and the lower bound on the earned profit. Via empirical study, we demonstrate that the proposed auction is dominantly more effective than the fixed-rate mechanism. We further our study by conducting sensitivity analysis on the carriers' willingness to participate in the UCC operation. We demonstrate that if UCC is non-profit seeking, yet staying self-sustained, higher willingness is favorable towards achieving greater good for all: achieving higher environmental sustainability, helping carriers to save more, while making sure that the operation of UCC doesn't incur losses.

Moving forward, we aim to address the problem of providing proper incentives to carriers so that bidding their true benefits is in their best interests. We also intend to study the adoption of combinatorial auction in the UCC context. Last but not least, we aim to develop good heuristics to allow scaling up the proposed bi-objective winner determination program and solve it in a time-efficient manner.

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