Chapter 23

Industrial Procurement Auctions

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1 Introduction

As illustrated in the previous chapters, combinatorial auctions have successfully been applied to various application domains, such as the allocation of airspace system resources (Chapter 20), truckload transportation (Chapter 21) and bus routes (Chapter 22). Industrial procurement is potentially a huge application domain for combinatorial auctions, and it has turned into a topic of interest for software vendors and procurement managers in the B2B domain. A number of applications have been reported, but unfortunately, possibly because of efforts to protect proprietary information and competitive advantages, there is little documentation and public information on details of the design of combinatorial auctions in industrial procurement. The focus of this chapter is on describing current practice in this domain. We will also provide a case study of procurement auctions at Mars, Incorporated in order to illustrate the particularities in this field.

Several authors have analyzed the dynamics of traditional procurement auctions (Dasgupta and Spulber 1989, Laffont and Tirole 1993). While some firms, GlaxoSmithKline for example, are already using electronic auctions for over a third of their spending (Hannon 2004), the average level of adoption is much lower. The Center for Advanced Purchasing Studies CAPS interviewed e-auction users, suppliers who have participated in e-auctions, technology and service providers and firms that have rejected the use of e-auctions. The study found that more than 35% of firms who spend $100 million or more are using e-auctions. The level of spending users put through e-auctions is less than 5%, but growing steadily (Beall et al. 2003). Estimating the monetary value of goods awarded through electronic auctions is very difficult, and comprehensive quantitative data are not available. Below is a summary illustrating estimates of purchasing via electronic auctions.

- The 2004 global volume being purchased using electronic auctions is on the order of hundreds of billions of euros (Plant 2004)
- More than 40% of large firms (over $100 million
ing), surveyed in North America, are using auctions for procurement up from 20% two years ago (Beall et al. 2003)
- Less than 3% of large firms (over $100 million in spending), surveyed in North America, say that they have completed their adoption of e-procurement business processes (Beall et al. 2003)

[Insert Figure 23.1 around here.]

Nearly all of the procurement auctions being run today in the private sector are single unit English auctions. The fact that it is very difficult to satisfactorily value the complex nature of business relationships in a single price parameter accounts for much of the negative press written about electronic auctions. Many procurement negotiations require the use of special auction protocols that allow for negotiation of multiple attributes, multiple units, or multiple items. Auctions with such complex bid types are also called *multidimensional auctions*. Combinatorial auctions have emerged as a powerful mechanism to automate complex procurement negotiations on multiple items.

Some of the first procurement applications of combinatorial auctions include Net Exchange's auction for Sears Logistics (Ledyard et al. 2002), a combinatorial auction at The Home Depot (Elmaghraby and Keskinocak 2002), a combinatorial auction for school meals in Chile (Epstein et al. 2002) and one for packaging materials and raw materials for different manufacturing locations at a large chocolate manufacturer (Hohner et al. 2003). Some companies already provide software platforms for conducting combinatorial procurement auctions, such as CombineNet (http://www.combinenet.com), Net Exchange[1] (http://www.nex.com), and TradeExtensions (http://www.tradeextensions.com), and several applications have been reported by these software vendors in press releases (P&G, Siemens, and Volvo). This chapter draws on information from these primary vendors of combinatorial auction software, as well as the practical experience of Mars, Incorporated with proprietary combinatorial auction software, developed with IBM's T.J. Watson Research Lab.

2 Procurement operations

Industrial procurement managers are customarily responsible for the whole sourcing process. They determine specifications, choose a portfolio of possible suppliers, and negotiate price/conditions simultaneously through multiple bilateral bargaining. Typically, in the private sector, they commit to particular negotiation parameters such as quality, quantity, and price as late as possible. Prolonging commitment to any particular parameter is often seen as best practice in that it allows all possible conditional offers from the supply pool. For a purchasing manager with a complex set of parameters and constraints, this iterative bargaining process allows them to find a feasible solution within their constraints while maximizing the number of bids received from their supply pool. In contrast, in the public sector legal requirements often dictate a more formal process with commitment earlier on in the process: a completely defined specification, preferences for some supplier categories (e.g., minority owned businesses), written submissions of bids, and publication of all offers received.

2.1 Procurement auctions

When industrial procurement managers use auctions, they need to commit to certain product specifications and constraints early in the process, which is similar to public sector negotiations. Procurement managers first need to define their requirements, analyze market conditions for the materials and service markets in which they operate, commit to a specification, and finally develop a portfolio of potential suppliers. Only then do they begin the process of requesting bids. The general process is illustrated in Figure 23.2.

[Insert Figure 23.2 around here.]

This process requires many industrial procurement managers to adapt their negotiation behaviour considerably. For example, in combinatorial procurement auctions, buyers have to exactly define the items, which need to be purchased, as well as various additional constraints on the number of winners, etc. (see Section 3.5). In the private sector precisely defining many goods and services for an auction may be a challenge. This is especially true when the items are complex or part of contracts where extra non-quantifiable benefits are included. Complex items are often purchased from incomplete specifications. This is particularly true if the item has been developed with a single supplier. Standard practice within the supplier's operations sometimes are not codified in the specification. In large consumer packaging contracts research and development support and product innovation are often included as non-invoiced benefits in the contract. Also deciding on the granularity of items in a package auction can be a challenge.

In addition, a purchasing manager has to balance many competing business issues, such as:

- Significance of the material or service to the overall business
- Cost, and variance at risk, of the material or service
- Market power of suppliers
- Number of suppliers available
- Cost of switching suppliers
- Cost of managing additional suppliers
- Risk of reduced supply pool
- Assurance of long term supply

In a combinatorial auction, some of these issues can be considered as overall allocation constraints, but they need to be defined at the beginning. Also here, procurement managers have difficulties committing to particular constraints a priori. Therefore, in many cases in private industry, auctions are run without commitment on the buyer's side. In most cases, even the winner determination is not entirely automated, and there is some human judgment involved. This is often referred to as *scenario analysis*, where after each round the auctioneer performs some type of what-if-analysis and reveals their current preferred scenario. This scenario analyses can be performed manually by solving various winner determination problems, or even automated (Boutilier et al. 2004). As a consequence, software for combinatorial procurement auctions needs to be flexible in a variety of ways. First of all, it must support a rich bidding language (see Section 3.3). Apart from simple package bids, purchasing managers use multi-attribute bids, volume discount bids, and combinations of all three.

Second, in order to reach implementable solutions, it is essential that procurement managers can easily define various types of allocation constraints to express legal, contractual, and business rules capturing strategic and operative considerations (see Section 3.5).

2.2 The use of combinatorial auctions in procurement

Combinatorial auctions have been used for many varied materials and services including various types of packaging (bottles, cans, cartons, flexibles, etc.), chemicals, road construction and repair in different geographical areas, office supplies, etc. Goods and services purchased with combinatorial auctions tend to be comprised of large numbers of discrete items some of which have strong complementarities (e.g., routes within a logistics network, or packaging materials fabricated on the same production equipment). Transportation (see Chapter 21) is a huge application area for all combinatorial auction providers. To date, most have involved high spending levels. In packaging and logistics, renegotiations incur high transaction costs, and switching costs from one supplier to another are high, therefore it is standard practice to commit to long-term contracts of one year or more, in order to recoup the costs. However, software automating combinatorial auctions has the potential to significantly reduce the transaction costs of the renegotiation process.

In our survey of combinatorial auction software vendors, the number of items included in private procurement auctions ranged from 10 to nearly 100,000. In public procurement, the span was more moderate ranging from 20 to 50 items per auction. The number of bidders ranged from only a few up to several hundreds, but 10-20 bidders were most common. This is also the maximum number of suppliers a buyer would negotiate with simultaneously. Using the automation of electronic auctions significantly lowers the time investment required per participating supplier;

consequently bids may be collected from a larger pool of suppliers. In this aspect, commitment is pushed to the end of the process by maintaining a larger supply pool into the bidding. More suppliers are active in the process for a longer period, increasing competition.

Over the last five years there has been a trend towards the reduction in the supply base for large companies. The control of allocation constraints (e.g., the number of suppliers receiving business, see Section 3.5) in combinatorial auction software has been considered very useful in this respect. One vendor even reported an application with more than 130,000 constraints. In general, the size of problems (number of items and suppliers) reported varied considerably across the participating vendors. Often combinatorial auctions have led to high reductions in procurement costs. Some part of these reductions may accrue by using a small number of low cost suppliers. Such extreme outcomes need to be managed using allocation constraints since in most strategic sourcing exercises, maintaining a good supplier pool is an important goal. Table 23.1 provides a summary of responses from CombineNet, Net Exchange, and TradeExtensions.

[Insert Table 23.1 around here.]

3 Procurement auction design

In the following we summarize some of the particularities of designing combinatorial procurement auctions. We will discuss auction design goals, the protocols used, winner determination, and the allocation constraints typically used in procurement operations.

3.1 Auction design

Mechanism design questions and various types of sealed bid and iterative auction formats have been discussed in Part I of this book. One goal in economic theory is the *allocative efficiency*, in which the auction mechanism maximizes the total payoff across all agents. Another goal is the *revenue maximization (cost minimization respectively)*, in which the auction maximizes the revenue to a particular participant, usually the auctioneer. Cost minimization is also considered a central design goal for purchasing managers.

In addition, procurement specialists involved in combinatorial auctions highlight design issues, which are less well defined. For example, *supplier perceived fairness* is rated very high. This is achieved through higher transparency of the negotiation, but also through additional *allocation constraints*, which guarantee that all suppliers are considered in the allocation, or that certain minority suppliers receive a particular share of the pie. The notion of fairness is considered critical in strategic procurement, in which long-term relationships are key. One specific notion of fairness that we will discuss in detail in later chapters is related to time of bid arrival. In cases where there are multiple cost minimizing allocations, it is important that bids that arrived early are given some preference. This is in fact quite common since in a competitive bidding situation there are often multiple solutions and tie-breaking policies need to be well thought out.

Speed of the auction is considered important by some of the purchasing managers. After the initial savings have been accrued, efficiency of the process continues to deliver savings to the business. For example, without the use of formal protocols (such as auctions) the negotiation process itself might take weeks. However, the use of auction protocols often helps to substantially reduce the time to reach an outcome. Other design goals have to do with the software implementations in use. Combinatorial auction software needs to be *robust*, and *easy to use*. In addition it should be *flexible* and allow for various types of *allocation constraints* and various *types of* *bids*, which will be discussed in the next section. This is important, since the requirements tend to vary considerably across different procurement applications, depending on the type of good and the particular market structure.

3.2 Auction protocol

A*uction design* can be described as a set of rules, which motivate the bidders to reveal their true valuations to the extent that makes it possible for the auctioneer to solve for the cost minimizing allocation. We will categorize these auction rules as follows:

- the *auction protocol*, i.e. the syntax, semantics (i.e. bidding language), and sequence of messages exchanged throughout the auction.
- the *winner determination rules*, which include the overall objective of the allocation (i.e. efficiency vs. cost minimization), as well as additional allocation constraints.
- the *payment rules*, which determine the payment to the winner(s).

Part I of this book discusses a number of different auction protocols, including sealed-bid combinatorial auctions, Vickrey Clarke Groves (VCG) mechanisms, as well as various types of iterative auction formats. To our knowledge, the VCG mechanism [and not in italics] has not been used for procurement auctions, because of the unreasonable demands it would place on bidders. First of all, bidders need to reveal their entire utility function, i.e. to submit bids for all $2^m - 1$ possible bundles, where m is the number of items. This leads to a high valuation complexity for the bidders, but also to a large input size to the winner determination problem. In addition, the determination of the Vickrey payments itself becomes a computationally hard problem. Another problem is the need of a trusted auctioneer. The winner in a second price auction needs to be sure that the auctioneer does not reveal his valuations to other auction participants, or to the buyer, which might put his in a disadvantage in future negotiations. Finally, there is the issue of budget balance. If Vickrey payments are made to all participants including the buyer then the total Vickrey payments might actually be less than the total revenue realized from the auction – this is clearly not acceptable and hence some modified versions of VCG that incorporate budget balance as a hard constraint need to be considered, as in Parkes et al. (2001).

Generalizations of the *first-price sealed bid auction* have been used in public procurement, which is a huge application area. For example, European government spending on goods and services represents about 16% of the EU-wide GDP. For the future, the European Commission has proposed to allow for the implementation of more dynamic methods in public procurement, i.e., the use of iterative reverse auctions (http://europa.eu.int). The majority of procurement auctions in the private sector are run as *multiple-round auctions*. The main differences of these multiple-round formats lie in the information feedback that is given to the bidders in each round. Most vendors provide at least price information about the winning bid set. Some vendors also allow for the computation of linear prices, such as in Kwasnica et al. (2003), and some applications even use non-linear prices. In particular, if the complementarities are considerable, the price feedback becomes more important. Clock auctions have not been mentioned by any of the vendors.

One observation is that many bidders are used to bidding in traditional Request for Quotes (RFQ), where the initial round of bidding is often followed by additional rounds of bilateral bargaining. Using straightforward sealed-bid combinatorial auctions often leads to the fact that bidders bid too high. This corresponds with the claim by some procurement specialists that iterative combinatorial auction formats induce competition among suppliers. Additionally, most bidders are not able or not willing to bid on all possible combinations. In general, iterative combinatorial auctions avoid the need for the supplier to specify the entire cost structure at once, and are helpful for the bidders, in particular when the bidders' values are correlated, because they allow bidders to learn about the value of the good by seeing other bidders' bid (Milgrom and Weber 1982). In general, the burden of reporting entire cost might not be eliminated by an iterative procedure. However, in a well-designed auction the items and the price feedback are chosen in a way that reduces a chance of potentially having to elicit too many valuations. A frequently used argument for both the bidders and the auctioneer is that iterative combinatorial auctions lead to a more transparent market because the alternative to conducting combinatorial procurement auctions is usually simultaneous bilateral bargaining, where there is no transparency whatsoever. This way, suppliers get a better understanding of competitive market rates.

Iterative combinatorial auctions are the most common auction protocol for procurement applications. A number of issues need to be considered in iterative combinatorial auctions. One of these issues is *tie breaking*. Consider the following example: a combinatorial auction is created to purchase some quantities of items A, B, C. In the first round of the auction Supplier 1 makes a bid b1 for items A, B, C at a price of $100, and Supplier 2 submits a bid b2 of $30 for item A. Finally, Supplier 3, enters the auction with a bid b3 for items B, C at $70. There are two potential solutions to this winner determination problem: either bid b1 or the combination of bids b2, b3. In both cases the total cost to the buyer is $100. Time stamping is one method do deal with these situations. We refer the reader to Parkes (Chapter 2), Hohner et al. (2003) and Pekeč and Rothkopf (2003) for a discussion of tie breaking strategies and many other issues in iterative combinatorial auctions such as the setting of minimal bid increments, reserve prices, and strategies for dealing with infeasibilities in initial auction rounds.

3.3 Bidding languages

Procurement specialists in the field emphasize the importance of flexible bidding languages. The flexibility of the bidding language is important because it can enhance or hinder the ability of bidders to express their preferences. In addition, the expressiveness allowed has a considerable impact on the economic and computational properties of the auction. This has prompted research that examines bidding languages and their expressiveness and the impact on winner determination (see Chapter 9).

The bidding language is closely related with the type of goods and the market structure. For example, in markets where multiple units are being bought or sold it becomes necessary to allow bids that express preferences over multiple units. Some common bid types that have been examined in the literature in addition to package bids are:

- indivisible bids with price-quantity pairs, where the price is for the total amount bid and this is to be treated as an all-or-nothing bid, as is typically the case in multi-unit auctions.
- divisible bids with a price schedule, for example volume discounted bids, such as in Davenport and Kalagnanam (2000).
- multi-attribute bids, which specify various attribute levels and a price (Bichler 2001).

Volume discount auctions are specifically tailored to industries where volume discounts are common, e.g., bulk chemicals, and agricultural commodities. In a volume discount auction, suppliers provide bids that are specified as a curve with a quantity range associated with each price level (e.g., $500/unit up to 100 units, $450/unit over 100 units). These auctions may deal with one product or many. Multi-attribute bids are used for the procurement of complex goods and services. These auctions allow bidding on price and qualitative attributes, where bids are evaluated by a scoring rule or function. Multi-attribute auctions are useful if supplier offerings are close substitutes. We will refer to these different bid types as the bidding language and discuss some of the known types briefly.

With multiple items or multi-attribute bids the preference structure of bidders can be exponentially large. As already discussed in previous chapters, if there are *m* items and the bidder has superadditive preferences then in general the bidder could specify 2^m bids. Multi-attribute offers with multiple binary attributes lead to a similar informational complexity. Therefore an additional consideration is to provide a compact bid representation language that allows bidders to easily specify a large space of possible offers. Several researchers have proposed mechanisms for specifying bids logically. These combinatorial bids, a.k.a. logical bidding languages have two flavours:

- logical combinations of goods as formulae
- logical combinations of bundles as formulae

Nisan (Chapter 9) provides an overview focusing on combinatorial auctions. Similar issues of concise representation of preferences over multi-attribute items are explored in Bichler and Kalagnanam (2004).

Software for combinatorial procurement auctions typically supports various logical combinations of package bids. Multi-attribute bidding is common and is a way to incorporate qualitative attributes such as ISO certification, brand name, etc. Threshold levels and weighted additive scoring functions are often used to evaluate these multi-attribute bids (Keeny and Raiffa 1993). In addition, there are many cases, where qualitative attributes are added to traditional package bids. Volume discount bids are less commonly available in commercial software.

3.4 Winner determination

Winner determination has been discussed in detail in Part III of this book. Ideally every time a new bid is received in an iterative procurement auction, bid evaluation could be triggered to identify the provisional winners. However, since winner determination in combinatorial auctions is NP-hard, this is usually impractical. In addition, the introduction of allocation constraints impacts the runtime to solve these problems, as shown in Davenport and Kalagnanam (2000) As a result it is difficult to identify the provisional winners with every new bid. The compromise is typically a multi-round design where the new bids are accumulated within a certain time interval.

Although it might seem computationally expedient, but approximate solutions are considered unacceptable in procurement auctions that are run with commitment, because the difference between an approximate solution and the real solution can significantly change how much and exactly which business a single supplier receives. For example, a supplier who receives an allocation in the optimal[2] solution might receive nothing in an approximate solution. These types of occurrences, if made public, could destroy the credibility of an auction mechanism. However, as indicated, in the private sector auctions are often run without commitment. In some cases (e.g., scenario analysis) the combinatorial optimization is used to perform an accurate dollar valued trade off analysis after each round of bidding, but buyers do not commit to any of the constraints until at some point they make a decision.

The winner determination depends essentially on the bidding language and the allocation constraints used. Many software vendors use their own custom code to solve these problems, but also commercial-off-the-shelf mixed integer programming solvers are used. For scenario analysis, as it was discussed in the last paragraph, companies such as CombineNet offer complete packages that help the user analyze various allocations, mostly including multiple items and attributes (Boutilier et al. 2004, Sandholm and Suri 2001).

3.5 Allocation constraints

There are many types of allocation rules that need to be considered throughout an auction, such as eligibility, reservation prices, etc. Some of them need to be considered while solving the winner determination problem. Winner constraints, budget limits, market share constraints and quality constraints are general types of allocation constraints that can be found in many procurement auctions.

Procurement experts typically distinguish between *single-sourcing* or a *multi-sourcin*g. This determines whether the goods are purchased from a single supplier or multiple ones. On a more general level, a *winner constraint* in a combinatorial auction determines the minimum and maximum allowable number of winning bids. For example, buyers want to make sure that the entire supply is not sourced from too few suppliers, since this creates a high exposure if some of them are not able to deliver on their promise. On the other hand, having too many suppliers creates a high overhead cost in terms of managing a large number of supplier relationships.

In long-term relationships with multiple suppliers *market share constraints* on a group-level are of considerable importance. For example, representation constraints specify that at least one minority supplier is included in the set of winners. Winner constraints can also be considered as a special case of market share constraints. This means, the number of winners and market share that are required from different supplier groups can be restricted.

Another constraint is *volume-based budget limits*, which are often placed as an upper limit on the total volume of the transaction with a particular supplier. In a reverse auction, these limits could either be on the total spending or on the total quantity that is awarded to a supplier. These types of constraints are largely motivated (in a procurement setting) by considerations that the dependency on any particular supplier is managed. Similarly, often constraints are placed on the minimum amount or minimum spend on any transaction, i.e. if a supplier is picked for sourcing then the transaction should be of a minimum size. Such constraints reduce the overhead of managing a large number of very small contracts.

Some combinatorial reverse auctions also consider multiple attributes of a purchase, where it is necessary to restrict qualitative attributes of an allocation. Threshold levels for qualitative attributes can easily be checked at the time of the bid submission. Others need to be considered during the winner determination. For example, one constraint is to specify that all the winning bids must have the same value for some attributes. For example, if boxes are being bought from three different suppliers, then it is important that all boxes perform identically in the packaging equipment. Such constraints can be generalized to allow selection of winning bids such that for an attribute of interest all bids have values adjacent to each other.

Software vendors such as CombineNet or TradeExtension offer a wide variety of such constraints and distinguish among several dozens or hundreds of constraint classes (average capacity, attribute value, etc.). Most common are quality constraints as well as winner constraints. Allocation constraints can impact the runtime of the winner determination considerably. A detailed discussion can be found in Davenport and

Kalagnanam (2000, 2004) . The question whether to communicate allocation constraints to the bidders is an important design question, which could impact bidder behaviour. Experimental analysis might help to analyze the impact of this and many other design choices in combinatorial auctions (e.g., limits on the number of bids per bidder, etc.)

3.6 Business impact

There are a number of reasons why procurement managers use combinatorial auctions. The primary motivation is cost savings in complex negotiation scenarios. Using package bids, it is possible to represent complementarities or substitutabilities that occur as a consequence of production and/or transportation cost savings. As described in Section 3.3, many complex auctions are not limited to package bids. Some vendors emphasize, that their tools allow users to accurately model and analyze the thousands of price and non-price attributes that influence the true cost of sourcing. The respective software packages are sometimes used more as decision analysis tools that allow procurement managers to understand the effects that their business rules and other constraints have on the total spend. A secondary benefit, which is shared by all participants, is time efficiency. Huge amounts of data can be uploaded and processed with great increased effectiveness.

In addition, combinatorial auctions provide an opportunity to impact the market structure. In price-only procurement auctions suppliers can only submit bids on the entire contract, restricting competition to big suppliers. Combinatorial auctions make it easier to split large contracts into smaller ones, allowing small bidders to compete. This is an important issue in some public procurement operations or for private firms developing their supply base.

From a supplier's point of view, the main advantage of package bids is the elimination of the exposure problem. Some bidders find it quite natural to submit package bids, others have problems with the new technology and do not make use of package bids at all. As a result, the calculation of market clearing prices still is an issue, as well as decision support for bidders to help them make better bids. Some suppliers emphasize the increased market transparency as compared to multiple bilateral bargaining, others mention the high perceived fairness of the procedure, although there are different opinions on this issue. Some of these issues will be discussed in the case study in the next section.

4 Case study: Mars, Incorporated

In the following section, we will highlight some of the main aspects of combinatorial auctions used at Mars, Incorporated. These auctions are run with commitment and illustrate a number of typical features of procurement auction applications[3].

4.1 Procurement operations at Mars, Incorporated

Mars, Incorporated relies on a limited number of suppliers for each material and service it procures. Small supply pools may arise by necessity as well as design. For example, many agricultural inputs are available from a limited number of origins, a limited number of brokers, and/or under tariff regimes that limit the number of supplies. Buyers are responsible for existing supplier relationships and the development of new sources as well as contract conditions and price. A buyer may be responsible for up to 50 relationships. Many different buying techniques are used to address the large number of different purchasing situations. One-to-one bargaining and sealed bid tendering are the most common forms of negotiation. In addition, auctions have emerged as a popular mechanism for implementing negotiations. Procurement auctions take place with a set of pre-certified suppliers on an electronic private exchange.

Combinatorial auctions are used for strategic purchases, typically characterized by (1) small and fairly static supply pools, (2) long-term relationships, and (3) significant business integration. The contracts in strategic purchases typically are of high value, are renewed quarterly or annually, and require the use of special business rules to constrain the winner determination.

4.2 Procurement auction design

Over eighteen months beginning in early 2000 Mars, Incorporated worked together with IBM Research to create an electronic private exchange supporting a variety of multidimensional auction formats. The bidding language consists of:

- Package bids
- Volume discount bids, where suppliers could specify price schedules such as $3000 for up to 125 units, $2900 for 126 - 150 units, etc.
- Multi-attribute bids, where buyers pre-defined the attributes required for an item (e.g., payment terms, turnaround time, delivery schedule, product quality: material, color, etc.).

Of these types volume discount bidding and multi-attribute bidding have been the most utilized.

The design goals were to support complex procurement auctions, in a "do it yourself" software environment for the buyer, to provide optimization of complex bids that buyers could not perform for themselves, to lower transaction costs, and to increase the transparency of the process.

Mars, Incorporated has a strong corporate culture of mutuality with its suppliers, which determined some of the auction design choices, and therefore, unlike many private industrial auctions, Mars chose to run auctions with commitment on both sides (as long as reserve prices were met). Mars chose an *iterative auction format* for the following reasons:

(1) It mirrored the iterative nature of negotiations, a process the supply pool was familiar with and accepted

(2) It allowed suppliers to rethink and resubmit bids that were not competitive or submitted by mistake.

(3) It was simple and time-efficient. Suppliers submitted only bids on bundles they were interested in, as opposed to VCG mechanisms.

Another important aspect of the design was related to specific criteria for tie-breaking that was closely associated with the supplier perceptions of “fair allocations”. It is often the case that in intermediate rounds new bids arrive that lead to multiple cost minimizing allocations. In these settings, it is very important that the allocation engine does not change the set of suppliers at the same cost level in subsequent allocations. These were handled by the engine by providing time stamps to the bids based on their time of arrival and evaluating the bids on the primary criteria of cost minimization and as a secondary criterion of minimizing the sum of time-stamps for an allocation. The implications of this on the allocation engine are discussed in the next section.

The winning set of bids is announced to all participants. Non-winning bids are only visible to the supplier who placed them. While, this methodology negates the possibility of suppliers formulating complementary package bids based on others’ bids, the loss was not felt to be significant. Suppliers create package bids that reflect their own particular complementarities, and they create package bids for the purpose of volume aggregation, with accompanying price discounts. A particular aspect of this combinatorial procurement auction was that typically each bidder provides per unit prices for each of the items and typically provides package bids as discounting rules for allocations of multiple items. In each round, the lowest per unit prices for each item provides a basis for calculating the prices for non-winning bundles. Up until now, there is very little evidence of strategic behaviour amongst bidders. On average less than 5% of the bids placed were package bids. There also has been a notable occurrence of superadditive bids (e.g., package bids where the price exceeds the sum of prices for single items). In contrast, during volume discount auctions more than 80% of the bids placed utilized the ability to vary price with volume, rather than offering a constant price. This might be explained by that fact that the bid expression for volume discount bids is quite similar to standard price quoting practices in situations where it was utilized. In contrast, bid expression for package bidding was not familiar to any of our participants prior to the auction.

Suppliers may remain active throughout the auction without placing a bid. All bids placed must be a certain percentage lower than any previous bid placed by that supplier on the particular package.

The auctions run on the Mars, Incorporated private electronic exchange typically run for one hour (longer if the number of bids or value of the auction was particularly large). Once the stated end time has been reached, the active time is extended in 10-minute increments as long as bids are received. As soon as there is a 10-minute period without a new bid placed the auction ceases.

4.3 Winner determination and allocation constraints

The winner determination engine for Mars, Incorporated was developed as an independent optimization module in C++ that was then integrated with a web-based auction platform. Combinatorial optimization was used for this problem by modelling it as an integer program and using a commercial-off-the-shelf MIP solver. The winner determination algorithms have later been extended and embedded in a Java object framework (Bichler et al. 2002) to include multi-attribute auctions and volume discount auctions. In the following, we will describe a basic problem formulation used for winner determination in combinatorial procurement auctions, and the most important allocation constraints. A more detailed description including volume discount auctions can be found in Davenport and Kalagnanam (2000).

We are given $j \in L$ bids, and a set of M items indexed with $k = 1,..., m$. Each supplier $i \in N$ submits a set of L^i bids. We associate with each bid B_{ij} a zero-one vector a_{ij}^k , where $a_{ij}^k = 1$ if bid B_{ij} will supply the entire quantity demanded for item k, and zero otherwise. Each bid B_{ij} offers a price p_{ij} at which the bidder is willing to supply the combination of items in the bid. The basic mixed integer programming formulation for the reverse combinatorial auction can be written as follows:

$$\text{Minimize } \sum_{i \in N} \sum_{j \in L} p_{ij}\, x_{ij}$$

$$\text{subject to } \sum_{i \in N} \sum_{j \in L} a_{ij}^k\, x_{ij} \geq 1 \quad \forall\, k \in M, \qquad (a)$$

$$x_{ij} \in \{0,1\} \qquad \forall\, i \in N, \forall\, j \in L^i \quad (b)$$

The decision variable x_{ij} takes the value 1 if the bid B_{ij} is a winning bid in the auction, and 0 otherwise. Constraint (a) states that the total number of units of each item in all the winning bids must satisfy the demand the buyer has for this item. Note, that an optimal supply solution may over-satisfy demand. If there is free disposal or no considerable holding costs, this might be acceptable or even desirable. A departure from the conventional combinatorial auction formulation is that the solver software considers a number of additional allocation constraints:

- The total number of winning suppliers must be at least a minimum number to avoid depending too heavily on just a few suppliers.
- The total number of winning suppliers must be at most a maximum number to avoid the administrative overhead of managing a large number of suppliers.
- The maximum amount procured from each supplier is bounded to limit exposure to a single supplier.
- The minimum amount procured from each supplier is bounded to avoid receiving economically inefficient orders (e.g., less than a full truck load).
- If there are alternative winning bid sets, then one needs to pick the set that arrived first.

The following winner constraints can be added to the MIP formulation as follows:

$$W_{i,min} y_i \leq \sum_{k \in M} \sum_{j \in L} a_{ij}^k Q^k x_{ij} \quad \forall i \in N \qquad (c)$$

$$\sum_{k \in M} \sum_{j \in L} a_{ij}^k Q^k x_{ij} \leq W_{i,\,max}\, y_i \quad \forall i \in N \qquad (d)$$

$$\sum_{j \in L} x_{ij} \geq y_i \quad \forall i \in N \qquad (e)$$

$$S_{min} \leq \sum_{i \in N} y_i \leq S_{max} \qquad (f)$$

$$y_i \in 0,1\} \quad \forall i \in N$$

For each item there is a demand for Q^k units of the item. The terms $W_{i,min}$ and $W_{i,max}$ define the minimum and maximum quantity that can be allocated to any supplier i. Constraints (c) and (d) restrict the total allocation to any supplier to lie within the range ($W_{i,min}$,$W_{i,max}$). Note that y_i is an indicator variable that takes the value 1 if supplier i is allocated any item. Notice that if $W_{i,min}$=0 then y_i becomes a free variable. In order to fix this, a constraint (e) is introduced which ensures that y_i=0 if no bids from supplier i are chosen. S_{min} and S_{max} relate to the minimum and maximum number of winners required for the allocation. Constraint (f) restricts the total number of winners to be within the range (S_{min} , S_{max}).

The impact of these allocation constraints is as follows: bid submissions for each supplier are restricted by the minimum/maximum quantity limits. If a bid is submitted by a supplier that violates this constraint the bid is removed from consideration. An important auction design question is whether this constraint is made public to the supplier. If bidders know, or assume that there are additional allocation constraints, this can impact strategic bidding behaviour and needs to be taken into consideration together with other design decisions. In the Mars case a bidder knows all their own constraints, maximum allowed volume, and the minimum contract size globally and per lot. A bidder knows if Mars wants multiple suppliers, but they don't observe how many suppliers are bidding, or the exact minimum or maximum number of winners.

The maximal problem size is given as 30 suppliers and 400 items. Without allocation constraints these problem sizes can be solved within seconds. The consideration of allocation constraints makes fundamental impact on the feasibility of the problem. With limits on the quantity allocated to each supplier and on the total number of winners, a feasible solution might not exist or might be difficult to find. These side constraints can also have significant impact on the cost of procurement—a tight constraint can often force the cost to be higher than a constraint free solution.

4.4 Business impact

The auctions have yielded consistent cost savings. The efficiencies come from matching supplier capabilities and the company's needs and thus increasing suppliers' margins, part of which are to provide Mars with savings. Mars procurement managers have found that when buyers were willing to change the size of the supplier pool or shift large amounts of business, the auctions yielded greater savings. The payback on Mars' investment was much less than a year.

Once they have been integrated into the business process, auctions took much less time than multiple bilateral bargaining. This is a benefit to both buyers and suppliers. Mars buyers, as a result, have more time to align businesses and to seek synergistic value from suppliers. No suppliers have refused to participate once an auction has been scheduled.

It usually takes a day or two to set up an auction in the software, and train suppliers for auctions the first time they are run. As an auction is repeated, training times for suppliers drop from one hour for first-time users to less than 10 minutes for repeat users. While complex auctions may take weeks to design, auctions have never taken more time than the traditional ways of bargaining they replaced. In the most significant reported time savings, a 40-minute auction replaced a price-only negotiation process that had lasted over two weeks and required the buyer to make nine separate air trips to finalize only the prices and volumes of the contract.

5 Conclusion

Traditional price-only auctions are unable to handle indivisibilities and other real-world market complexities. Package bids and other types of multidimensional bidding enable suppliers to take advantage of their unique abilities and put forth their best offers. This stimulates competition by freeing the suppliers to express their strengths and competitive differences, as opposed to forcing them to compete as if they were the same.

A few aspects of industrial procurement auctions might be considered as distinct. First of all, due to the variety of goods and services that need to be purchased, it is important to allow for a rich bidding language. Second, allocation constraints are key to address the many strategic and operational issues a procurement manager faces, and to achieve implementable solutions.

Although, combinatorial auctions have been used for industrial procurement for several years, their adoption process has been slow. Combinatorial auctions are provided by a number of specialized software vendors, but have not been picked up by large procurement or ERP software vendors yet. A number of reasons have been mentioned for this:

- Purchasing managers are not used to commitment early on in the process. This requires considerable change in the negotiators behaviour.
- Many private companies are still struggling to get their procurement processes organized and save money with restructuring and automating processing steps. Although, there are a number of success stories, people are still struggling with the question of whether combinatorial auctions will improve their purchasing or not.
- Many private companies are concentrating on fully exploiting the relatively easy applications that can be purchased via price-only auctions.
- Combinatorial auctions are used for complex negotiation scenarios. In addition to a combinatorial optimization engine, their introduction requires a great deal of experience and know-how about how to set up a combinatorial auction properly.

Not many people do have experience with combinatorial auctions yet. In other words, there is a certain time and financial investment required to get an auction up and running (typically a couple of months for the first example). This is also an education exercise. Often inexperienced bidders have difficulties bidding in combinatorial auctions.

At this point in time, combinatorial auctions are mostly used for strategic sourcing, where the stakes are high, i.e., for large and time-consuming purchases, where an automatic process incorporating optimization has undisputed advantages. Only when both buyers and suppliers become familiar with the process more routine purchases may warrant the use of this tool. Combinatorial auctions, however, are still very new to both suppliers and buyers. As with many new business processes, combinatorial auctions require time before they become a standard business practice.

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[1] The focus of auctions conducted by Net Exchange and Schneider Logistics is primarily on transportation auctions.

[2] This refers to optimality of the optimization, not to ”optimality“ in the sense of ”optimal mechanism design“.

[3] An overview of the Mars, Incorporated procurement auction project has been published in (Hohner et al. 2003).

	Minimum	Average	Maximum
Number of items	10	250	90,000
Number of bidders	2	15	300
Transaction volume / auction	$50,000	$5 Million	$1 billion
Reduction in procurement cost	0%	13%	75%
Reduction in size of Supplier Base	10%	25%	50%
Duration of the auctions (active bidding)	30 minutes	1 day	Several Weeks

Table 23.1: Summary of data and estimates provided by selected software vendors

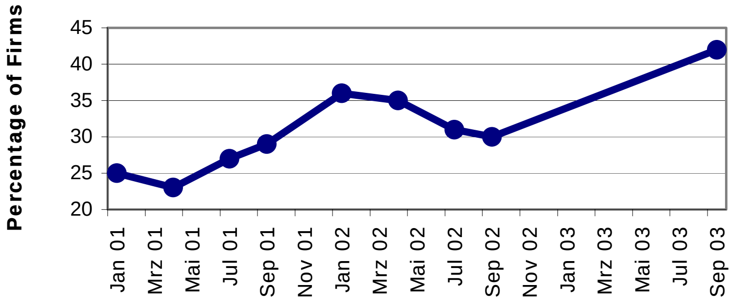

Figure 23.1: Percentage of Firms using Internet Auctions for Procurement (Beall et al. 2003)

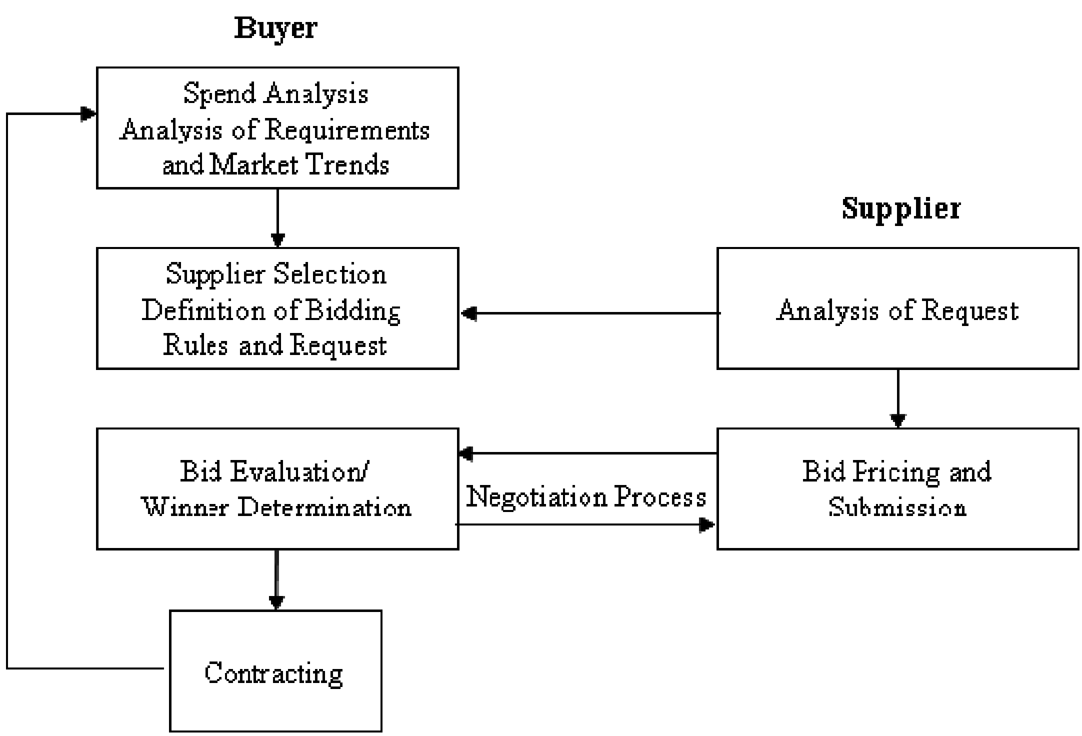

Figure 23.2: Sourcing Cycle