

Combinatorial Auctions in Procurement¹

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1. Introduction

Everyday, companies struggle with multiple decisions in the fight to increase their profitability. Complex decisions a company must make include, (1) how much should we order from our suppliers and when?, (2) how should we organize our supply chain and logistics?, (3) how much should we produce (4) what price should we charge or pay for goods and services?

Making the “right” pricing decision in sales or procurement is a complex task. While the types of pricing policies/methods used in the exchange of goods and services vary greatly, we can divide these mechanisms under two broad categories: posted price mechanisms and price discovery mechanisms. Under a posted price mechanism, a good is sold at a take-it-or-leave-it price determined by the seller. A posted price can be dynamic, i.e., the seller may offer different prices to different customers (customized prices) or change prices dynamically over time (intertemporal prices). In a price discovery mechanism, prices are determined via a bidding process.

A commonly used price discovery mechanism that has experienced a tremendous growth in use is an auction. In a forward auction, the seller puts out an item (or a set of items) for sale, and buyers compete in a bidding process. In a reverse (procurement) auction, a buyer puts out a request for quote (RFQ) for a service or a product(s), and prices are determined by a competition among potential sellers. Auctions implemented over the Internet have several benefits compared to traditional auctions, including lower information, transaction, and participation costs; increased convenience; ability for asynchronous bidding; and access to larger markets [9]. Hence, companies increasingly use Internet auctions to buy and sell excess inventory, first-run goods and commodities, to test prices for new consumer goods, to market one-to-one, and to fine-tune inventory levels.

Most of the B2B auctions involve the exchange of multiple products/goods. Despite this salient characteristic of B2B auctions, the research in auction theory has traditionally focused on single-unit auctions, i.e., only a single unit is to be traded via the auction or bidders only wish to acquire a single unit. In addition, while designing, implementing or studying auctions for multiple goods, a strong assumption that has been often made in the literature is that bidders experience no synergies or complementarities in values across multiple units. Two objects are said to be complements, have superadditive values, or exhibit synergies, when their value together is more than the sum of their individual values. For example, in the recent FCC spectrum auctions, bidders, comprised of US telecommunication companies, cellular telephone companies, and cable-television companies, competed to win various spectrum licenses for different geographical areas. The synergies arising from owning licenses in adjoining geographical areas create dependencies in (some) bidders' valuations for individual licenses. Similarly, in manufacturing there may be synergies, or economies of scale, in producing larger quantities, while in logistics there may be synergies associated with acquiring adjacent lanes or lanes that form a closed loop.

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While bidders experience synergies across multiple items in numerous settings, most auctions in use today are simple auctions, i.e., each unit (or bundle of units) is auctioned independently of all other units and the lowest bidder wins in each auction. A simple auction is an attractive selection mechanism because it is simple to evaluate the bids and determine the winner. However, when multiple units are auctioned and there is a strong presence of synergies in production costs, a simple auction cannot adequately allow suppliers (or buyers) to reflect their synergies in production over multiple units.

An alternative format to a simple auction is a package or combinatorial auction. In a combinatorial auction, bidders can submit all-or-nothing bids on packages of goods in the form “I will pay \$X if I win goods A and B or I will pay \$Y for only A and \$Z for only B (where $X > Y + Z$)”. A combinatorial auction is an effective mechanism when there exist strong complementarities over several goods, and the source of those complementarities varies for different suppliers.

In the remainder of this paper, we give an overview of combinatorial auctions and discuss a recent application of combinatorial auctions by The Home Depot in the procurement of transportation services. A teaching case study on this application is presented in [2].

2. Combinatorial auctions

The use of combinatorial auctions in industrial settings has increased of late. Sears Logistics Services and The Home Depot, Inc. are two examples of companies using combinatorial auctions for procurement of logistical services; Sears Logistics saved over \$84 million running six combinatorial auctions [6]. Additional examples include Walmart Stores, Compaq Computer Co., Staples Inc., The Limited Inc. and Kmart Corporation, who implemented combinatorial auctions for procurement with the aid of Logistics.com. With the application of Logistics.com’s procurement solutions, Limited Logistics Services, the supply chain arm of The Limited Inc., saved \$1.24 million in shipping costs in year 2001 compared to the previous year [8].

Combinatorial auctions are auctions where bidders can name their prices on combinations of items, as opposed to individual items. Each combination of items submitted to the auctioneer is called a bundle or a package. A bid consists of a bundle and its price, and bidders are usually allowed to submit multiple bids. Due to the conditional format of the bids, combinatorial auctions lend themselves to environments where bidders have high synergies across multiple items. Despite this attractive feature, the use of combinatorial auctions has not traditionally been commonplace. The challenge facing academics and practitioners alike is how to design a combinatorial auction that will allow bidders to effectively incorporate their synergies (the mechanism design problem) without posing an unnecessary burden on the auctioneer when computing the optimal allocation (the winner determination problem). In an effort to address these issues, there is a growing body of literature on the use and design of combinatorial auctions.

A serious issue that limits the use of combinatorial auctions in real applications is the Winner Determination Problem. After all the bids are submitted, the auctioneer needs to determine the optimal selection of winning bids. The winner determination problem for combinatorial auctions is NP-complete, i.e., no algorithm is guaranteed to find the optimal solution in polynomial time [10]. Several researchers have designed fast search algorithms to solve for the exact optimal solution [16][17][3]. While solving for the optimal solution would be ideal, in most business

environments, a near-optimal solution that can be obtained quickly is widely acceptable. Therefore, several approximate solution methods have been developed by academics [14][3][7].

In addition to the burdensome nature of the winner determination problem, submitting combinatorial bids pose an equally challenging problem from the bidders' perspective. In an auction with n items, there are $2^n - 1$, i.e., exponentially many, possible combinations or bundles a bidder can choose from. Furthermore, determining the appropriate bidding price on the bundles, taking into account not only one's own costs and resources but also the competitors, is an equally challenging task.

Clearly, the bidders' bidding decisions and the result of the auctions will depend heavily on the auction format. For example, should bidders be allowed to submit bids on any possible package or should only certain package bids be allowed? One possibility to ensure that the winner determination problem can be solved optimally in polynomial time is to restrict the number and the type of bids that can be submitted [10]. Unfortunately, restrictions on the bids lead to similar economic inefficiencies that exist in non-combinatorial auctions, since bidders may not be able to bid on the combinations they prefer [15].

Another critical design question is whether the auction should be comprised of several bidding rounds or limited to only a few. A single round auction format that received particular attention in the literature is the Generalized Vickrey Auction (GVA) [7][18]. In a GVA, each winning bidder is charged the total social surplus that would be possible if that bidder did not participate in the auction at all. In this mechanism, the dominant strategy for each bidder is to report his true value for each bundle and GVA allocation maximizes the sum of the true valuations of the bidders, i.e., the social welfare. While it has the attractive feature of truthful bidding, the GVA is computationally burdensome on the auctioneer, and requires that the bidders submit their valuations over all possible bundles.

One motivation to have multiple rounds in a combinatorial auction is to relieve the computational burden the GVA and other single-round formats place on the bidders during the bid preparation process [11][12][13][1][4][20][21]. In multi-round combinatorial auctions, bidders can submit bids on different bundles of items as prices change, and make new bids in response to bids from other agents. In a multi-round combinatorial auction bidders are allowed to submit bids on subsets of bundles in each round, which can be easier (as compared to GVA) for bidders with limited or costly computational resources. Furthermore, a multi-round combinatorial auction allows the auctioneer to solve a sequence of smaller winner determination problems, than a large, complex problem such as the one resulting in a single round GVA.

In the next section, we discuss the experiences of The Home Depot in its implementation of a combinatorial auction. The design decision of The Home Depot was to use a single round combinatorial auction, although they eventually had a second round for a limited number of lanes and a selected group of carriers. The winner determination problem was solved using an integer programming based algorithm.

3. Case Study: Procurement of Transportation Services via Combinatorial Bidding at The Home Depot

The Home Depot was founded in 1978 in Atlanta, Georgia, and is currently the world's largest home improvement retailer with over 1000 stores and 37 distribution centers in 45 states of the

United States, as well as in five Canadian provinces, Puerto Rico, and Chile. The Home Depot expects to be operating over 1,900 stores in the Americas by the end of the year 2003.

Home Depot stores cater to do-it-yourselfers, as well as home improvement, construction and building maintenance professionals. An average Home Depot store is approximately 130,000 square feet, and stocks approximately 40,000 to 50,000 different kinds of building, home improvement, and lawn and garden products, including variations in color and size. The newer stores also include a 15,000-25,000 square foot garden center.

In June 1999, Home Depot launched its expanded Website (www.homedepot.com) which includes more than 150 interactive how-to projects, personalized customer home pages and interactive features such as project calculators. In the near future, Home Depot plans to fully integrate its Website with its stores that will allow consumers to use the Internet and the stores in combination. Home Depot customers will be able to check product availability on-line and purchase in a store, order on-line and pick up at a store, buy on-line and return a product to a store and utilize an in-store kiosk for project information and product listings, among other options.

For the year ended Jan. 28, 2001, Home Depot's sales increased 19 percent to \$45.7 billion compared with \$38.4 billion for the year ended Jan. 30, 2000. Revenues are expected to grow between 15 and 18 percent annually from 2002 through 2004. Home Depot's stock is publicly traded (NYSE:HD) since 1981 and is included in the Standard & Poor's 500 Index and the Dow Jones 30 Industrial Index.

3.1. Logistics and transportation challenges at Home Depot

The Home Depot is credited as being the innovator in the home improvement retail industry by combining the economies of scale inherent in a warehouse format with a high level of customer service. In the warehouse-style retail format pioneered by the company, each of the Home Depot stores is also a warehouse, where industrial racks are used to display the merchandise and to stack the inventory. Combining a retail store and warehouse in one location helps the company to keep the costs down by reducing the overhead and to increase customer satisfaction by offering a wide variety of products and reducing stock-outs. Home Depot's retailing strategy also focuses on high quality merchandise and excellent customer service. Home Depot stores offer a variety of services, including, free design and decorating consultations, truck and tool rental, home delivery, free potting, and many other services to accommodate customers' home improvement needs.

Managing the logistics of this retailer giant is no easy task. It requires the coordination of over 7000 suppliers, numerous carriers and over 1000 stores and 37 distribution centers. Adding to the complexity is the rapid growth of the company with its plan to expand to over 1,900 stores in the Americas by 2003. The company's logistics infrastructure also needs to support its growing online operations. Home Depot's current e-commerce strategy utilizes the company's existing stores as fulfillment centers or pick-up centers for products being ordered on-line by customers. A key component of Home Depot's logistics is managing the transportation of over 40,000 SKUs between suppliers, warehouses and retail locations. Over 90% of Home Depot's products move via trucks. In 1999, the company made approximately 7.1 million less-than-truckload (LTL) shipments and 219,000 truckload (TL) shipments. With the planned addition of new stores and the new logistics strategy, these volumes are expected to change to 4.7 million (LTL) and 877,000 (TL) in 2003, with a significant growth in TL shipments and a reduction in LTL shipments. Home Depot is planning to expand its existing network with cross-dock facilities,

which will allow them to consolidate the shipments from the suppliers and to the stores and reduce the total amount of LTL shipments.

3.2. Traditional process for transportation bidding

Up until about four years ago, Home Depot's transportation bidding process was completely manual. Home Depot would provide the carriers with origin and destination zip codes for the locations in its network, and aggregate demand forecasts (expected number of annual moves) for each origin-destination pair (referred to as a lane). Carriers did not, however, have information on Home Depot's demand or growth patterns. Based on this sparse and aggregate information, carriers would bid on each origin-destination pair separately.

One of the drawbacks of this bidding process was that it lacked the flexibility for carriers to reflect groups of lanes that they wished to win together. This was a serious omission from the bidding process: Due to the physical considerations and cost structure of operating a truck, carriers can operate some groups of lanes more efficiently (cost effectively) than any subset. Bidding for each lane individually made it difficult for carriers to incorporate cost synergies (across lanes) into their bids.

In an effort to improve the efficiency of the bidding process, in 1996, Home Depot semi-computerized the bidding process by asking the carriers to submit their bids on a standardized Excel spreadsheet on a diskette. Nevertheless, Home Depot continued to procure bids for lanes on an individual basis and limit the information that was provided to the carrier regarding the flow of orders on a lane. Carriers continued to be unable to make informed bidding decisions or adequately reflect any synergies across lanes. In the absence of accurate demand data, carriers made several assumptions about the actual distribution of demand throughout the year. One optimistic approach employed by carriers was to assume that the demand is distributed evenly throughout the year; a pessimistic approach was to estimate that all the demand realizes during one week or one month of the year. Either estimate was very likely to be far away from reality, and could result in a carrier either bidding too low and losing money, or bidding too high and not winning a potentially profitable lane.

In summary, the traditional bidding process had a number of serious limitations:

- (a) It did not provide the carriers with good visibility to Home Depot's network and lacked detailed demand information on the network.
- (b) It did not allow carriers to bid on combinations of lanes to achieve potential synergies. This, combined with the lack of detailed demand information, prevented the carriers from submitting bids that accurately reflect their cost structures.
- (c) The manual bidding process was very inefficient.

3.3. An innovative process for transportation bidding

To achieve higher efficiency and effectiveness in transportation services, Home Depot partnered with i2 Technologies to develop a flexible bidding mechanism for truckload shipments. The new bidding process provides detailed information to the carriers about Home Depot's network and demand, and allows carriers to bid for combinations of lanes, as well as for individual lanes. This helps carriers to better analyze the impact of certain bidding alternatives on their own network, and to achieve synergies, for example, by creating "continuous" moves which don't require empty travel between the lanes. Furthermore, the new bidding mechanism is Internet-based,

which allows carriers to create and submit their bids electronically via a standard format. The first successful application of this new bidding process was completed in January 2000.

3.3.1. Information provided by The Home Depot

Before the bidding process begins, Home Depot provides potential bidders with information on

- origin and destination locations,
- lane details, and
- demand forecasts.

A *location* is a title for one or more actual origin(s) or destination(s). A location could be a *point*, such as a single vendor, distribution center or store, or it could be a *zone*, such as a cluster of vendors or a cluster of stores. As before, a *lane* is a unique origin-destination pair requiring a specific type of service and equipment. Lanes can be point-to-point (e.g., vendor to DC), point-to-zone (e.g., DC to cluster of stores), zone-to-point (e.g., cluster of vendors to DC), or zone-to-zone (e.g., cluster of vendors to cluster of stores). Under the new bidding process, in addition to its origin and destination, Home Depot specifies for each lane the average route distance, average number of stops, demand forecast (truckloads), equipment requirements (e.g., dry van, 53' van, flatbed, decked van) and service requirements (e.g., linehaul or linehaul to DC). Aggregated demand volume forecasts for different equipment types and for different lanes are presented in Tables 1 and 2. Detailed daily and weekly demand forecasts are also provided to the bidders, which include seasonal fluctuations in demand and new stores through December 2000. New stores are modeled after existing stores with similar characteristics and their estimated opening dates are provided to the bidders.

Table 1: Demand forecasts by equipment type (year 2000)

Equipment type	Lanes	Loads
Dry van	317	41,847
53' van	25	5,343
Flatbed	268	5221
Decked van	13	41
Total	623	52,452

Table 2: Demand forecasts by lane type (year 2000)

	Loads	Lanes
Point-to-point	24,574	171
Point-to-zone	25,153	402
Zone-to-point	146	3
Zone-to-zone	2579	47
Total	52,452	623

3.3.2. Bidder information

In addition to selecting carriers that could satisfy Home Depot's transportation needs at a reasonable price, Home Depot was also concerned with selecting carriers that were of an acceptable quality and with whom Home Depot could develop a promising business relationship. In order to achieve this end, Home Depot screened carriers before inviting them to participate in the bidding process. Carriers were asked to supply Home Depot with information concerning

their financial stability, geographic coverage, claim history, equipment age, total yearly revenues, etc. While the carriers were asked to provide this information voluntarily, most of these statistics can be obtained from outside sources (for example, the Department of Transportation).

Based on the carriers' characteristics, Home Depot was able to eliminate several carriers with whom they did not feel they could establish a fruitful business relationship. The primary reason that carriers were not invited to bid was questionable financial stability. Some carriers were eliminated due to poor quality records while others were considered to be too small in size to become a significant partner with Home Depot. In addition to using this information to screen bidders, Home Depot would use this information throughout the bid evaluation process when developing feasible solutions when selecting winning bidders.

3.3.3. Bidding software

Three main pieces of software were used during the bidding process: (1) Shipper bid support (SBS), (2) Carrier bid response tool (CBR), and (3) Bid selection optimization.

The SBS module assists Home Depot in analyzing their network and in deciding on which lanes to put out for bid. For the first implementation of the new bid process, Home Depot decided to focus only on a specific part of their business, namely, on vendor-to-store direct shipments. The lanes that were put out for bid accounted for about 52,000 moves, approximately one fourth of all the in-bound moves to stores within Home Depot's network. Next year, Home Depot plans to include the DC-to-store lanes in the bidding process as well.

To help carriers analyze the demand data provided by Home Depot and create bids that complement their existing networks and cost structures, Home Depot created the CBR module. This module was made available to carriers for download via the Home Depot website. The CBR module includes a graphical user interface to help carriers visualize the physical structure of the shipper's network and the relative locations of the lanes in a potential combination bid. The module also has the standard template for carriers to prepare and submit their bids. Via this module, carriers can submit their bid on selected lanes and lane groups. In addition to their minimum price requirements, carriers can convey to Home Depot the type of equipment they plan to use if awarded the lane(s), the maximum number of moves and the maximum dollar volume they wish to be awarded.

3.3.4. Bidding rules

Under the new bidding process, carriers are able to bid on groups of lanes in addition to bidding on individual lanes. Lane groups may represent geographic areas, groups of facilities or may simply be created by the carrier to fit into his existing schedule. To maintain maximum flexibility, and at a possible cost to computational complexity, Home Depot decided to not restrict the lane groups on which a carrier can bid. That is, a carrier was allowed to bid on any combination of lanes; a lane could be bid as many times and in as many combinations as a carrier wanted.

A particular origin-destination route may contain more demand volume than any one carrier can handle (or more than is desirable to assign to only one carrier). Therefore, Home Depot, when necessary, partitioned the demand and creates several distinct lanes. This allowed them to restrict carriers to bid for all of the volume on a lane.

A carrier's bid for a lane (or lane group) represents the minimum price that carrier must be paid in order to service that lane (or lane group). In order to avoid situations where the carriers do not wish to service the lanes they have been awarded, Home Depot allows carriers to specify additional restrictions (or "constraints") on their aggregate bids. For example, to ensure that the total lanes awarded to a carrier do not exceed its available capacity, a carrier might limit the number of loads awarded by geographical area or by asset usage. In addition, carriers can specify the total dollar volume of business that they wish to win. In addition, carriers can submit "OR" bids of the following form: "I would like to be awarded either combination bid A or combination bid B, (but not both)". Given the flexibility provided by this bidding structure, carriers are bound to execute any bid submitted in the event that they are awarded that bid. As a further deterrent to carriers renegeing on their awarded lanes, Home Depot informed all bidders that in the event of renegeing on a bid, Home Depot would take that lane plus other (possibly more profitable) lanes that the carrier had won.

The carriers had no information about their competitors' bids when they placed their own; that is, the bids were sealed. Home Depot preferred the single round, sealed-bid approach to a multi-round sealed bid or iterative open cry process (whereby bidders can see their competitors' bids as they are placed and respond accordingly). They believed that, were the bidding to be conducted such that bidders had the opportunity to respond to their opponents' observed bids, it could result in a damaging price war between carriers, with some carriers submitting unprofitable bids. While procuring transportation services at a lower price could bring a short-term gain to Home Depot they also recognized the negative effects of low prices on the quality of their carriers' service. Lower quality could manifest itself in service problems, reducing the priority of Home Depot as a shipper, and likely default in service. All these negative outcomes would eventually be more costly than any short-term rate savings. Hence, it was not in Home Depot's best interest to have carriers bid below their reservation prices and operate at a loss - They felt that a single round would minimize this possibility.

3.3.5. Selection of the winning bids

After all the bids are submitted, Home Depot selects the "best" collection of bids and awards the lanes to the carriers in that set. The best solution takes into account the carriers bids, restrictions on lanes awarded and several (nonexplicit) factors that are of importance to Home Depot. In the selection process, Home Depot solves what is called a *set partitioning* problem. The goal is to select a subset of the submitted bids, such that: (1) the collection of the selected bids covers the lanes originally put out for bid, (2) Each lane belongs to at most one selected single or combination bid, (3) The selection satisfies shipper and carrier constraints, and (4) In addition to being at a reasonable cost, the selection meets Home Depot's objectives on several non-price dimensions; for example carrier reliability, load balancing among carriers, and giving preference to incumbent carriers. Carriers do not have any knowledge of Home Depot's preferences nor of how these factors will influence the selection of the awarded bids

Before starting the selection process, Home Depot screens or preprocesses all the submitted bids and eliminates the ones that are "dominated" by others. For example, if two carriers submitted the exact same combination bid, and one bid is better than the other one in terms of the multiple selection criteria, then the lower quality bid can sometimes be eliminated without affecting the quality of the final solution.

The number of possible combinations one needs to consider for selecting the winning bids is enormous. To effectively search for the "best" solution, Home Depot uses an integer

programming based optimization tool for this process. Because of the combinatorial nature of the process, the lowest cost bid on a lane or group of lanes may not always win a lane.

3.4. Implementation and results of the new bidding process

Since the new bidding process is significantly different than the previous bidding process, Home Depot conducted a one week long training program for the carriers in late August 1999, before the bidding process began. The training program consisted of 2 sessions per day, with approximately 10 carriers attending each session. Each carrier sent one representative to attend the training, and the backgrounds of the attendees ranged from pricing specialists, to operations managers to sales representatives. Home Depot also provided the carriers with a toll-free number for assistance about the questions on the bidding process, and the line was very well utilized receiving hundreds of calls with various questions. In order to improve the training process for the next round of bidding, Home Depot kept detailed records of these calls in a database, including information about the company name, caller's name and position, the type of questions asked, etc.

Home Depot initially designed the bidding process to be completed in one round. However, due to unsatisfactory solutions on particular lanes in the first round, some of the lanes were opened up again for bidding in a second round. The due date for the bids in the first round was the last week of September. The results of the first round were announced before the end of October, where about 80% of the lanes were (conditionally) awarded. For the remaining 20% of the lanes, Home Depot held a second round of bidding and invited only 62 bidders, of which 36 submitted bids. There were a number of reasons why Home Depot did not award all the lanes in the first round. For some of the lanes, Home Depot did not receive enough bids, which limited Home Depot's carrier selection alternatives for those lanes and in some cases none of the bids on a particular lane satisfied Home Depot's requirements. Before inviting carriers to bid in the second round, Home Depot used the bid selection optimization tool to do what-if analysis for identifying those carriers who were most likely to submit "acceptable" bids in the second round. After the bids from the second round were collected, Home Depot used the bid selection optimization tool again to award the remaining lanes.

A large number of carriers participated in the bidding process. A summary of carrier participation statistics is as follows:

- Provided carrier profile information: 192
- Invited to participate in bid: 111
- Submitted bids in round one
 - CBR-generated: 91
 - Backup rate matrix only: 5
- Invited to continue to round two: 62
- Submitted bids in round two: 36

Most of the carriers utilized the carrier response tool (CBR) in creating and submitting bids. A handful of carriers (mainly those carriers who found the combinatorial bidding process too complicated) chose to submit backup rate matrices instead, where they submitted rates in a 48×48 matrix for each pair of states. In that case, the rate for transporting goods from a location in state i to a location in state j was indicated by entry (i,j) of the matrix.

A good number of bids were received on each lane. A summary of bid statistics is as follows:

Number of carriers bidding in a lane

- Average 14
- Minimum 2
- Maximum 33

	<u>% lanes</u>	<u>% loads</u>
At least 5 carriers bidding	94.4	97.1
At least 10 carriers bidding	73.4	86.7

The contracts with the carriers were finalized by early January 2000 and the new rates became effective right after that.

As we mentioned before, Home Depot expected that carriers had the capability to execute any bid they submitted. For some reason if a carrier is not able to provide the capacity he promised for certain lanes on a continuous basis, Home Depot can either renegotiate the price with the carrier or find another carrier to award those lanes. The bid selection optimization tool aids Home Depot in the process of price negotiation and alternative carrier selection as well, via providing solutions to what-if scenarios.

3.5. Lessons learned

The new bidding process was a big success. It not only provided Home Depot with better rates, but many of carriers also expressed increased satisfaction from the part of the business they were awarded. Home Depot intends to continue to use this new bidding process, with additional enhancements, such as more thorough training given to the carriers and inclusion of less-than-truckload bids.

From the Home Depot experience, we learned that while suppliers enjoy the ability to express their synergies, it is not always straightforward how to incorporate those synergies into “good” bids and a bidding strategy. In order to make a combinatorial auction work effectively, suppliers must have a bidding decision support tools that aid them in preparing bids.

After the bidding process was completed, Home Depot surveyed the carriers and received feedback ranging from “This is great, this is the future!” to “This is too complex, it can’t work”. Part of the reason why some carriers found the process too complex can be attributed to the very short training time. One representative from each carrier attended a half-day session to learn about the bidding process and the bidding software, and this was clearly not enough. Another problem was that the representatives attending the training session were specializing in one part of the carrier’s business such as operations, sales or pricing, but the bidding process clearly requires expertise in more than one area. In the future, Home Depot plans to have a two-day training session and invite at least two representatives from each carrier, one from operations and one from pricing. The training session will also increasingly emphasize the importance and the potential benefits of combination bids.

Another lesson learned is that there are multiple ways to design a combinatorial auction and attain a desirable outcome. Home Depot was not the first company to employ this type of conditional bidding in the selection of their transportation. In the early 90’s, Sears Logistics Services (SLS) saved over \$84 million (over 13% of their costs) by running six combinatorial bids for selecting its transportation providers over 854 lanes. Interestingly, there are several differences in the structure of the SLS bidding process and the one finally chosen by Home Depot. The bidding process employed by Sears is run in an iterative setting, i.e., bidders are provided with several

rounds in which to change their bids, in response to information revealed by their competitors in the previous rounds. In addition, SLS chose to greatly restrict the number of carriers who would be eligible to participate in the bidding process. After carefully evaluating several carriers' operational and financial characteristics, only 14 carriers were deemed "qualified" to participate in the bidding process. A common feature to both the SLS and The Home Depot auctions was that the companies chose to notify all bidders of the identity of all other carriers who were invited to bid.

4. Conclusion

In this paper, we provided an overview of the major challenges in designing, implementing and participating in combinatorial auctions. We also discussed a successful implementation of combinatorial auctions for transportation services procurement at The Home Depot and gained insights into the critical components of a successful combinatorial auction.

Combinatorial auctions are a powerful tool for auctioning off multiple non-identical units with complementarities or synergies. Combinatorial auctions allow a bidder to submit a bid for a group of items, or package bids, and the bidder wins either all, or none of the items in a package. Such auctions allow bidders to incorporate their synergies into their bids. However, combinatorial auctions present the auctioneer with the challenging problems of auction design and winner determination, and the bidders with the problem of preparing and pricing a collection of package bids. Given the difficulty of solving these problems in practice, and the lack of decision support tools, especially for the bidders, combinatorial auctions have not been used much in practice in the past. However, given their salient characteristics in capturing synergies, their use has been increasing rapidly in recent years. Given the millions of dollars of business at stake, it is imperative to further develop our understanding of combinatorial auctions.

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