10-2016

Achieving economic and environmental sustainabilities in urban consolidation center with bicriteria auction

Stephanus Daniel HANDOKO
Singapore Management University, dhandoko@smu.edu.sg

Hoong Chuin LAU
Singapore Management University, hclau@smu.edu.sg

Shih-Fen CHENG
Singapore Management University, sfcheng@smu.edu.sg

Citation
HANDOKO, Stephanus Daniel; LAU, Hoong Chuin; and CHENG, Shih-Fen. Achieving economic and environmental sustainabilities in urban consolidation center with bicriteria auction. (2016). *IEEE Transactions on Automation Science and Engineering*. 13, (4), 1471-1479.
Available at: https://ink.library.smu.edu.sg/sis_research/3362

Published in IEEE Transactions on Automation Science and Engineering, October 2016, Volume 13, Issue 4, pp. 1471-1479.
http://doi.org/10.1109/TASE.2016.2563459

Achieving Economic and Environmental Sustainabilities in Urban Consolidation Center With Bicriteria Auction

Stephanus Daniel Handoko, Hoong Chuin Lau, and Shih-Fen Cheng, *Member, IEEE*

***Abstract*— Consolidation lies at the heart of the last-mile logistics problem. Urban consolidation centers (UCCs) have been set up to facilitate such consolidation all over the world. To the best of 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 bicriteria 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 biobjective programming model. We then present a systematic way to generate the Pareto frontier to characterize the tradeoff between achieving economic and environmental sustainabilities in urban logistics. Finally, we demonstrate that our proposed bicriteria auction produces the solutions that significantly dominate those obtained from the fixed-rate mechanisms. Our sensitivity analysis on the willingness of carriers to participate in the UCC operation reveals that higher willingness is favorable toward achieving greater good for all, if UCC is designed to be nonprofit 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 the 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 bicriteria auction that considers both the economic and environmental sustainability aspects when performing winner determination. We then present a systematic way to characterize the tradeoff 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.**

***Index Terms*— Environmental economics, logistics, multi-agent systems, sustainable development, urban pollution.**

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 the consolidation and coordination of last-mile deliveries in a number of cities around the world. Inbound freight from different carriers arrive at the UCC is 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 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 needs 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 the best of 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.

Manuscript received November 17, 2015; revised February 29, 2016; accepted April 29, 2016. Date of publication June 8, 2016; date of current version October 4, 2016. This paper was recommended for publication by Associate Editor D.-H. Lee and Editor R. Uzsoy upon evaluation of the reviewers' comments. This work was supported by the Agency for Science, Technology and Research within the Science and Engineering Research Council, Singapore, under Grant 1224200002. *(Corresponding author: Hoong Chuin Lau.)*

The authors are with the School of Information Systems, Singapore Management University, Singapore 178902 (e-mail: dhandoko@smu.edu.sg; hclau@smu.edu.sg; sfcheng@smu.edu.sg).

Participating carriers submit their requests for consolidation and are charged according to the 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 the 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, and agricultural products are commonly sold through auctions. The 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 the 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 bicriteria auction for the UCCs to achieve both economic and environmental sustainabilities.

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 sustainabilities.

Our contributions can be summarized as follows.

1) We identify three determining factors from the UCC operation, which contribute to the environmental sustainability.
2) We formulate the winner determination problem of the bicriteria auction as a biobjective program.
3) We present an iterative algorithm to systematically populate the Pareto frontier of the bicriteria auction.
4) We study the efficacy of the proposed bicriteria auction computationally and assess the effects of the carriers' willingness to share their cost savings to the success of the proposed auction scheme.

The remainder of this paper is organized as follows. Section II presents a brief literature review on logistics and multiattribute auctions. Section III establishes the UCC problem addressed in this paper. Section IV details the proposed bicriteria 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 the 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 modeled 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. Reference [11] characterized the 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 the service of carriers. These demands are commonly uncertain, making the decision process a stochastic problem. Reference [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 nonprice attributes, such as quality and 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]–[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]–[26]. Separately, [27] presented a biobjective winner determination problem (BO-WDP) 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 that a delivery operation incurs a cost of δ per unit distance traveled. In addition, 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

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

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 Section I, 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:

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

where a_i and ℓ_i are arrival and deadline periods, respectively (the planning horizon is assumed to be T time periods), υ_i is the order volume, z_i is the destination zone, and p_i is the highest price that the carrier is willing to pay for the order. In this paper, 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 $\omega\varsigma_{c_i z_i} \geq \upsilon_i r_{z_i}$ (c_i is the carrier owning order i), a proxy bid will be placed, with $p_i = \upsilon_i r_{z_i}$. In both allocation schemes described earlier, 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, the number of time periods be T, the 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.

In terms of objective functions, the economic function, denoted by 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

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

[1] In most cases, 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.

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

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

$$f_4(\mathbf{X}) = \sum_{i,k,t} \upsilon_i x_{ik}^t. \quad (6)$$

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–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 the number of trucks used. Second, 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 $Nf_2(\mathbf{Y}, \mathbf{C}) - f_3(\mathbf{X}) - (1/V) f_4(\mathbf{X})$, where the weights are defined as $N = |\mathcal{B}|$ and $V = \sum_i \upsilon_i$.

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 (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:

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

$$\sum_{k,t} x_{ik}^t \leq 1 \quad \forall i \quad (8)$$

$$\sum_z y_{kz}^t \leq 1 \quad \forall k \forall t \quad (9)$$

$$x_{ik}^t \leq y_{kz_i}^t \quad \forall i \forall k \forall t \quad (10)$$

$$c_j \geq \mathbb{I}_j \quad \forall j \quad (11)$$

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

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

$$\sum_i \upsilon_i x_{ik}^t \leq Q \quad \forall k \forall t. \quad (14)$$

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 the consolidation of an order with the 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 require $c_j = 1$, thereby disallowing the deactivation. Finally, (14) is the capacity constraint.

We now propose our method to solve the BO-WDP. First, we solve the following problem that maximizes the environmental sustainability. That is

$$\arg\min_{\mathbf{X},\mathbf{Y},\mathbf{C}} \left[Nf_2(\mathbf{Y}, \mathbf{C}) - f_3(\mathbf{X}) - \frac{1}{V} f_4(\mathbf{X}) \right] \quad (15)$$

subject to (7)–(14) and

$$\sum_{k,z,t} y_{kz}^t \leq M \quad (16)$$

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

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

$$\arg\max_{\mathbf{X},\mathbf{Y}} f_1(\mathbf{X}, \mathbf{Y}) \quad (18)$$

subject to (7)–(14), (16), and

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

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

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

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

Algorithm 1. Approximating Pareto Frontier to BO-WDP

```
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) and (17). However, we consciously avoid such approach, since the very reason that 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.

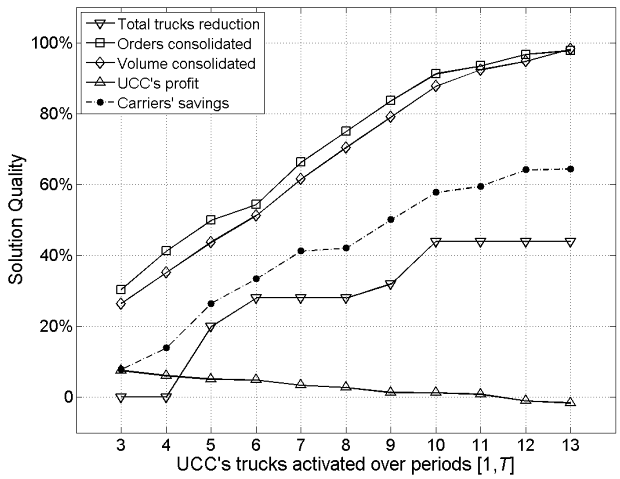

Fig. 1. Comparison of Algorithm 1's performance with increasing number of activated trucks.

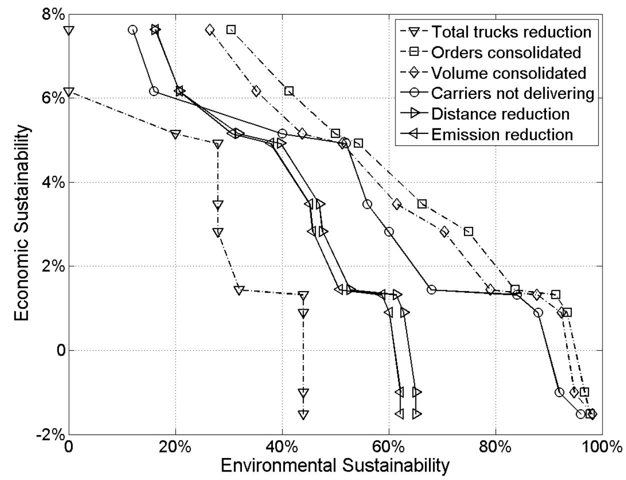

Fig. 2. Pareto frontier of the auction mechanism.

V. Numerical Experiment

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

A. Experimental Setup

We consider a city with five zones (Z) and a planning horizon of five time periods (T). The UCC of the city owns a fleet of 5 trucks (K), each with a 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 is measured using a number of metrics and shown in Fig. 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 biobjective, a Pareto frontier is necessary to illustrate the tradeoff between economic and environmental considerations. One such Pareto frontier is shown in Fig. 2.

The impact of UCC is 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 the performance comparison across different scenarios, we normalize UCC profit over the 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.

1) *Total Truck Reduction:* Without UCC, all carriers will need to utilize their own trucks to make deliveries. With UCC, the number of activated trucks is optimized as $f_2(\cdot)$. Therefore, the reduction in the number of trucks is simply $C - f_2(\cdot)$.
2) *Orders Consolidated:* Essentially $f_3(\cdot)$.
3) *Volume Consolidated:* Essentially $f_4(\cdot)$.
4) *Carriers Not Delivering:* Essentially $\sum_j (1 - c_j)$, indicating the number of carriers whose orders are fully served by UCC.
5) *Distance and Emission Reductions:* The decrease in distance/emission after the introduction of UCC.
6) *Carrier's Savings:* For a carrier, its saving due to UCC is computed by finding the difference between (variable) costs paid to deliver all orders on its own (which include distance and emission charges) and 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 a smaller fleet size is actually better for the UCC operator in terms of profits earned, as profits continue to fall as UCC

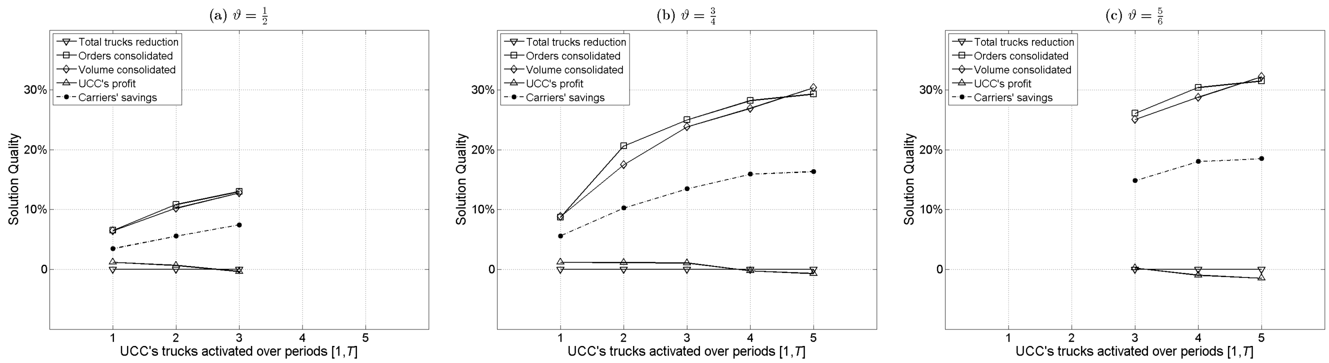

Fig. 3. Fixed-rate mechanism with different values of ϑ. Comparison of Algorithm 1's performance with increasing number of activated trucks.

fleet size expands. If we choose to maximize only UCC profits, only three trucks would be deployed, resulting in the 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 shown in Fig. 2, we can present to the decision maker a wide selection of potential policies, with tradeoffs clearly illustrated. It then depends completely on individual decision makers to balance these two conflicting goals. Although not explicitly pointed out, all the points in Fig. 2 are produced by executing Algorithm 1, which places the decreasing limits on the UCC fleet size in the 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 the collected revenues from carriers are sufficient to cover the 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 outsource the delivery of its order i to UCC if the perceived benefit is greater than the charged price, that is $\omega\varsigma_{j_{z_i}} \geq v_i r_{z_i}$.

To see the impact of ϑ in carrier participation, we try to set ϑ to 1/2, 3/4, and 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).

We try to visualize the performance of fixed-rate mechanism, as shown in Figs. 1 and 2. In Fig. 3, we plot the performance of the mechanism over increasing fleet size, under different values of ϑ. Although UCC still can make a profit in most cases, it is 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 nontrivial carrier savings (although they are much lower than what is possible with auction markets). This is mostly due to the fact that carriers can outsource the orders to the UCC if those destinations would induce significant detours.

The tradeoffs between economic and environmental sustainabilities are shown in Fig. 4. The resulting plots are consistent with our previous findings, which show the UCC profit (economic sustainability suffers the most drops, while environmental benefits are also negatively impacted).

In both Figs. 3 and 4, we can see that the value of ϑ can greatly affect the effectiveness of UCC. Of all the values ($1/2$, $3/4$, and $5/6$), 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.

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 is not straightforward how to optimally set the right price centrally. On the other hand, auction mechanism, allows all carriers to participate and name their own prices, thus significantly increases market participation, making it much

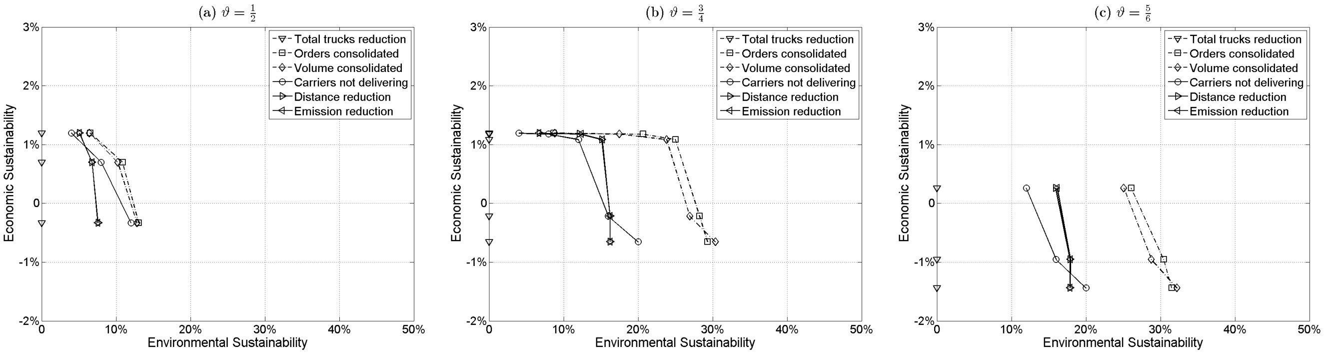

Fig. 4. Pareto frontier of the fixed-rate mechanism with different values of ϑ.

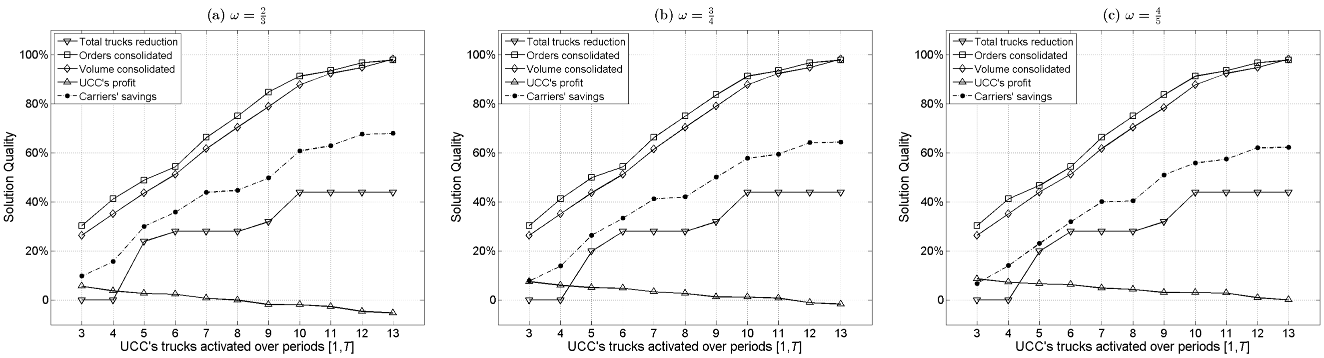

Fig. 5. Comparison of Algorithm 1's performance for the auction mechanism with different values of ω.

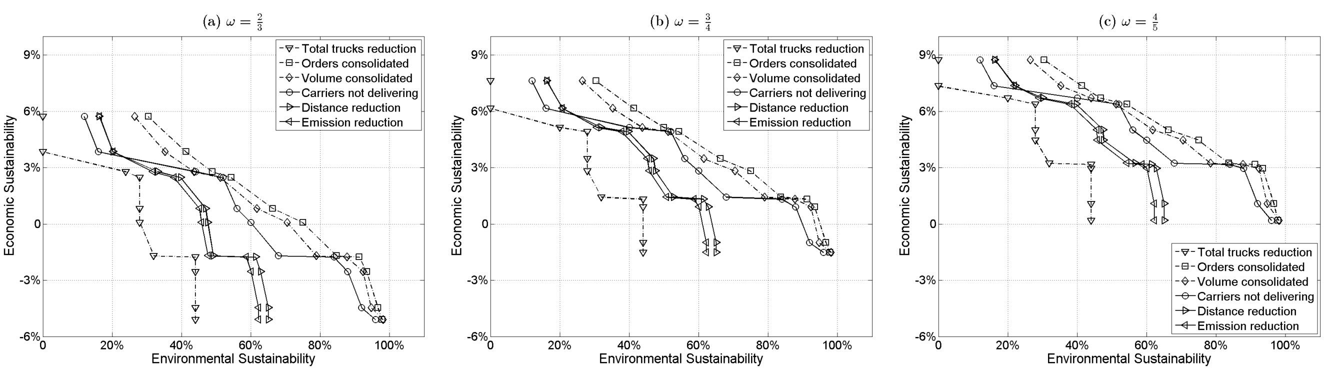

Fig. 6. Pareto frontier of the auction mechanism with different values of ω.

easily to identify a match and allow carrier-specific pricing by construction.

D. Sensitivity Analysis

Finally, for the auction mechanism, we want to explore the impact of discount parameter (ω used in computing perceived benefit) on UCC operations. In Sections V-A, V-B, and V-C, 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 shown in Figs. 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 shown in Fig. 5. On the other hand, carrier's saving, 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 eight 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 nonprofit 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 bicriteria auction for operating a UCC that aims to achieve both economic and environmental sustainabilities. We first define means in quantifying environmental sustainability. We then develop a biobjective 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 biobjective optimization problem multiple times, while incrementally adjusting the fleet size and the lower bound on the earned profit. Through the empirical study, we demonstrate that the proposed auction is dominantly more effective than the fixed-rate mechanism. We further our study by conducting the 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 toward achieving greater good for all: achieving higher environmental sustainability, helping carriers to save more, while making sure that the operation of UCC does not 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 biobjective winner determination program and solve it in a time-efficient manner.

References

[1] J.-P. Rodrigue, C. Comtois, and B. Slack, "The 'last mile' in freight distribution," in *The Geography of Transport Systems*, 2nd ed. London, U.K.: Routledge, 2009.

[2] L. Ping, "Strategy of green logistics and sustainable development," in *Proc. Int. Conf. Inf. Manage., Innov. Manage. Ind. Eng.*, vol. 1, Dec. 2009, pp. 339–342.

[3] A. McKinnon, M. Browne, A. Whiteing, and M. Piecyk, *Green Logistics: Improving the Environmental Sustainability of Logistics*, 3rd ed. London, U.K.: Kogan Page, 2015.

[4] T. van Rooijen and H. Quak, "Local impacts of a new urban consolidation centre—The case of Binnenstadservice.nl," *Proc.-Social Behavioral Sci.*, vol. 2, no. 3, pp. 5967–5979, 2010.

[5] S. D. Handoko, D. T. Nguyen, and H. C. Lau, "An auction mechanism for the last-mile deliveries via urban consolidation centre," in *Proc. IEEE Int. Conf. Autom. Sci. Eng. (CASE)*, Aug. 2014, pp. 607–612.

[6] J. H. R. van Duin, L. A. Tavasszy, and E. Taniguchi, "Real time simulation of auctioning and re-scheduling processes in hybrid freight markets," *Transp. Res. B, Methodol.*, vol. 41, no. 9, pp. 1050–1066, Nov. 2007.

[7] J. Song and A. Regan, "Combinatorial auctions for transportation service procurement: The carrier perspective," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 1833, pp. 40–46, 2003.

[8] O. Ö. Özener and Ö. Ergun, "Allocating costs in a collaborative transportation procurement network," *Transp. Sci.*, vol. 42, no. 2, pp. 146–165, May 2008.

[9] R. Agarwal and Ö. Ergun, "Network design and allocation mechanisms for carrier alliances in liner shipping," *Oper. Res.*, vol. 58, no. 6, pp. 1726–1742, Nov. 2010.

[10] R. Agarwal and Ö. Ergun, "Ship scheduling and network design for cargo routing in liner shipping," *Transp. Sci.*, vol. 42, no. 2, pp. 175–196, 2008.

[11] C. Caplice and Y. Sheffi, "Combinatorial auctions for truckload transportation," in *Combinatorial Auctions*, P. Cramton, Y. Shoham, and R. Steinberg, Eds. Cambridge, MA, USA: MIT Press, 2005.

[12] Z. Ma, R. H. Kwon, and C.-G. Lee, "A stochastic programming winner determination model for truckload procurement under shipment uncertainty," *Transp. Res. E, Logistics Transp. Rev.*, vol. 46, no. 1, pp. 49–60, Jan. 2010.

[13] N. Remli and M. Rekik, "A robust winner determination problem for combinatorial transportation auctions under uncertain shipment volumes," *Transp. Res. C, Emerg. Technol.*, vol. 35, pp. 204–217, Oct. 2013.

[14] S. D. Jap, "The impact of online reverse auction design on buyer–supplier relationships," *J. Marketing*, vol. 71, no. 1, pp. 146–159, 2007.

[15] L. Pham, J. Teich, H. Wallenius, and J. Wallenius, "Multi-attribute online reverse auctions: Recent research trends," *Eur. J. Oper. Res.*, vol. 242, no. 1, pp. 1–9, Apr. 2015.

[16] R. D. Ellis, Jr., and Z. J. Herbsman, "Cost-time bidding concept: An innovative approach," *Transp. Res. Rec.*, vol. 1282, pp. 89–94, 1990.

[17] Z. Herbsman and R. Ellis, "Multiparameter bidding system—Innovation in contract administration," *J. Construction Eng. Manage.*, vol. 118, no. 1, pp. 142–150, 1992.

[18] Z. J. Herbsman, "A+B bidding method—Hidden success story for highway construction," *J. Construction Eng. Manage.*, vol. 121, no. 4, pp. 430–437, 1995.

[19] G. Lewis and P. Bajari, "Procurement with time incentives: Theory and evidence," *Quart. J. Econ.*, vol. 126, no. 3, pp. 1173–1211, 2011.

[20] D. Gupta, E. M. Snir, and Y. Chen, "Contractors' and agency decisions and policy implications in A+B bidding," *Prod. Oper. Manage.*, vol. 24, no. 1, pp. 159–177, Jan. 2014.

[21] D. R. Beil and L. M. Wein, "An inverse-optimization-based auction mechanism to support a multiattribute RFQ process," *Manage. Sci.*, vol. 49, no. 11, pp. 1529–1545, 2003.

[22] M. Bichler, *The Future of e-Markets: Multidimensional Market Mechanisms*. Cambridge, U.K.: Cambridge Univ. Press, 2001.

[23] M. Bichler and J. Kalagnanam, "Configurable offers and winner determination in multi-attribute auctions," *Eur. J. Oper. Res.*, vol. 160, no. 2, pp. 380–394, Jan. 2005.

[24] C.-H. Chen-Ritzo, T. P. Harrison, A. M. Kwasnica, and D. J. Thomas, "Better, faster, cheaper: An experimental analysis of a multiattribute reverse auction mechanism with restricted information feedback," *Manage. Sci.*, vol. 51, no. 12, pp. 1753–1762, 2005.

[25] D. C. Parkes and J. Kalagnanam, "Models for iterative multiattribute procurement auctions," *Manage. Sci.*, vol. 51, no. 3, pp. 435–451, 2005.

[26] G. E. Kersten, "Multiattribute procurement auctions: Efficiency and social welfare in theory and practice," *Decision Anal.*, vol. 11, no. 4, pp. 215–232, 2014.

[27] T. Buer and G. Pankratz, "Solving a bi-objective winner determination problem in a transportation procurement auction," *Logistics Res.*, vol. 2, no. 2, pp. 65–78, Sep. 2010.

[28] "2015 government GHG conversion factors for company reporting: Methodology paper for emission factors," Dept. Energy Climate Change, London, U.K., Tech. Rep. PB 13988, 2015. [Online]. Available: http://www.ukconversionfactorscarbonsmart.co.uk/Documents/Emission%20Factor%20Methodology%20Paper%20-%202015.pdf