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Enabling Carrier Collaboration via Order Sharing Double Auction: A Singapore Urban Logistics Perspective

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Abstract

A recent exploratory study on the collaborative urban logistics in Singapore suggests that cost reduction and privacy preservation are two main drivers that would motivate the participation of carriers in consolidating their last mile deliveries. With Singapore's mild restrictions on the vehicle types or the time windows for the last-mile delivery, we believe that with proper technology in place, an Urban Consolidation Center like the Tenjin Joint Distribution System in Fukuoka Japan may be implemented to achieve cost reduction with some degree of privacy preservation. Participating carriers keep their respective private orders and have the option to get their remaining shareable orders consolidated with those from the other carriers' fleet. To this end, we propose in this paper a double auction mechanism that enables such consolidation with an objective to maximize the total cost savings attained by all participating carriers. Our experimental results on 5 zones of delivery in Singapore CBD demonstrate that the proposed double auction is able to bring about reductions in the number of inter-zone travels, thereby producing cost savings to the participating carriers.

1. Introduction

Last-mile deliveries in urban areas exert serious pressures on the environmental, social, and economic well-being of many major cities around the world. These three aspects are usually referred to as *planet*, *people*, and *profit* (Quak

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and Tavasszy, 2011). On the planet, the impacts are contributed by the use of unsustainable natural resources like the fossil fuel. On the people, the impacts are primarily due to air pollution and noise. On the profit, the impacts encompass economic losses because of traffic congestion and low utilization of transport vehicles. In addressing these issues, many local authorities have imposed time windows and vehicle restrictions on last-mile deliveries, which complicate the operations of the deliveries from the perspective of the carriers. Consequently, receivers experience longer wait times and service performance is affected. One solution is for carriers to operate small electric vehicles for deliveries into the city center; however, these are not efficient for long-distance inter-city transport.

An urban consolidation center (UCC) provides a plausible solution to this phenomenon. La Petite Reine and Binnenstadservice represent two contemporary examples of UCCs implemented in Paris and the city of Nijmegen in the Netherlands, respectively. These UCCs operate their own eco-friendly last-mile delivery trucks. To enhance the financial sustainability of this type of UCCs, Handoko et al. (2014) recently proposed an auction mechanism which seeks to maximize the profit of the UCCs. By completely passing their last-mile delivery responsibilities to these UCCs at some costs, participating carriers can retain the use of their large trucks for the economies of scale outside the city center, while overcoming the vehicle-type restriction and simultaneously addressing the complicated scheduling caused by the time-window restriction in last-mile deliveries. However, these carriers will no longer be able to retain and choose to deliver their private orders themselves to the respective receivers.

A recent exploratory study on the collaborative urban logistics in Singapore (Lindawati et al., 2014) suggests that *cost reduction* and *privacy preservation* are two main drivers that would motivate the participation of carriers in the UCC. In Singapore, the government authority imposes mild restrictions on the vehicle types or the time windows for last-mile delivery. Rather, electronic road pricing (ERP) that depends on the vehicle type has become the means to discourage urban traffic during peak hours. This suggests that a UCC like the Tenjin Joint Distribution System in Fukuoka, Japan (Panero et al., 2011) may be implemented to achieve cost reduction with some degree of privacy preservation. Participating carriers keep their respective private orders and have the option to get their remaining shareable orders consolidated with other carriers' fleet. This enables carriers to reduce the amount of fragmented deliveries (i.e. small deliveries to diverse locations).

For this to work, the underlying technology that performs multi-party consolidation of freight for last-mile delivery must take into consideration cost efficiency and privacy preservation. In this paper, we propose a double auction mechanism that enables such consolidation. For simplicity, our objective is to maximize the total cost savings attained by all participating carriers. Note that the model presented in this paper is aimed at solving the basic problem to perform order sharing with privacy preservation. Practical considerations such as admin and warehousing costs, shipment requirement and compatibility can be easily incorporated as objective and constraints of the model. We also assume for simplicity that the UCC serves as the auctioneer and provides facilities to perform physical transfers (cross-docking) of the shareable orders from one truck to another.

2. Literature review

Urban logistics involves multiple stakeholders (Ambrosini and Routhier, 2004) which include the receivers, the carriers, the shippers, as well as the public authorities. To reduce congestion and environmental impacts related to urban freight deliveries, several schemes have been proposed in the literature (Muuzuri et al., 2005; Benjelloun et al., 2010; Russo and Comi, 2010). Mancini et al. (2014) groups these actions into three main categories: (1) policy actions, (2) organizational actions, and (3) technological actions. Effective combination of all three categories of actions would enable efficient reduction of the travelled distances, thereby reducing congestion and minimizing environmental nuisances (Gonzalez-Feliu, 2012). For this reason, it is attractive to focus on the schemes where different actors bring their freight to the consolidation platform, which mainly is located in the surroundings of a city, from where commodity needs to be transported to the customers within the city (Crainic et al., 2012).

Allen et al. (2007) defines an Urban Consolidation Center (UCC) as "a logistics facility situated in relatively close proximity to the geographic area that it serves (a city centre, an entire town, or a specific site such as a shopping centre), to which many logistics companies deliver goods destined for the area, from which consolidated deliveries are carried out within that area, in which a range of other value-added logistics and retail services can be provided." Urban consolidation has thus become one of the pillars of city logistics, which can take place at different stages of the

urban supply chain (Morana, 2013) and utilize various existing urban logistics facilities in the urban areas (Boudoin et al., 2014).

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 platform, there could be bipartite auction containing both carriers and suppliers as bidders (van Duin et al., 2007). Solving winner determination problem in logistics auction is equivalent to solving scheduling problem to minimize the transportation cost in the form of combinatorial optimization problem (Caplice and Sheffi, 2005). Combining different service providers to fulfil transportation demands can be modelled as set partition problems (Regan and Song, 2003) or lane covering problems (Ozener and Ergun, 2008; Agarwal and Ergun, 2010). Several efficient methods for procurement scheduling can be found in Agarwal and Ergun (2008), which studied the liner shipping problem. Caplice and Sheffi (2005) characterized auctions held by distributors and e-commerce companies for carriers to bid on contracts as combinatorial reversed procurement auction. In such contract auction, shippers as the auctioneer need to estimate their future demands to procure service of carriers. These demands are commonly uncertain (Caplice and Sheffi, 2005), making the decision process a stochastic problem. Ma et al. (2010) 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 (Remli and Rekik, 2013).

In the context of the last-mile logistics, Handoko et al. (2014) recently proposed a single-shot profit-maximizing auction mechanism that addresses the economic sustainability of the UCC. Wang et al. (2014) then extended the work to the problem involving a rolling horizon.

3. Proposed mechanism

The double auction mechanism proposed in this paper aims at facilitating the consolidation of non-private (known in this paper as *sharable*) orders. A shareable order served by one carrier can be transferred and hence delivered by another carrier with the same or higher service level. For the ease of discussion when introducing the double auction mechanism, we assume—without loss of generality—that all carriers are of similar service level. Should the need arise to have multiple service levels, additional constraints can be easily incorporated either to the auction protocol or to the winner determination problem formulation. In the following, we will first introduce the auction protocol and then formulate the winner determination problem.

3.1. Auction protocol

The order sharing mechanism proposed here is a single-round sealed-bid double auction, for which we assume truthful bidding and no collusion. As soon as the auction starts, the participating carriers post the information about their shareable orders. This includes the volume and the destination zone of the orders. Additionally, they inform the auctioneer their corresponding offer prices and the spare capacities of their trucks. These carriers then search and bid for posted orders that are of interest to them and specify their asking prices to the auctioneer for them to deliver those orders. As this auction deals with transfers of shareable order among trucks, a carrier with multiple trucks has to make separate offers and/or bids for each of its trucks. Note that the only information revealed publicly is the volume and destination zone of the shareable orders. The spare capacities as well as the offer and asking prices are only communicated to the auctioneer. At the end of the bidding phase, all bids with an asking price higher than the offer price will be eliminated and the winners will then be determined in the scheme as follows.

3.2. Winner determination

We let $\mathcal{S}_k$, $\mathcal{D}_k$, and $\mathcal{R}_i$ be the sets of orders supplied (offered) by carrier k, orders demanded (requested) by carrier k, and carriers that are interested in serving order i, respectively, whereas V_k, v_i, p_i, and q_{ik} denote the spare capacity of carrier k, the volume of order i, the offer price of order i, and the asking price of carrier k to deliver order i, respectively. Denoting if order i is transferred and if carrier k obtains order i as $x_i \in \mathbf{X}$ and $y_{ik} \in \mathbf{Y}$, respectively, the

successful transfers at the end of each auction are determined by the following binary integer program that maximizes the actual cost saving attained by all participating carriers subject to the *integrity* constraint (2), the *capacity* constraint (3), the *consistency* constraint (4), and the *individual rationality* constraint (5). The consistency constraint ensures that a carrier can only obtain the shareable order for zone z from another carrier if it has not successfully transferred its own shareable order for zone z, if any. The individual rationality constraint ensures that carriers have the incentive to participate in the auction.

$$\max_{X,Y} \sum_i \left(p_i x_i - \sum_{k \in \mathcal{R}_i} q_{ik} y_{ik} \right) \tag{1}$$

s.t.

$$\forall i \ \sum_{k \in \mathcal{R}_i} y_{ik} = x_i \tag{2}$$

$$\forall k \ \sum_{i \in \mathcal{D}_k} v_i y_{ik} - \sum_{i \in \mathcal{S}_k} v_i x_i \leq V_k \tag{3}$$

$$\forall i \ y_{jk} + x_i \leq 1 \text{ where } owner(order_i) = k \text{ and zone(order\_i)=zone(order\_j)} \tag{4}$$

$$\forall k \ \sum_{i \in \mathcal{S}_k} \left(p_i x_i - \sum_{k' \in R_i} q_{ik'} y_{ik'} \right) + \sum_{i \in \mathcal{D}_k} q_{ik} y_{ik} \geq 0 \tag{5}$$

$$x_i \in \{0,1\} \tag{6}$$

$$y_{ik} \in \{0,1\} \tag{7}$$

For each successful transfer, i.e. for each i and k for which $y_{ik} = 1$, the carrier that offers order i will pay carrier k an amount of q_{ik}.

4. Computational study

To assess the efficacy of the proposed mechanism, we subjected the double auction for order sharing described in the preceding section to a number of sets of randomized deliveries representing various scenarios possibly encountered in the last-mile logistics. In the following, we first describe the setup of our experiments and then present the results taking into account both the ideal and the practical situations.

4.1. Experimental setup

Destinations. We consider multiple last-mile delivery destinations that spread across 5 zones in Singapore CBD: *Harbourfront*, *Raffles Place*, *Bugis*, *Orchard*, and *Novena*. For simplicity, we assume a high-level cost structure: traveling within the same zone incurs negligible cost; meanwhile, traveling between zones incurs considerable cost. Herein, we consider the travel cost to be a function of travel time and distance. The average inter-zone travel costs are shown in Table 1.

Table 1. Average inter-zone travel costs.

	Harbourfront	*Raffles Place*	*Bugis*	*Orchard*	*Novena*
Harbourfront	~0	40.5	88.4	85.4	153
Raffles Place	48	~0	17.4	42.3	76.7
Bugis	88.4	18.6	~0	31.2	23.8
Orchard	66	32.8	28	~0	27.2
Novena	151.2	74.4	30.4	36.9	~0

Deliveries. To represent the various scenarios that can possibly be encountered at the UCC, we generate 100 sets of randomized deliveries to any of the 5 zones in the CBD of Singapore mentioned above. In each set, we generate K nearly full truckloads. Each truck is exclusively owned by one carrier. In this work, we assume each carrier only dispatches one truck. Owned by different carriers, different trucks assume different travel costs and different private orders. The cost matrix of each carrier is randomized according to some normal distribution around the average inter-zone travel costs to reflect the varying degrees of efficiency of the different carriers. Meanwhile, the number of private orders is uniformly randomized between zeros and one less than the total number of zones the carrier is delivering to. The zones with the private orders are then selected randomly with equal probability. Individual delivery in each truck is randomized repeatedly until at least 90% of the truck capacity is utilized. Setting the capacity of the truck to 100, we uniformly randomize the volume of each delivery between 10 and 50.

Prices. Determination of the offer and the asking prices is done using the concept of *minimum marginal cost saving* mcs_min and *maximum marginal cost increment* mcs_max, respectively. For each of its shareable orders, a carrier calculates the marginal cost saving by not delivering that order and considers all possible scenarios to determine the minimum marginal cost saving attainable. The carrier then offers to pay up to $\phi \times$ mcs_min to any other carrier interested to deliver that order. Note that only the auctioneer knows the offer prices. Subsequently, for each order in the marketplace ready to be shared, a carrier calculates the marginal cost increment to deliver the order and considers all possible scenarios to determine the maximum marginal cost increment needed. The carrier then asks for $\varphi \times$ mci_max to deliver the order. Similarly, only the auctioneer knows the asking prices. Intuitively, $\phi \leq 1$ and $\varphi \geq 1$.

4.2. Ideal scenarios

Ideally, $\phi = \varphi = 1$ for all carriers. This means all of them bid truthfully. They are not trying to make profit from the exchange of the shareable orders. Rather, they focus on earning the maximum cost saving attainable socially. Table 2 summarizes our findings for the case in which there are $K = 30$ trucks participating in the double auction. The proposed mechanism manages to reduce the total cost of all deliveries. This is achieved by reducing the number of inter-zone travels, which results in the shorter total distance traveled and the lower number of vehicles in the same area at the same time. The earlier leads to lower fuel consumption, hence lower emission of pollutants. Meanwhile, the latter produces less congestion, which translates into less man-hours and even lower fuel consumption, hence even lesser pollution. Ultimately, the proposed double auction addresses all the three aspects of the negativity of the last-mile logistics in the urban areas.

Table 2. Results of order sharing via double auction over 100 ideal scenarios.

	Number of Inter-zone Travels		Total Cost Savings
	Before	**After**	
minimum	46	34	43.04
maximum	68	59	825.77
average	55.25	46.60	369.78

4.3. Sensitivity analysis

Herein, we will further discuss the efficacy of the proposed double auction mechanism against various settings of the parameters. We observed that higher cost savings are generally attainable with: 1) higher participation K, 2) higher willingness ϕ to share the cost saving, and 3) lower inclination φ to make profit from the order sharing. All the three factors bring about higher chance for achieving successful exchanges, hence higher cost savings.

Participation Level. To understand the effects of various participation levels to the proposed double auction mechanism, we vary the number of participating trucks K from 30 to 3 in steps of 3 while setting $\phi = \varphi = 1$. Since the original datasets describe the deliveries of 30 trucks, the same sets have been used but only K trucks are considered to have taken part in the double auction at the UCC.

In Table 3, the success rates of the double auction in bringing about some cost savings to the participating carriers are tabulated. A clear trend is observable. With more participation, higher success rate can be attained. When $K = 30$,

the double auction manages to bring about some cost savings to the participating carriers in all the 100 scenarios. This number is reduced as K decreases. In only less than 25 out of 100 scenarios does the double auction bring about cost savings to the participating carriers when K is as low as 6 or 3.

Table 3. Percentage of successful scenarios for various participation level K.

K	Success Rate
30	100%
27	94%
24	94%
21	92%
18	90%
15	77%
12	68%
9	40%
6	22%
3	24%

In Figure 1, the statistics of the total cost savings obtained are shown in boxplots. Like the success rates, higher cost savings are generally attainable with more carriers participating in the double auction. The median cost saving decreases as K gets smaller. It drops to 0 when only less than 10 trucks participate in the double auction.
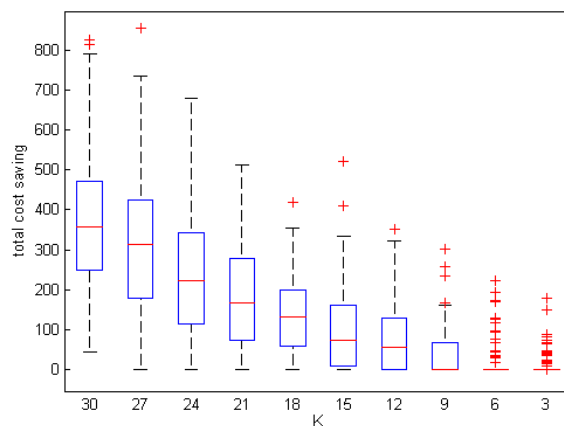

Fig. 1. Statistics of the total cost savings attained with various participation level K.

Offer Price. The prices offered by a carrier for other carriers to deliver its shareable orders are determined by its willingness to share the anticipated cost savings should it need not deliver the shareable orders on its own any longer. To understand the effects of the various degree of the carriers' willingness to the total cost saving attainable, we vary the willingness coefficient ϕ from 1.0 to 0.1 in steps of 0.1. This directly translates into various offer prices that may be encountered by the UCC since the offer price of a shareable order is given by $\phi \times$ mcs_min where mcs_min is the minimum marginal cost saving achievable when the carrier responsible for the order no longer needs to deliver it on its own. Herein, we set $K = 30$ and $\varphi = 1$.

Table 4 tabulates the success rates of the proposed double auction in producing some cost savings as the willingness coefficient ϕ for all carriers is reduced from 1.0 to 0.1 in steps of 0.1. It is clearly observable that higher willingness leads to higher success rate. Different from the case of less participation discussed previously, however, the decrease

in the success rate observed herein is rather insignificant. The proposed double auction still manages to yield cost savings in 95 out of the 100 scenarios even when $\phi = 0.1$, giving a success rate of 95%. Note that $K = 30$ trucks are considered to have participated in the double auction. All carriers are also assumed to be truthful in specifying their asking prices, i.e. $\varphi = 1$. This implies that each asking price is exactly the maximum marginal cost increment.

Table 4. Percentage of successful scenarios for various willingness factor ϕ.

ϕ	Success Rate
1.0	100%
0.9	99%
0.8	99%
0.7	99%
0.6	99%
0.5	99%
0.4	98%
0.3	96%
0.2	96%
0.1	95%

Observing the statistics of the total cost savings attained shown as boxplots in Figure 2, an almost perfectly linear trend can be seen on the range of the total cost savings with respect to the willingness coefficient ϕ. This observation also holds for the three quantiles of the total cost savings attained. Note that the total cost savings presented in Figure 2 is the ones known to the UCC as the auctioneer, that is the value of the objective function (1). Hence, the almost perfectly linear trend observed in Figure 2 is an indication that the double auction produces nearly the same exchanges regardless of the value of ϕ. With participation from 30 carriers in the double auction and the lack of profit-seeking behavior in computing the asking prices, it is almost always the case that there will be one carrier that could deliver a shareable order with lower cost. As ϕ is getting very low, however, profitable exchanges may no longer be feasible at times. This then results in the slightly lower success rates for ϕ as low as 0.3.
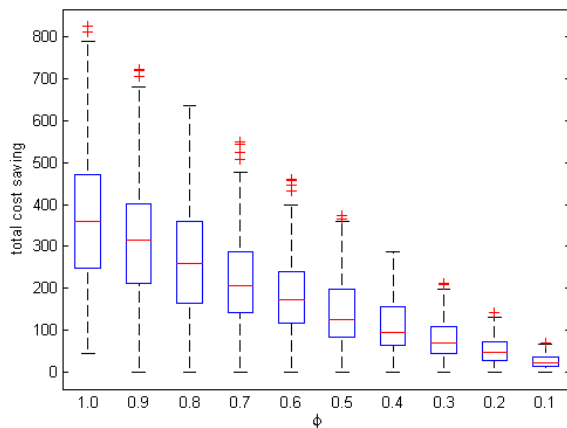

Fig. 2. Statistics of the total cost savings attained with various willingness ϕ of carriers to share their potential cost saving.

Asking Price. The prices requested by a carrier to perform the delivery of the shareable orders offered in the double auction are dependent on the inclination of the carrier to seek profit from the successful exchanges. In order to understand the effects of the various degree of carriers' inclination towards profit-seeking behavior, we experiment

with the inclination coefficient φ, setting it to between 1.0 and 1.9 in steps of 0.1. This translates into various asking prices that may be encountered by the UCC since the asking price to deliver a shareable order is given by $\varphi \times$ mci_max where mci_max is the maximum additional cost necessary to deliver the order. Herein, we set $K = 30$ and $\phi = 1$.

Table 5 tabulates the success rates of the proposed double auction in producing some cost savings as the inclination coefficient φ for all carriers is increased from 1.0 to 1.9 in steps of 0.1. Clearly, it is observable that higher inclination leads to lower success rate. Like before, the decrease in the success rate witnessed herein is quite insignificant compared to the case of fewer carriers participating in the double auction. The proposed double auction still manages to yield cost savings in 99 out of 100 scenarios when $\varphi = 1.9$, giving the success rate of 99%. This phenomenon is also observed when reducing the willingness coefficient ϕ up to 0.5, i.e. up to a factor of 2. As the matter of fact, herein we only vary the inclination coefficient φ up to a factor of almost 2. This is again some indication that the double auction produces similar exchanges regardless of the value of φ. With 30 trucks participating in the double auction and the willingness coefficient ϕ set to 1 for all carriers, it is almost always the case that there will be some shareable order with rather high offer price such that an asking price for delivering that order becomes sufficiently low, even when multiplied by a factor of nearly 2.

Table 5. Percentage of successful scenarios for various inclination factor φ.

φ	Success Rate
1.0	100%
1.1	99%
1.2	99%
1.3	99%
1.4	99%
1.5	99%
1.6	99%
1.7	99%
1.8	99%
1.9	99%

Figure 3 portrays the statistics of the total cost savings attained as boxplots. Note that the total cost savings shown in Figure 3 is the actual cost savings attained by the participating carriers. With ϕ set to 1, the offer prices represent the potential cost savings that can really be earned by the offering carriers. Regardless of the value of φ, successful transfers will require the offering carriers to pay the amount indicated in the asking prices. Hence, higher value of φ translates to lower the total cost savings attained statistically as depicted by Figure 3.
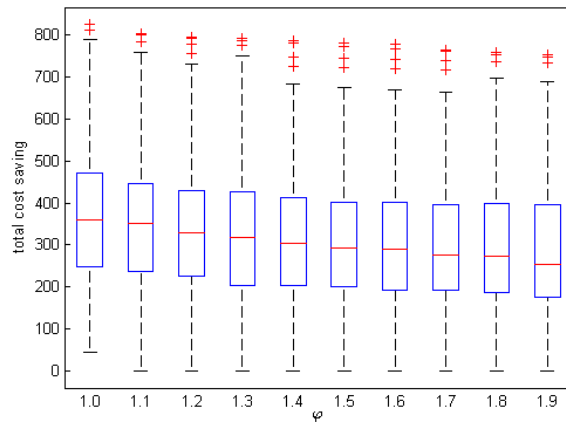
Fig. 3. Statistics of the total cost savings attained with various inclination φ of carriers to try to make profit from the order sharing.

4.4. Practical scenarios

To this end, we have witnessed that the participation level determines the efficacy of the proposed double auction. Varying either the willingness coefficient ϕ or the inclination coefficient φ while keeping the other one ideal has little effect to the success of the double auction in producing some amount of cost savings for the participating carriers. In practice, both willingness and inclination coefficients may vary. Thus, herein we uniformly randomize both ϕ and φ in the range of $[0.1, 1.0]$ and $[1.0, \ 1.9]$, respectively. We set $K = 30$.

Table 6. Results of order sharing via double auction over 96 practical scenarios.

	Number of Inter-zone Travels		Total Cost Savings
	Before	**After**	
minimum	46	35	8.14
maximum	68	61	429.07
average	55.33	47.78	160.02

Table 6 summarizes our findings in applying the proposed double auction to practical scenarios. Similar to the case where the double auction is subjected to the ideal scenarios, it is also able to reduce the number of inter-zone travels, eventually producing some cost savings. Unlike in the ideal case, however, the double auction only manages to produce cost savings in 96 out of 100 practical scenarios. Combination of lower willingness to share the potential cost savings and higher inclination to try to make profit out of the order sharing is the main cause of the lower success rate of just 96%.

5. Conclusion

In this paper, we identified a form of carrier collaboration that simultaneously allows cost reduction and privacy preservation, the two main driving factors that would motivate the participation of carriers in the UCC for possible implementation in Singapore. We then propose a double auction mechanism to maximize the total cost savings attained by all the participating carriers via consolidation of their shareable orders. Our experiments on 5 zones of delivery in Singapore CBD confirm that cost reduction is truly attainable. This is achieved via the reduction in the number of inter-zone travels. Furthermore, since our cost metric is a function of travel time and distance, the cost savings attained is related to the reduction in fuel consumption as well as fewer man-hours as the results of traveling

shorter total distance and less congested travel. As the aim of the carrier collaboration presented here is the reduction in fragmented deliveries, less traffic congestion is realized with fewer vehicles in the same area at the same time. Our proposed auction mechanism thus simultaneously addresses the planet, the people, and the profit aspects of the last-mile logistics in the urban areas.

Acknowledgements

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