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An Auction with Rolling Horizon for Urban Consolidation Centre

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***Abstract*— A number of cities around the world have adopted urban consolidation centres (UCCs) to address some challenges of their last-mile deliveries. At the UCC, goods are consolidated based on their destinations prior to their deliveries into the city centre. In many examples, the UCC owns a fleet of eco-friendly vehicles to carry out the deliveries. A carrier/shipper who buys the UCC's service hence no longer needs to enter the city centre in which time-window and vehicle-type restrictions may apply. As a result, it becomes possible to retain the use of large trucks for the economies of scale outside the city centre. Furthermore, time which would otherwise be spent in the city centre can then be used to deliver more orders. With possibly tighter regulation and thinning profit margin in near future, requests for the use of the UCC's service shall become more and more common. In [1], the authors proposed a profit-maximizing auction mechanism for the use of the UCC's last-mile delivery service. In this paper, we extend that work with the idea of a rolling horizon to give bidders greater flexibility in competing for the UCC's resources in advance. In particular, it addresses the challenge that many shippers/carriers plan their deliveries many weeks ahead, and simultaneously allows last-minute bidders to compete for the UCC's resources.**

I. INTRODUCTION

Last-mile deliveries in urban areas exert serious pressures on environmental, social, and economic well-being of a city. These three aspects are usually referred to as *planet*, *people*, and *profit* [2]. 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 include economic losses because of traffic congestion and low utilization of transport vehicles. Addressing these issues, local authorities may then impose time-window or vehicle-type restriction. The earlier complicates the scheduling of the last-mile deliveries from the perspective of carriers/shippers. Quite-so-often, wait time becomes inevitably necessary. Efficiency of the deliveries has thus been compromised. The latter, on the other hand, forces the carriers/shippers to operate small eco-friendly trucks for deliveries into the city centre. These trucks, however, are not efficient for long-distance inter-city transport. It is then clear that one aspect may be affected while addressing the others. Both the time-window and the vehicle-type restrictions affect the profit while trying to address the planet and the people. This prompts carriers/shippers to collaborate and consolidate shipments for greater efficiency.

The urban consolidation centre (UCC) is an alliance concept where oders served by various participating carriers get consolidated at the UCC. First, they are sorted according to their destination addresses. Then, they are assigned to a sufficient number of vehicles for the actual last-mile deliveries. The cost savings obtained are finally shared among the relevant carriers. As a consequence, higher truck utilization is attained, fewer trucks are required, and lower delivery cost is incurred. This effectively addresses the potential inefficiency due to the time-window restriction. The possible wait time suffered by those 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 centre. A fair allocation of the total savings earned among participating carriers enhances the profit.

To-date, there have been a number of UCC establishments with their own transport vehicles that are in compliance with the rules and regulations set by local authorities. These UCCs provide last-mile delivery service at a charge. Occasionally, the UCCs may be governments' initiatives or pilot runs and provide last-mile delivery service free-of-charge. In essence, carriers/shippers can simply drop their loads off at the UCCs and pay the UCCs accordingly to get the loads delivered into the city centre. Examples of these UCCs are La Petite Reine in Paris, France, Westfield Consolidation Centre in London, and Binnenstadservice.nl in Nijmegen, the Netherlands. This addresses not only the time-window but also the vehicle-type restrictions. By using the UCCs' service, carriers/shippers no longer need to enter the city centre. Retaining the use of large trucks for the economies of scale outside the city centre thus becomes possible. Besides, the time which would otherwise be spent in the city centre may then be used to deliver more orders. With these incentives, requests for using the UCCs' service would intuitively become more common. The UCCs could soon receive more demands than what they are capable of serving.

To our knowledge, most—if not all—UCCs operate with some fixed-rate mechanism on a first-come-first-serve basis. We found no literature discussing the automatic matching of orders to the available fleets of UCCs' transport vehicles for the efficient last-mile deliveries. We believe [1] to be the first auction mechanism proposed for the last-mile delivery via the UCC. Compared to the fixed-rate mechanism, the proposed auction is distinctively aimed at achieving both operational efficiency and economic viability—both of which are important for the sustainability of the UCC.

The basic auction mechanism proposed in [1] is however quite restrictive in that bidders are only allowed to compete for the UCC's resources in the immediate period following

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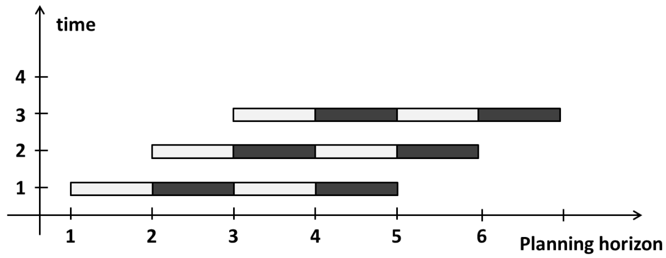

Fig. 1. A rolling horizon framework.

the winner determination. In that paper, a period of one week was observed. Indeed, one can argue that this is somewhat unrealistic as many shippers/carriers plan for their deliveries far in advance. To address this issue, not only the period needs to be lengthened but the auction needs to be conducted over a rolling horizon. This is as illustrated in Figure 1. The UCC starts Auction #1 at the beginning of Week #0 and accept bids for deliveries on Week #1 to Week #4. Prior to the start of Week #1, the UCC determines the winning bids for Auction #1. The UCC then starts Auction #2 at the beginning of Week #1 and accept bids for deliveries on Week #2 to Week #5, and so on. This gives greater flexibility for the bidders in that the participating shippers/carriers can choose to bid far in advance or in the last minutes. A unlike the basic UCC auction model, there are some overlap in the planning horizon of the UCC between two consecutive auctions. Intuitively, there may be only a few bids for deliveries on Week #4 in Auction #1. Profitable consolidation may thus be impossible at the time the winners of Auction #1 is determined. However, there should be more bids to come for deliveries on Week #4 in Auction #2 to Auction #4. Hence, profitable consolidation may in fact be possible after the upcoming auctions. This suggests that the UCC needs to be able to anticipate the potential revenue due to future bids in the upcoming auctions. For deliveries on Week #3, there may be enough bids to consolidate but some of the bids have low bid prices. Rather than accepting bids with low value to make profitable consolidation, it could be better for the UCC to accept only highly profitable bids in the current auction in the anticipation of other highly profitable bids in the upcoming auctions.

Our contribution in this paper is an auction mechanism with a rolling horizon that determines which demands are to be served in the anticipation of future demands. This is achieved by pricing the unused capacity, and our second contribution is to propose how to price the unused capacity. Note that this is not trivial problem, since the price should not be too conservative nor too optimistic. We then verify this through computational experiments. To our knowledge, this is the first auction with rolling horizon in the context of last-mile deliveries via the urban consolidation centre.

The remaining of this paper is then organized as follows. Section II briefly reviews some related works on auction in the logistics. Section III elaborates the basic auction mechanism presented in [1] and forms the basis of our extension described in this paper. Section IV proposes the auction mechanism in elaborative manner. Mathematical formulation of the augmented winner determination problem is also presented therein. Experimental results are subsequently presented and discussed in Section V. Finally, Section VI concludes the paper.

II. Related Works

Auction has been commonly used in the logistics context. Solving winner determination problems in logistics auctions is often equivalent to solving scheduling problem in order to minimize some transportation costs. Combining the services provided by different providers to fulfill some deliveries can be modelled as the set-partitioning [3] or lane-covering [4][**?**] problems. Commonly, the models are mixed-integer program (MIP) formulations with an objective of minimizing the costs subject to constraints on delivery time, capacity, and network structure. Such MIP formulations—when optimally solved—guarantees the least-cost solutions preferred by the planners. It can, however, be computationally-expensive even for just the medium-sized problems. A linear relaxation may be used to come up with a feasible solution in polynomial time [**?**]. A greedy algorithm may also be used to provide an efficient method for procurement scheduling [6]. The greedy approach is first used to construct the initial sub-solutions to different scheduling components. The Benders- or column-generation-based algorithm is then used to optimize the combination of the lanes. A column-generation-based algorithm solves some form of a restricted problem with a set of selected columns, reducing the size of the original problem quite considerably. Benders-based algorithm, also known as the row-generation-based algorithm, solves optimization problems in two stages. In the first stage, the master problem is solved to formulate some constraints for the sub-problems. In the second stage, scheduling solution is identified for each sub-problem. Note that despite the numerous literature on logistics auction, we found none pertaining to the use of the UCC. Furthermore, the concept of rolling horizon [7] has been extensively used for decision making[8][9][10] . Recently, the rolling horizon concept has also been adopted in transportation and logistics context [11][12][13].

III. Basic UCC Auction

At the UCC, packages to be delivered to the same zone in the city centre are consolidated to achieve the economies of scale. In [1], it is assumed that shippers/carriers are aware of the potential cost savings they can benefit from when using the service offered by the UCC for their last-mile deliveries. It is further assumed that the UCC operates its own resources to consolidate and deliver orders to the city centre. A profit-maximizing auction mechanism was proposed for the use of the UCC's service in [1]. The proposed auction mechanism requires the UCC to know only its operational costs, namely the *delivery* and *storage* cost. For the sake of simplicity, it is assumed that the UCC operates homogeneous fleet of trucks. Therefore, the delivery cost is the cost of operating any truck to zone z in the city centre and is denoted by c_z. The storage cost, on the other hand, is the cost of storing a unit volume of package overnight in the warehouse and is denoted by c_w. With these costs known, the mechanism also ensures budget balance on the resulting allocation.

A. Auction Protocol

To plan for the last-mile deliveries in its nearest upcoming planning horizon, a UCC will conduct an auction and invite some shippers/carriers to submit their bids to be considered in utilizing the last-mile delivery service offered. A bid b_i is defined as a tuple:

$$[v_i, d_i, a_i, \ell_i, p_i]$$

where

- v_i is the volume of the package,
- d_i is the destination of the package which belongs to a non-overlapping zone z in the city centre,
- a_i is the arrival day of the package at the UCC,
- ℓ_i is the delivery deadline of the package, and
- p_i is the price the bidder is willing to pay the UCC.

B. Winner Determination

When the auction is closed, the UCC would have received a set of bids $\mathcal{B} = \{b_i\}$. It then has to determine the winning bids and notify their respective bidders. This is equivalent to determining which bids are to be served such that the profit of the UCC over its planning horizon is maximized. For that purpose, our proposed mechanism first computes the sum of the prices at which the winning bidders would pay the UCC and then subtracts it by

1) the total storage cost for all the packages delivered not on their arrival days, and
2) the total delivery cost over the planning horizon,

subject to the following operational restrictions.

1) There are a limited number of trucks.
2) Each truck has a limited capacity.
3) Each truck only serves one zone at a time.
4) There is only one delivery per day per truck.

This gives rise to the following basic winner determination problem for the first-price auction at the UCC.

Definition 1 (Basic Winner Determination Problem): Let i, k, z, and t, respectively, be indices of the bids, the trucks, the zones, and the days over the planning horizon. Let V be the homogeneous capacity of the trucks. Denoting decisions on day t whether the i-th bid is delivered using the k-th truck and whether the k-th truck is deployed to serve the z-th zone as binary variables $x_{ik}^t \in \mathbf{X}$ and $y_{kz}^t \in \mathbf{Y}$, respectively, the basic winner determination problem (WDP) aims to identify

$$\arg\max_{\mathbf{X},\mathbf{Y}} \left\{ \sum_{i,k,t} \left[p_i - c_w v_i (t - a_i)\right] x_{ik}^t - \sum_{k,z,t} c_z y_{kz}^t \right\} \quad (1)$$

subject to

$$\forall i \sum_{k,t} x_{ik}^t \leq 1 \quad (2)$$

$$\forall k \forall t \sum_{z} y_{kz}^t \leq 1 \quad (3)$$

$$\forall k \forall t \sum_{i} v_i x_{ik}^t \leq V \quad (4)$$

$$\forall i \forall k \sum_{t \notin [a_i, \ell_i]} x_{ik}^t = 0 \quad (5)$$

$$\forall k \forall z \forall t \sum_{i, d_i \in z} x_{ik}^t \leq |\mathcal{B}| y_{kz}^t \quad (6)$$

where $i = 1, 2, \ldots, |\mathcal{B}|$, $k = 1, 2, \ldots, K$, $z = 1, 2, \ldots, Z$, $t = 1, 2, \ldots, T$, and $x_{ik}^t, y_{kz}^t \in \{0, 1\}$ for all i, k, z, and t.

The profit of the UCC is depicted in (1) which constitutes the objective of the mixed-integer program (MIP) described in Definition 1. In essence, it is the sum of bid prices paid by the winning bidders subtracted by the storage costs incurred and the total delivery cost to various zones on different days. The storage costs are incurred when deliveries are performed on any day after and different from the package arrival day at the UCC. Note that the profit can never be negative, hence budget balance property is guaranteed. Rejecting all the bids will result in zero profit, which serves as the lower bound of the profit. Operational restrictions are enforced by (2)–(6) as follows.

- The *package integrity* constraint (2) ensures that every package is delivered at most once.
- The *resource uniqueness* constraint (3) ensures that any truck on any day serves at most one zone.
- The *vehicle capacity* constraint (4) ensures consolidated packages fit into the allocated trucks.
- The *delivery time* constraint (5) ensures that no package gets delivered before its arrival at the UCC or after its delivery deadline.
- The *resource activation* constraint (6) ensures that any truck on any day with at least one package to deliver is not idle.

For the simplicity of our further discussions, let us denote the profit in (1) as

$$\Upsilon(\mathbf{X}, \mathbf{Y}) \quad (7)$$

IV. Proposed UCC Auction with Rolling Horizon

Winner determination problem for the basic UCC auction elaborated in Section III assumes that the planning horizons of two consecutive UCC auctions never overlap one another.

As established in Section I, this restricts shippers/carriers as the bidders to compete only for the UCC's delivery resources in the immediate period following the winner determination.

In practice, longer planning horizon is often desirable so as to allow shippers/carriers to bid for delivery resources not only in the immediate period but also in the subsequent few periods following the winner determination. Announcement of the results of each auction—and hence, determination of the winning and the losing bids—should remain as frequent so that the losing bidders could have a chance to arrange for some other means of delivery or to alter their bid prices and resubmit their bids in the subsequent auction. This gives rise to the UCC auction with a rolling horizon. The requirements of longer planning horizon and high-frequency update makes the implementation of rolling horizon in the UCC auction an interesting and significant topic.

As illustrated earlier in Figure 1, winners for the multiple consecutive delivery periods across the planning horizon are determined simultaneously at the end of each auction before the start of the next auction. Upon closing Auction #1, bids for potential deliveries at any days on Week #1 to Week #4 could have been received and the corresponding winners are determined simultaneously. While the committed deliveries on Week #1 are carried out, Auction #2 is accepting bids for the potential deliveries at any days on Week #2 to Week #5. At the closure of Auction #2, the winners for deliveries on Week #2 to Week #5 are determined. Committed deliveries on Week #2 are then carried out while Auction #3 accepts bids for deliveries on Week #3 to Week #6. The cycle then continues. From this illustration, it is clear that the UCC's delivery resources in one period are considered in a number of auctions altogether. The delivery resources for Week #3, for instance, are considered in 3 consecutive auctions. When determining the winners of Auction #1, the auctioneer may intuitively wish to reserve some capacity for profitable bids yet to come in Auctions #2 and #3 for deliveries on Week #3. When determining the winners of Auction #3, however, it is intuitive to use as much remaining capacity as possible since capacity left unused will no longer have any potential value.

Motivated by this, we propose herein an augmentation to the profit expression of the winner determination problem in Definition 1. This augmentation aims at pricing the unused capacity with its potential to be allocated to more profitable bids in upcoming auctions. This is equivalent to introducing virtual bids to the current auction, which could potentially be replaced by real bids of equal or higher values in the future auctions. Other than reserving capacity for highly profitable future bids, such augmentation additionally allows selection of few profitable bids in the current auction as the winners although there may not be enough bids to realize profitable consolidation at the moment.

Precisely, we adjust the profit function as follows. Let q^t_{kz} denote the potential value of one unit of unused truck capacity if truck k delivers to zone z at day t and let V^t_k denote the remaining capacity of truck k at day t. If $y^t_{kz} = 1$, the potential value for the remaining capacity of the truck after the auction is $q^t_{kz}(V^t_k - \sum_i v_i x^t_{ik})$, and 0 otherwise. Additionally if truck k does not deliver to any zone in period t, we assume the potential value is the average potential value of the full truckload $(\sum_z q^t_{kz}/Z)V^t_k$. Hence, the profit after adjustment can be expressed as

$$\begin{aligned}\hat{\Upsilon}(\mathbf{X},\mathbf{Y}) :=\ & \Upsilon(\mathbf{X},\mathbf{Y}) \\ & + \sum_{k,z,t} q^t_{kz} \min\{M \cdot y^t_{kz},\ V^t_k - \sum_i v_i x^t_{ik}\} \\ & + \sum_{k,t} \left(\left(\sum_z q^t_{kz}/Z \right) V^t_k \left(1 - \sum_z y^t_{kz} \right) \right), \quad (8)\end{aligned}$$

where M in (8) is some large constant. In the rolling horizon implementation, we update the value of V^t_k in each auction, replace V in (4) by V^t_k and $\Upsilon(\mathbf{X},\mathbf{Y})$ by $\hat{\Upsilon}(\mathbf{X},\mathbf{Y})$, then solve the optimization problem (1)-(6) for new winning bids. This process is repeated for every auction.

A. *Pricing the Unused Capacity*

The value of q^t_{kz} is a critical parameter in rolling horizon implementation and has great impact on the performance. A reasonable value of q^t_{kz} can be roughly determined in the following way. Suppose the distribution of the ratio p/v of price to volume of bids is available or can be estimated from historical data, and let $F(\cdot)$ denote the cumulative distribution function of the ratio p/v. Then we want to fill the remaining truck capacity V_k with the bids with the highest value of price-volume ratio. If the total volume of the oncoming bids is V, then the best value of q is $F^{-1}(1 - V_k/V)$, as shown in Figure 2. This value is for the optimistic case where all bids with the high price-volume ratio can be consolidated into a truck load. However, this is almost not possible in reality due to non-splittable volume of bid and limited number of bids. Therefore, the value of q in practice should be set smaller than $F^{-1}(1 - V_k/V)$ appropriately.

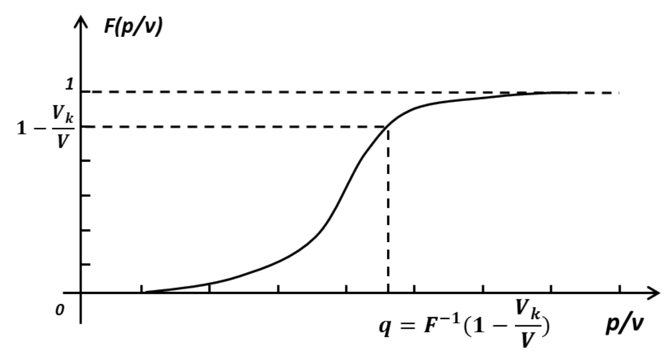

Fig. 2. Determination of value of potential value rate.

V. Experiments

A. The UCC

In this section, the efficacy of the proposed UCC auction with rolling horizon will be demonstrated via computational experiments. To understand the contribution of the rolling horizon framework more clearly and easily, we consider a problem with one zone and one truck with capacity 10. The planning horizon is 10 weekdays (2 weeks) and the auction result is released weekly. The delivery cost is deterministic and equals 10.

B. Bid Generation

For each auction, a total of 30 bids are generated in which 15 bids compete for the UCC's delivery resources on the first week of the planning horizon and another 15 for resources on the second week. The price-to-volume ratio of the bids is uniformly distributed between 0 and 3.

C. Efficacy of UCC Auction with Rolling Horizon

In our first experiment, we set $q_{11}^t = 0$ for each $t = 1, 2, ..., 5$ and $q_{11}^t = 1$ for each $t = 6, 7, ..., 10$ and let the simulation runs for 10 weeks. The truck load on Friday of the Week #2 to Week #10 are shown in Figure 3(a). The result of Week #1 is not shown since it is only involved in one auction and no truck load is committed before. In the figure, the circles show the truck load committed one week before the delivery date and the stars show the final truck load. It can be observed that in most of the days, the final truck load contains a portion that is committed one week before the delivery date. For truck load on Monday, Tuesday, Wednesday and Thursday we can also observe the similar pattern, which also lead to a weekly total truck load as shown in Figure 3(b). From Figure 3(b), we can observe that about half of the weekly truck load are committed one week before and this is shown specifically by Figure 4. In the figure, the dash line shows the percentage of the weekly load that is committed one week before. It can be seen that around 50% of the total load is committed one week before. In Figure 4, the solid line also shows the percentage of the total profit that is due to such load. In most weeks, the solid line is above the dash line, suggesting that by pricing the unused capacity properly (i.e. setting q_{kz}^t appropriately) the winning bids chosen one week before are more profitable.

D. Effect of Various Pricing of Unused Capacity

To further show the importance of the potential value rate, we let q_{11}^t where $t = 6, 7, ..., 10$ change from 0 to 3.4 while keeping q_{11}^t for each $t = 1, 2, ..., 5$ to see how the total revenue (profit) changes with the pricing of the unused capacity. Since the delivery cost remains the same for all cases, we just compare revenue contributed by different types of bids. The result is shown in Figure 5 where the darker bars at the bottom shows the revenue contributed by the winning bids for deliveries on the second week of the planning horizon and the lighter bars on the top corresponds to the revenue attributable to the winning bids for deliveries on the first week of the planning horizon. Note that when

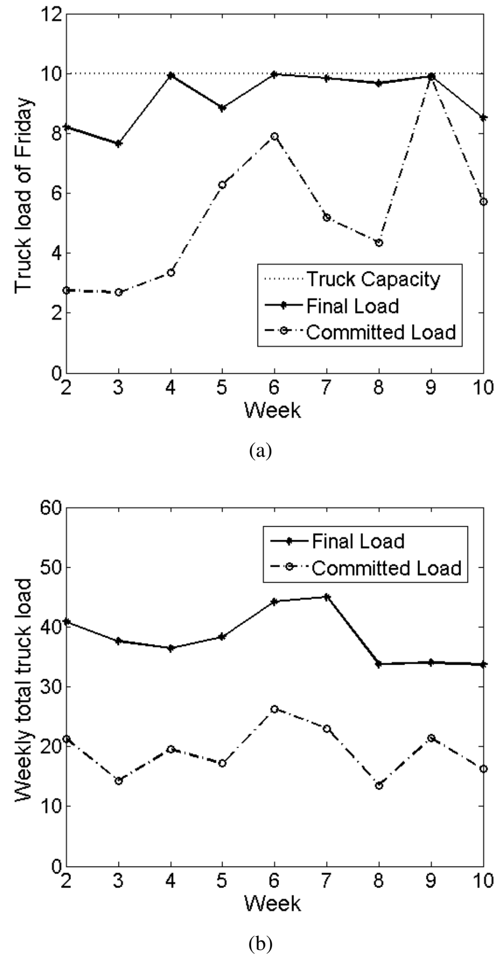

Fig. 3. (a) Truck load of Friday. (b) Weekly total truck load.

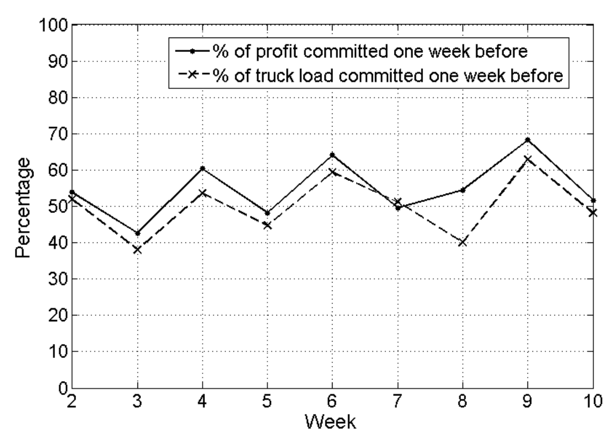

Fig. 4. Percentage of profit and truck load committed in advance (i.e. one week ahead of the actual delivery week).

$q_{11}^t = 0$, the winning bids are selected exactly according to (1). As q increases, the revenue contributed by the winners of the second week's delivery resource first increases and then decreases. The total revenue follows the same trend. When $q > 3$, all the shipping capacity is reserved for the very last auction before the delivery date as no bids have the price-to-volume ratio larger than 3. Therefore, there is no winning bids for deliveries on the second week of the planning horizon in such cases, and it is equivalent to run the auction with one week planning horizon every week without rolling horizon. Figure 5 also verifies the idea of choosing value of q described in Section IV. As the expected total volume of the 15 bids is 22.88, the value of q should be $3 * 10/22.88 = 1.31$ in the ideal case. But due to non-splittable bid volumes and the small number of bids, the best value of q appears around 1 which is smaller than 1.31.

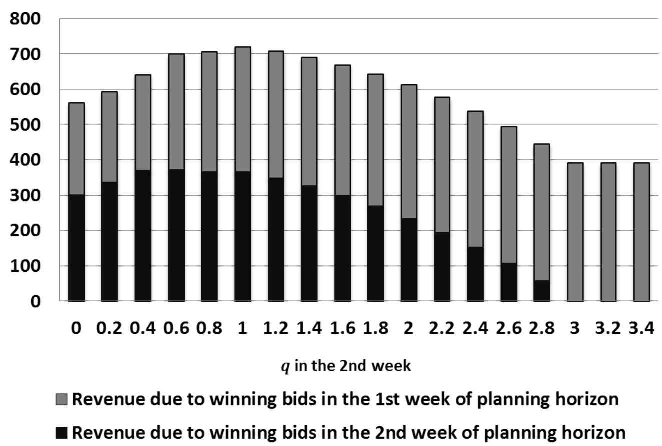

Fig. 5. Revenue v.s. value of q_{11}^t for all $t = 6, 7, ..., 10$.

VI. Conclusion

In this paper, we have presented auction mechanism with rolling horizon for the consolidation of last-mile deliveries into the city centre via an urban consolidation centre (UCC). To anticipate profitable bids in future auctions, we augment the profit function of the basic winner determination problem with additional terms to allow pricing of the unused capacity. This is essentially equivalent to introducing some virtual bids to the current auction, which may potentially be replaced by the real bids in the upcoming auctions.

More scenarios shall be explored in near future, especially those that represent more practical situations in reality. Many constraints not covered in this paper need to be considered. These include warehouse capacity, consolidation preference, routing consideration, as well as demand uncertainty.

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