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Changing the Game in Strategic Sourcing at Procter & Gamble: Expressive Competition Enabled by Optimization

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Procter & Gamble put into practice CombineNet's approach to building sourcing networks, called *expressive competition*. At its heart is a vision that looks past lowest-price reverse auctions and combinatorial package bidding toward a highly expressive commerce relationship with suppliers. It enables suppliers to make electronic offers that express rich forms of capabilities and efficiencies. As the buyer, P&G also uses an expressive language to state constraints and preferences. The detailed expressions of supply and demand are brought together via an advanced optimization engine to decide the optimal allocation of business to the suppliers. By March 2005, over a period of two and a half years, P&G had sourced over $3 billion through expressive commerce and seen $294.8 million (9.6 percent) in recommended savings. In the process, P&G's suppliers benefited from the win-win approach: expressive competition matched demand to the most efficient means of production (rather than squeezing suppliers' profit margins) and removed the exposure risks in making offers. Beyond direct monetary savings, the benefits included the redesign of supply networks with quantitative understanding of the trade-offs and the ability to implement in weeks instead of months.

Key words: games, group decisions: bidding, auctions; industries: consumer goods.

The large consumer-packaged-goods company Procter & Gamble ($57 billion) focuses on winning two moments of truth in the marketplace. The first is in the retail aisle when a consumer is faced with a choice of brands to purchase. Will it be a P&G product? The second is after the purchase of a P&G product. Was the experience satisfying enough to cause the consumer to purchase that product again?

This simple concept has driven the operating strategies across all disciplines in the company, right down to the way P&G manages its supply chain. P&G supply chain managers created a consumer-driven supply network in an effort to produce a low-cost yet robust supply chain from raw materials to delivery of final product. Optimization technologies had played important roles in bringing the strategy to market, but with P&G's increasingly complex global business—more than 300 brands, nearly 110,000 employees, tens of thousands of suppliers, and 140 countries in worldwide distribution—the process was bogged down.

Traditionally, companies made sourcing decisions through in-person negotiations with suppliers. The advantage is that the supplier and the buyer have a very expressive language for finding, and agreeing to, win-win deals. The deals can be implemented because the parties can express operational constraints and take them into account. However, the process is slow, lacks structure and transparency, induces low levels of competition among suppliers, and makes it difficult for the buyer to decide what to agree to with a supplier. (The decision depends on what the other suppliers, to be negotiated with later, would be willing to offer.) These problems and the overall complexity have been exacerbated by a dramatic shift in the 1990s from plant-based sourcing to global corporatewide sourcing. Leveraging the joint buying power of its plants through global (category-based rather than plant-based) sourcing events was a key goal in P&G's sourcing strategy.

The industrywide shift to global sourcing coincided with a shift to computerized sourcing in which suppliers submit offers electronically to the buyer. This process has the advantages of speed, structure and transparency, global competition, and simultaneous negotiation with all suppliers (which removes the difficulties associated with speculation about later stages of the negotiation process). The most notable class of such systems is the *reverse auction*, popularized in the mid-1990s by such vendors as FreeMarkets (now Ariba), Frictionless Commerce, and Procuri. The buyer groups the items into lots in advance and conducts an electronic descending-price auction for each lot. The lowest bidder wins. (In some cases, lowness is not measured in terms of price but in terms of an ad hoc score, which is a weighted function that takes into account the price and some nonprice attributes, such as delivery time and reputation.) Unfortunately, reverse auctions are not economically efficient, that is, they generally yield poor allocation decisions. The optimal bundling of the items depends not on the buyer's preferences, but on the suppliers' (which depend on such considerations as the set, type, and time-varying state of their production resources), which the buyer does not know when forming lots. Lotting by the buyer also hinders the ability of small suppliers to compete. Furthermore, reverse auctions do not support side constraints, which means (1) the buyer cannot express her business rules, making implementation of the auction allocation impossible, and therefore the screen savings of the auction do not materialize, and (2) suppliers cannot express their production efficiencies (differentiation) and are exposed to bidding risks.

In the past, P&G managers accelerated the sourcing cycle by simplifying the complexity inherent in their strategic sourcing. Conventional sourcing technologies, such as reverse auctions, limited the scope of sourcing events, lotted products for suppliers to bid on, and reduced the amount and type of input suppliers could provide. These methods reduced buyers' opportunities to save money by forcing suppliers to cut their profit margins without allowing them to compete on their strengths through collaboration and shared cost efficiencies with the buyer. Also, buyers lacked adequate tools for balancing cost savings against various stakeholder requirements, such as supply-base rationalization, product quality, supplier reliability, and delivery schedules.

P&G's Approach

To change the process, P&G realized that it needed a tool that would allow it to embrace complexity rather than simplifying it. P&G wanted to leverage the scale of its sourcing volume while maintaining its relationships and offering its suppliers options (Smock 2004).

P&G had used advanced analytical tools in sourcing with limited success, most notably in transportation and planning applications where sourcing was an integral part of the production-planning decision. The operations research group at P&G, known as IT Global Analytics (winner of the 2004 INFORMS Award), worked on these internal projects and on other projects concerning sourcing, supplier contracts, material forecasting, and make-versus-buy decisions in various business units over the years. However, no sustainable analytic capability had been developed for sourcing.

During the summer of 2001, CombineNet, a software company that provides solutions in the intersection of optimization and market design, approached P&G to demonstrate REV, an industry-independent optimization-based market-clearing engine. REV had helped H. J. Heinz Company save 12 percent and PPG Industries save 19 percent in sourcing events. REV enables companies to create richer marketplaces between buyers and sellers. Sellers can express creative proposals, such as bundled offers, conditional volume discounts, and innovative alternative item specifications, to take advantage of cost efficiencies. This expressiveness increases the options a buyer has to consider but has the potential for a much greater return. REV also takes into consideration the cost of business rules and stakeholder preferences, such as allocating a percentage of business to disadvantaged business enterprises (DBEs), providing incumbents advantage over new suppliers, and limiting the total number of suppliers that supply to a region or a specific location. REV enables buyers to manage this complexity by considering all the possible options they could select to find the one they should select.

The First Test

The operations research group at P&G was so intrigued by the tool's possibilities that it gave CombineNet a transportation-sourcing-optimization data set that another transportation-sourcing-optimization tool took about 30 minutes to solve. REV solved the problem to optimality in less than nine seconds. Based on this successful trial, P&G decided to apply REV to an aroma chemicals purchase involving more than 300 items and numerous suppliers. P&G saved 13.5 percent. It also reduced the number of suppliers, obtained a quantitative understanding of the cost of its preferences and business rules, and implemented its decision in weeks rather than months.

The Next Six Events

Based on the results, Dennis Begg, P&G's associate director of purchases innovation, convinced senior managers to use the technology on six sourcing events over a six-month period. P&G saved more than $100 million. Rick Hughes, vice president of global purchases, then persuaded A. G. Lafley, CEO, to sign a three-year contract with CombineNet, which has allowed P&G to expand the use of REV around the globe.

The Paradigm Shift: Expressive Competition

The idea behind REV was to allow suppliers and buyers to express supply and demand in dramatically more detail while participating in sourcing events in a structured electronic marketplace that algorithmically matches supply and demand. CombineNet calls this new paradigm *expressive competition* (or *expressive commerce*) and specified its two sides as *expressive bidding* and *expressive allocation evaluation* (or *expressive bid taking*) (Sandholm and Suri 2001b).

With *expressive bidding*, suppliers express their offers creatively, precisely, and conveniently using compact statements. Expressive bidding includes the following:

—Suppliers bid on an arbitrary number of self-constructed packages of items (not on predetermined lots as in basic reverse auctions). The packages can be expressed in more flexible and more usable forms than what is supported in vanilla combinatorial auctions.

—Suppliers can offer rich forms of discount schedules. (Simpler forms of discount schedules have already been addressed in the academic literature (Sandholm and Suri 2001a, 2002; Hohner et al. 2003).)

—Suppliers can offer conditional discounts. They can specify the trigger conditions and the effects in highly flexible ways.

—Suppliers can specify a broad variety of side constraints, such as capacity constraints (Sandholm and Suri 2001b).

—Suppliers can bid using attributes (Sandholm and Suri 2001b). This allows the buyer to leave the item specification partially open, so the suppliers can pick values for the item attributes, such as material, color, and delivery date, in a way that matches their production efficiencies. In this way, the suppliers can also express alternate items.

—Suppliers can express free-form alternates. This option fosters unconstrained creativity by the suppliers.

—Suppliers can express detailed cost drivers, such as setup costs, transshipment costs, and different material costs. In many of the sourcing events, the buyer collects tens or hundreds of cost drivers.

P&G uses all of these bidding features extensively. REV supports bidding through Web-based interfaces and through spreadsheets. In some cases, catalog prices from databases have also been used.

In *expressive allocation evaluation*, the buyer expresses preferences over allocations using a rich, precise, and compact language. The buyer can use it to express operational and legal constraints, business rules, prior contractual obligations, and other business caveats. Different types of side constraints are a powerful form of expressiveness for this purpose. For example, the buyer can state, "I don't want more than 200 winners" (to limit overhead costs), "I don't want any one supplier to win more than 15 percent" (to keep the supply chain competitive for the long term), "I want minority suppliers to win at least 10 percent," "Carrier X has to win at least $3 million" (because I have already agreed to that). In addition to side constraints, REV enables the buyer to express how REV should take into account item attributes (such as delivery date or transshipment specifications) and supplier attributes (such as reputation) when determining the allocation of business (Sandholm and Suri 2001b). A P&G buyer with potentially no background in optimization can set up a scenario by adding rules and preferences through an easy-to-use Web-based interface and use the optimizer to find the optimal allocation for the scenario (Figure 1). The buyer can also upload constraints from its business-rule databases.

By navigating multiple scenarios (changing the constraints and preferences and re-optimizing), the buyer obtains a quantitative understanding of the trade-offs between sourcing cost and other considerations. That enables the buyer to determine whether certain constraints and preferences are worth it. The quantitative understanding also helps align the members of a sourcing team, who may have different preferences, because the internal negotiation is based on facts rather than beliefs and philosophies.

A Case Study: Sourcing of Displays

P&G's procurement of in-store displays has always been a process closely managed by the marketing managers responsible for different product categories. One of P&G's first uses of REV was for sourcing these prepacked displays.

P&G uses prepacked displays to help retailers merchandise its products. A display can contain different sizes of one product or contain multiple products, for example, Crest toothpaste and Scope mouthwash. Retail stores place displays in the aisles or in promotional areas when there is some special activity, such as a sale or a coupon on the brand. P&G spends $140 million annually in North America on these displays.

Based on individual product-promotion schedules and display requirements, managers typically used incumbent suppliers to design, produce, and assemble turnkey displays for easy setup in the stores. While these solutions were of high quality, there was little visibility into the costs and quality of alternate methods.

P&G's corporate sourcing team thought that a more efficient way to source displays might exist and wanted to understand the cost trade-offs between buying the traditional turnkey displays and buying components, leveraging the size of P&G's entire operations.

Process

The P&G-CombineNet project team developed and executed a sourcing implementation designed to allocate P&G's annual spending on displays across a more efficiently utilized supplier base while also improving the reliability and quality of display production and services. The plan contained three key elements:

(1) A bidding structure designed to capture component-specific information,

(2) A simple way for suppliers to understand and participate in the bidding process, and

(3) Advantages for P&G's product managers that encouraged them to embrace the new process.

P&G's purchasing department invited all of the incumbents and some new suppliers to bid on the company's annual volume of displays. P&G's new capability to collect detailed cost information and solicit expressive or creative offers from suppliers allowed purchasing to put up for bid each of the supply chain cost drivers that contributed to the final cost of the display, such as display components as well as assembly and shipping costs that increase the base cost of the display materials. The purchasing department collected detailed information on the costs of materials, such as corrugated paper, film, and trays that hold the product, and the costs of holding inventory, of freight, and of printing. It invited suppliers to bid on specification and then to make alternate off-specification bids that would allow suppliers to suggest ways to reduce the cost of the display. (For example, using three-color printing instead of four-color printing for the header card, which advertises the product, would reduce its cost.)

Of the 40 suppliers that participated in the sourcing event, some were manufacturers only, some were assemblers only, and some could manufacture and assemble. There were four display categories (pallets, special packs, pigment/dye/quick (PDQ) trays, and wings and floor stands) covering 14 benchmark and unique displays. For roughly 500 display components, suppliers offered piece prices, substrate fluctuations, other fixed and variable costs, assembly rates, packaging, and freight. There were two online rounds of bidding followed by one round of off-line negotiation.

For suppliers, the flexibility of component-based bidding and the unique expressive bidding format

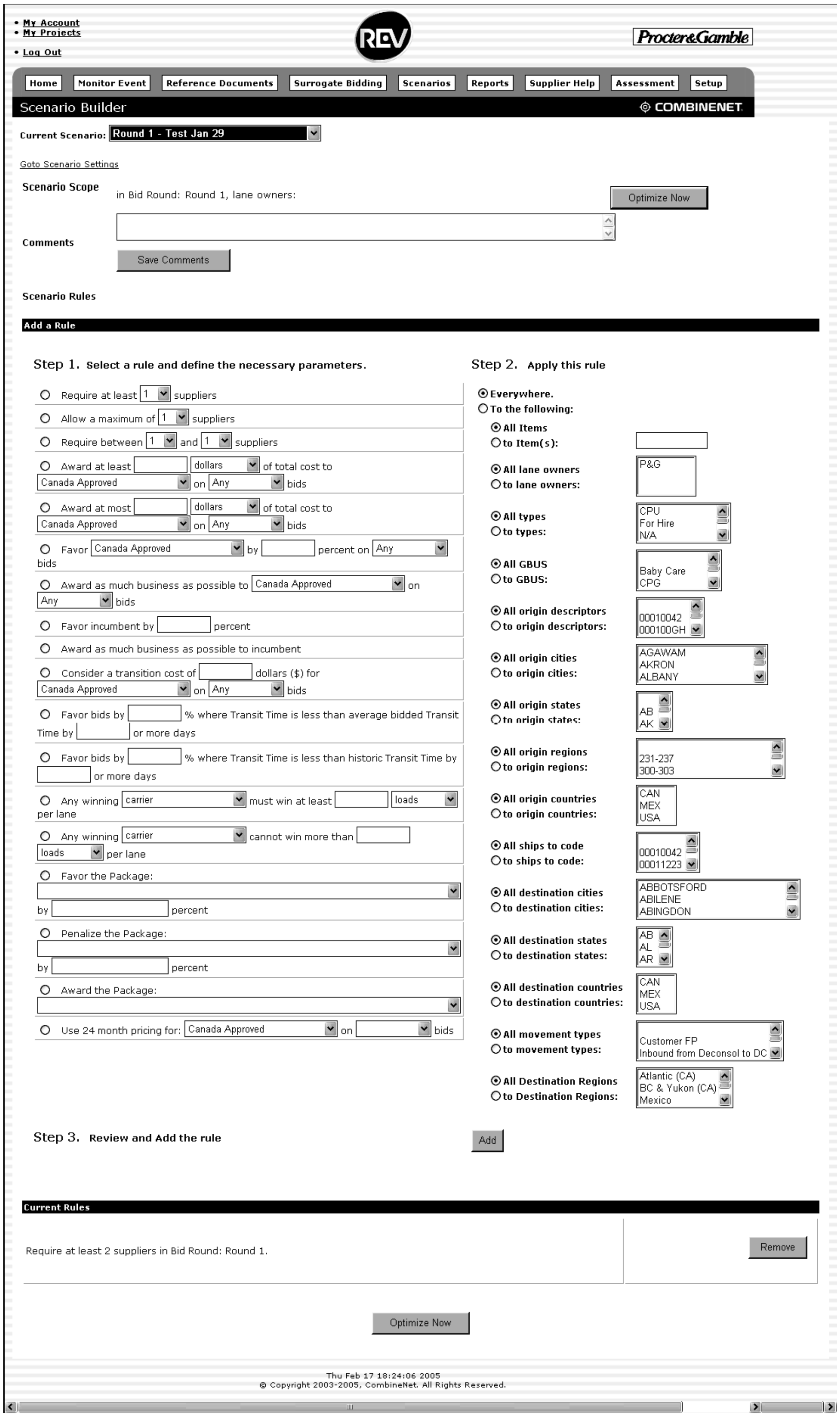

Figure 1: Using a Web interface for expressive allocation evaluation, the buyer can set up constraints and preferences one rule at a time by selecting the rule type and its parameter(s) on the left, and then selecting the scope to which the rule must apply on the right. As the third step, the buyer presses the Add button to add the rule to the scenario, and it will appear on the bottom in natural language, together with all the rules that the buyer has added to this scenario already. After specifying the scenario in this way, the buyer presses the Optimize Now button. This triggers the optimizer to find the optimal allocation for this scenario. © Combinet. Reprinted with permission.

allowed them to bid on their own terms, including volume discounts, bundled pricing, and alternate products or services. P&G encouraged the suppliers to submit two sets of bids, one identifying prices for full turnkey displays (including the aspects of production handled by others in their alliance networks) and a second bid for only those display components and services they could supply directly.

For P&G, the larger, more complex set of data generated greater business insight when analyzed using REV's Scenario Builder tool that enabled P&G to quickly and easily consider a large number of what-if scenarios by changing side constraints and preferences.

Results

—The unconstrained savings were nearly 60 percent. The implementable savings (that is, the savings P&G could achieve after applying its side constraints and preferences in REV) were nearly 48 percent ($67 million annually).

—The collaborative planning produced insights into costs and strengthened P&G's relationships with its suppliers.

—P&G's annual procurement cycle dropped from 20 to eight weeks, with the time for finding allocations to scenarios reduced from days to seconds.

P&G used REV's Scenario Builder to assess the cost impact of constraints and preferences, such as favoring incumbent suppliers and the cost of different mixes of display components. P&G gained the ability to separate the true cost of must-have components and services from nice-to-haves. This let P&G compare the cost of a supplier's turnkey display to the total cost of sourcing the display as its components and then managing the process. P&G realized that it could allocate much of its spending more efficiently.

The bidding and award process also improved P&G's relationships with its suppliers by promoting collaboration and allowing suppliers to leverage their strengths. REV's expressive bidding format gave suppliers an opportunity to bid on their own terms and did not commoditize their offerings. Both P&G and its suppliers benefited from a consolidated and easy-to-manage sourcing cycle.

Case Study 2: Sourcing of Truckload Transportation Services

Another example of the new paradigm is the sourcing of P&G's long-term contracts for all of its North American inbound and outbound truckload transportation services for the following 12 months—a sourcing of $885 million in one event. There were 7,161 lanes to be procured (multiple weekly shipments on each one) with 137 carriers as bidders.

Due to the flexibility and creativity allowed by expressive bidding, the carriers submitted 160,797 bids. The unconstrained savings potential of these bids amounted to $47 million. Three main factors contributed to these potential savings. First, carriers submitted 720 package bids. With such bids, carriers generally offer lower prices for combinations of lanes because they can reduce empty driving via backhauls and multileg routes. Second, carriers submitted 33 conditional discounts and six discount schedules. Third, P&G collaborated with two of its biggest retailers in a novel way: they invited the carriers to bid on both P&G's and the retailers' trucking lanes, allowing the carriers to construct beneficial backhaul deliveries and multileg routes even in ways that would have been impossible with P&G's lanes alone.

To build a quantitative, offer-driven understanding of the trade-offs in the supply chain, P&G used REV's Web-based Scenario Builder user interface to navigate through more than 550 scenarios before settling on the final award. The final scenario had 146,294 constraints in the optimization, which were automatically constructed from 120 business rules that P&G modeled using Scenario Builder. The implementable savings after applying the constraints and preferences were $6 million (0.7 percent), which was remarkable given that prices for truckload transportation had generally increased by six to nine percent.

Impact

The paradigm-shifting approach to sourcing has proven its effectiveness, as demonstrated by P&G's savings of $294.8 million (9.6 percent) on the slightly over $3 billion of spending that P&G put through REV in two and a half years by March 2005. (We compute P&G's savings number in each sourcing event by comparing the prices to the prices it paid for the same items the previous time it sourced them, usually 12 months earlier.) The unconstrained savings produced by expressive bidding were 16.9 percent ($517 million). As P&G took control of the sourcing by introducing side constraints and preferences into the optimization, the implementable savings ended up at 9.6 percent. The percentage savings by category are 3.6 percent in transportation (not adjusting for the general increase in transportation prices over the time frame), 23.3 percent in packaging, 29.8 percent in services, 10.9 percent in raw materials, and 23.9 percent in indirect materials.

These savings are sustainable, in contrast to the simple cost concessions acquired in traditional reverse auctions. The savings resulted directly from improved economic efficiency conveyed via expressive offers.

P&G achieved cost savings while at the same time achieving the other benefits of expressive competition, such as improved relationships with suppliers, greater participation of suppliers in sourcing events, implementable solutions that satisfy operational considerations, and solutions that strike the trade-offs in a data-driven way and align the stakeholders in the buying organization.

Designing Sourcing Networks

The relationships between companies that purchase materials, goods, and services and their suppliers can be viewed as a network, because many companies both purchase and supply. Another profound impact of expressive competition is the effect on the sourcing-network-design process. Traditionally, the buyer configures the network and then solicits offers from suppliers. This approach produces suboptimal results because it ignores suppliers' alternative capabilities. REV reverses the process by first collecting offers and then using optimization to configure the optimal network based on those offers.

CombineNet's approach is particularly relevant in transportation sourcing. Trucking networks, for example, evolved primarily to meet shippers' demands. By considering the most efficient routings that carriers can offer, both individually and collectively, REV develops more efficient networks than the current networks. Similarly, buyers can construct supply chains (networks) in light of supplier capabilities as expressed in their offers.

Streamlining the Sourcing Process

Companies can now make decisions on large baskets of items to be procured, rather than in a number of submarkets, naturally improving the allocation decisions. P&G's use of expressive competition enables it to manage and exploit complexity and rich data to obtain the best value. This includes:

—Moving from the old way of simplifying assumptions and potentially multiple suboptimal analyses to optimal sourcing solutions across the full scope of potential solutions,

—Enabling scenario navigation to incorporate professional purchasing knowledge through side constraints and preferences into the analytic rigor of the optimization, and

—Conducting complex analyses quickly.

In short, P&G is now faster, more rigorous, and better able to leverage its purchasing experts than it was. It obtains greater savings with every analysis than it could before it adopted CombineNet's REV.

Optimization to the End Users

The hosted, Web-based REV application with interfaces designed for domain specialists brings the power of complex optimization to end users. It captures modeling expertise in a form accessible to users who do not know optimization. It supports rapid deployment and refinement of both tailored applications and algorithmic advances.

REV is more than a group of complex tools and techniques packaged for end users. Those users must have confidence that the tools do what they expect, and they gain that confidence from the robust solving engine that they can drive (even remotely), that they know others drive, and that they know is maintained on the cutting edge of technology.

In addition, as was the case for P&G's 1996 Edelman finalist application (Camm et al. 1997), the value brought by providing advanced analytical tools to P&G's business motivated it to establish a permanent analytical capability in the purchasing organization to identify opportunities across the entire function.

Next Steps

Procter & Gamble's relationship with CombineNet is ongoing and expanding to other business functions beyond sourcing, some of which are new applications for optimization.

CombineNet expects to continue to show dramatic recommended savings in sourcing as P&G applies its technology to more and more events, as sourcing managers become more proficient with the technology and tools, as suppliers become more proficient with the expressive bidding capabilities now available to them, and as CombineNet improves its algorithms and functionality and introduces new products.

Savings Summary

By March 2005, over a period of two and a half years, P&G had saved $294.8 million by applying expressive competition to 29 complex events in sourcing over $3 billion worth of transportation, raw ingredients, services, and packaging. Furthermore, CombineNet has begun other high-profile optimization projects to help P&G reduce costs and increase profits. As of March 2005, P&G had used REV on 10 percent of its $28 billion of spending and plans to increase that to between 20 and 30 percent over the next one or two years. If the same savings-to-spending ratio holds, REV will help P&G save $1 billion over four years.

Overall, from 2001 to March 2005, CombineNet used its REV technology to host about $20 billion of sourcing events for Global 2000 companies, yielding more than $1.5 billion in hard-dollar savings in economic efficiency, among other benefits. Case studies are available on its Web site at www.combinenet.com/customers/success_stories/.

These savings numbers do not include suppliers' savings, which are harder for us to measure because the suppliers' true cost structures are proprietary. However, strong evidence shows that the suppliers also benefited, so a win-win was indeed achieved: (1) suppliers who participated in the expressive-competition events recommend its use to other buyers, (2) suppliers who boycotted reverse auctions return to negotiate with expressive competition, and (3) suppliers provide positive feedback about their ability to express differentiation and creative alternatives. Our figures on savings also omit savings from reduced effort and event time lines.

Appendix

Optimization to Enable Expressive Competition

A challenge in making expressive competition a reality is that the expressiveness makes the problem of allocating the business across the suppliers an extremely complex combinatorial optimization problem. Specifically, the *clearing problem* (also called the winner-determination problem) is deciding which bids to accept and reject (and to what extent in the case of partially acceptable bids) so as to minimize sourcing cost (adjusted for preferences) subject to satisfying the demand and the side constraints. Even in the vanilla combinatorial reverse auction where the only form of bidding is package bidding and no side constraints or preferences are allowed, the clearing problem is NP-complete and inapproximable (in the worst case) in polynomial time (Sandholm et al. 2002). Expressive competition is a much richer problem; thus, the NP-hardness and inapproximability carry over. (Müller et al. 2006 review the worst-case complexity of the clearing problem of different variants of combinatorial auctions.) Therefore, the clearing problem requires sophisticated optimization techniques.

Optimization Program Formulation

We describe a simplified version of the optimization problem formulation.

The system tries to fulfill demands for *items* at the lowest cost while meeting applicable business rules and supplier constraints. An item is a good or service to be purchased. The buyer usually groups multiple items in an *event*, for which *offers* (including price and terms) are requested. Denote the set of items in an event by $M = \{1, 2, \ldots, m\}$. Each item i has lower and upper demand quantity bounds, L_i and U_i. Supplier (vendor) offers include *bids*, each with a price on specified quantities of one or more items, and other offer components, such as discounts, that may apply to more than one of their bids. The procurement problem is to decide which bids to accept. Our support for a variety of bid formats relies on decision variables that have similar roles for different bid types:

x_j for whether binary bid j is accepted ($x_j = 1$) or rejected ($x_j = 0$) (let J be the set of all binary bids),

y_k for whether, and how many times, integer bid k is accepted (let K be the set of all integer bids), and

z_f for whether, and how many (possibly fractional) times, fractional bid f is accepted (let F be the set of all fractional bids).

The basic minimization problem (excluding discounts, side constraints, and preferences) is

$$\min \sum_{j\in J} p_j x_j + \sum_{k\in K} p_k y_k + \sum_{f\in F} p_f z_f,$$

$$x_j \in \{0,1\},\ y_k \in N,\ z_f \geq 0,$$

$$\text{s.t. } L_i \leq \left(\sum_{j\in J} q_{ij} x_j + \sum_{k\in K} q_{ik} y_k + \sum_{f\in F} q_{if} z_f\right) \leq U_i,$$

where p_j, p_k, and p_f are the prices of the corresponding binary bid, integer bid, and fractional bid, respectively. Similarly, q_{ij}, q_{ik}, and q_{if} are the quantities of item i offered by the respective binary bid, integer bid, or fractional bid.

From this starting point, it is conceptually straightforward to add side constraints and expressive offer components, such as conditional discounts and discount schedules. As an example of the general nature of REV's side constraints, we implement constraints on the maximum number of winning suppliers using *counting constraints*. These constraints rely on the concept of a *bid group*, which can be any set of bids. In the case of a supplier limit, each bid group consists of all of the bids from one supplier. The formulation to limit the number of winning suppliers to value Max is

$$\sum_{i=1}^{g} \alpha_i \leq \text{Max}, \quad \alpha_i \in \{0,1\},$$

where $\{1, 2, \ldots, g\}$ is the set of bid groups to which Max applies, and α_i is a binary indicator variable that is set to 1 only if at least one of the bids in its corresponding group wins (if the decision variable corresponding to the bid is greater than 0).

In scope, a side constraint can cover either all bids or a specified subset of bids (for example, by business unit or geographic region). For example, bid groups may correspond to all suppliers or to only incumbent suppliers or to any other selection of suppliers.

In procurement auctions, we use preprocessing to implement nonprice item and bid adjustments. (In *exchanges* this is not possible, and they need to be incorporated into the optimization itself (Sandholm and Suri 2001b).) For example, we can apply a favorable bid adjustment of 10 percent to bids by incumbent suppliers by multiplying the price of each bid from those suppliers by 0.9. We can also make absolute bid adjustments, for example, by decrementing each bid from a specified group of suppliers by 0.50 €. Item adjustments may be absolute or per item, that is, based on the quantity of the item in the bid. A rich set of logical operations in REV allows the buyer (and the bidders) to combine terms into complex (and sequence-dependent) adjustment expressions.

Optimization Technology

Prior to REV, no technology could solve clearing problems of the scale and expressiveness that CombineNet's customers wanted to solve; for example, Hohner et al. (2003) found integer-programming techniques to be effective for problems only as large as 500 items and 5,000 bids. As discussed above, even on the trial instance that P&G gave CombineNet (a fairly easy instance on which REV took nine seconds), the fastest competing product took half an hour. While that was already a decisive speed difference, since that time CombineNet's technology development has yielded a further speed improvement of two to three orders of magnitude in REV.

There is significant structure in the expressive competition problem instances, and it is paramount that the optimizer be sophisticated enough to take advantage of the structure. Mixed-integer-programming (MIP) techniques for tree search are quite good at taking advantage of the structure, and REV takes advantage of those techniques. However, the general-purpose MIP techniques embodied in the leading general-purpose MIP solvers are not sufficient for the clearing problem in expressive competition.

REV uses sophisticated tree-search algorithms to find the optimal allocation. Given that the algorithms find the optimal answer and the problem is NP-complete, in the worst case the run time has to be more than polynomial in the size of the input (unless P = NP). However, in practice on the real-world sourcing-optimization problems, the algorithms are extremely fast: the median run time is less than one second and the average is 20 seconds, with some instances taking days. The algorithms are also anytime algorithms: they provide better and better solutions during the search process.

CombineNet began to develop its algorithms in 1997, and it has 16 people working on the algorithms, half full time. They have tested hundreds of techniques (some from the operations research and computer science literature and some invented at CombineNet) to find those that shorten solve time for expressive competition clearing problems. Some of the techniques are specific to market clearing, and others apply to combinatorial optimization more broadly. CombineNet published in detail the first generations of its search algorithms (Sandholm 2002a, Sandholm and Suri 2003, Sandholm et al. 2005, Gilpin and Sandholm 2006, Conitzer et al. 2004, Sandholm 2006). The new ideas in these algorithms included different formulations of the basic combinatorial-auction-clearing problem (branching on items, branching on bids, and multivariable branching), upper and lower bounding across components in dynamically detected decompositions, sophisticated strategies for selecting branch questions, dynamically selecting the branch-selection strategy at each search node, the information-theoretic branching approach, sophisticated look-ahead techniques, solution seeding, primal heuristics, identifying and solving tractable cases at nodes, techniques for exploiting part of the remaining problem falling into a tractable class, domain-specific preprocessing techniques, fast data structures, methods for handling reserve prices, and incremental winner determination and quote-computation techniques. Sandholm (2006) provides an overview of these techniques.

CombineNet has also invented a host of proprietary techniques in the tree search algorithms, including different formulations of the expressive competition clearing problem, new branching strategies, custom cutting plane families, cutting plane generation and selection techniques, and machine learning methods for predicting what techniques will perform well on the instance at hand (for use in dynamically selecting a technique).

While academics writing on combinatorial auctions have focused on a variant in which package bidding is the only form of expressiveness (sometimes supplemented with mutual exclusion constraints between bids), in CombineNet's experience with real problems, the complexity is dominated by side constraints. Therefore, CombineNet has put a great deal of effort into developing techniques to deal with side constraints efficiently. CombineNet has faced several hundred different types of real-world side constraints. REV supports all of them by abstracting them into eight classes from an algorithmic perspective. This way, speed enhancements within each class get automatically leveraged across all the side-constraint types within the class.

The resulting optimal tree search algorithms are often 10,000 times faster than the state-of-the-art general-purpose MIP solvers on hard instances of real-world expressive competition clearing, largely because CombineNet specializes in a subclass of MIP problems and has 32,000 real-world instances in this subclass on which to improve its algorithms. The speed has allowed CombineNet's customers to handle drastically larger and more expressive sourcing events, sometimes with over 2.6 million bids (on 160,000 items, multiple units of each) and over 300,000 side constraints.

The state-of-the-art general-purpose MIP solvers fail also due to numeric instability on about four percent of these real-world sourcing-optimization instances. They err on feasibility, on optimality, or on both. CombineNet has therefore invested considerable effort on stability, obtaining techniques that are significantly more robust.

CombineNet incorporated its technology in a back-end clearing engine, ClearBox, which it uses for all its sourcing events, customers, and industries.

End-User-Tailored On-Demand Optimization in a Hosted Mode

REV's fast solution time changes the sourcing process. Sourcing specialists get results in seconds, not months, and can therefore explore vastly more (and more complex) alternatives than they could in the past. They can drive out unnecessary costs while meeting their quality and service requirements, find new savings opportunities, rationalize their supply base, and build long-term supplier relationships. Data drives the process: users do not have to define constraints, preferences, and trade-offs up front. Instead, they can explore them with data in hand, with the expressive offers from suppliers providing the cost bases of different potential outcomes.

CombineNet packaged its technology for use by domain experts, not optimization experts. Intuitive Web-based interfaces designed for the buyer and the suppliers bring the power of optimization to users with expertise in sourcing, not in optimization. They express their preferences through interfaces that use sourcing terminology rather than optimization terminology. The interfaces support simple click-through interaction rather than requiring the user to know any syntax.

A key point is that the interfaces feed the problem description into the back end using a high-level XML language, *combinatorial exchange description language* (*CEDL*), and the back end then automatically formulates the optimization problem for the search algorithms. In contrast, in the traditional mode of using optimization, consultants with optimization expertise build the model. The automated approach is much faster (seconds rather than months) and avoids errors.

CombineNet's Web-based products and application-service-provider (ASP) business model make optimization available on demand. With no client-side software installation necessary, customers avoid expensive hardware investments. (On many problem instances, the search algorithms use over two gigabytes of RAM, making 32-bit architectures unusable and requiring a 64-bit architecture.) Furthermore, with its ASP mode, CombineNet can quickly and transparently tune its algorithms and provide enhancements to all customers simultaneously.

Market Design

While most of the savings can be attributed to the application of optimization to the sourcing process, another important factor is market design, for example, what forms of expressiveness are allowed and what forms of feedback are given to bidders during the event. REV supports sealed-bid events (with winners determined at the end), events that have a (small) number of rounds (with winners determined and feedback provided at the end of each round), and live events (with winners determined and feedback provided every time any participant expresses anything new). Traditionally, events have been limited in scale and complexity by solving capabilities; methods of accommodating solving limits, such as prelotting and acceptance of suboptimal solutions, contributed to inefficiency and reduced profits.

Scenario Navigation

The buyer is typically not a single individual but an organization consisting of several individuals with different preferences over allocations. For example, finance people seek low cost, plant managers prefer small numbers of suppliers, and marketing people want a high average carrier-delivery-on-time rating. The buying organization therefore must manage trade-offs, often with little visibility into the motivation behind specific preferences.

REV allows buyers to understand the available trade-offs based on data. After buyers collect the (expressive) bids, they go through a process called *scenario navigation*. At each step of that process, the buyers specify a set of side constraints and preferences (together these define the *scenario*) and run the optimizer to find an optimal allocation for that scenario. They thus obtain a quantitative understanding of how different side constraints and preference expressions affect the sourcing cost and all other aspects of the allocation.

Rapid clearing time allows the buyer to explore the effects of various side constraints and parameter settings, such as the maximum number of suppliers at a specific warehouse location, at each location, or overall. In practice, CombineNet has found that a buying organization will navigate an average of 100 scenarios per sourcing event. (P&G set a record with 1,107 in one sourcing event.)

With rapid clearing, scenario navigation can be driven by the actual offers. Most prior approaches required the user to define the scenario (side constraints and preferences, if any) prior to analysis with too little time and too few modeling experts to try even a small number of alternative scenarios. Data-driven approaches are clearly superior because the actual offers provide accurate costs for the various scenarios.

With scenario analysis, buyers develop allocations that can be put into practice directly, because all side constraints are satisfied and all trade-offs are resolved based on input from all stakeholders in the buying organization.

The next generation of REV will support *automated scenario navigation*, which will permit a more systematic and less wasteful navigation of the scenario space than the current manual scenario navigation. The system queries the sourcing team about its preferences, using, for example, trade-off queries ("How much hassle would an extra supplier be in dollars?

Give me an upper or lower bound.") and comparison queries ("Which of these two allocations do you prefer?"). The system poses queries in a data-directed way, asking for refinements in preferences only as needed. (This method is desirable because internal negotiation within the team is costly in terms of time and goodwill.) Based on all the offers from suppliers and all the answers from the sourcing team to previous queries, the system strives to minimize maximum regret. At each iteration of automated scenario navigation, the system finds a *robust solution* that minimizes maximum regret (because the sourcing team has not fully specified its preferences, the system's recommended allocation may not be optimal in light of unstated preferences). At the other step of each iteration, the system poses a query to refine the team's preferences so it can reduce the maximum regret further. The maximum regret also provides a quantitative measure that indicates when further negotiation within the team is no longer worthwhile and the team should implement the current robust allocation. CombineNet pioneered automated scenario navigation, including its different design dimensions and algorithms (Boutilier et al. 2004). The optimization problem of finding the most robust allocation is even more complex than the clearing problem. CombineNet has developed the algorithms and a prototype of automated scenario navigation, and P&G is providing feedback on this new approach.

Consumable Technology for Smoothing the Adoption Path

REV promotes incremental transition from traditional sourcing to expressive competition by supporting existing ways of doing business and intuitive interfaces.

Behind the REV front ends reside a general-purpose back-end market-clearing engine and modeling language. The front ends support various business units (different spending categories), mapping specific events to the clearing engine via the CEDL modeling language. Users interact with REV via these front ends that use language that they are familiar with. User training typically takes just a few hours. New front ends typically take days or weeks to go from project specification to deployment.

Some suppliers may not be sophisticated enough to bid expressively at all, yet they can participate in the same sourcing events using traditional bidding constructs in the same system. This paves a smooth road for adoption, which does not assume sudden process changes at the participating organizations.

Expressive Competition as a Generalization of Combinatorial Auctions

A relatively simple early form of expressive competition is a combinatorial reverse auction (Sandholm et al. 2002), in which the only form of expressiveness that the suppliers have is package bidding and the buyer has no expressiveness. In its predecessor, the combinatorial auction, the bidders are the buyers (and there is only one unit of each item and no side constraints). Combinatorial auctions (Rassenti et al. 1982; Sandholm 1993, 2002b; Ledyard et al. 1997; Rothkopf et al. 1998; Kwasnica et al. 2005; Sandholm et al. 2005; Sandholm and Suri 2003; Hoos and Boutilier 2000; Boutilier 2002; de Vries and Vohra 2003) enable bidders to express complementarity among items (the value of a package being more than the sum of its parts) by using package bids and substitutability (the value of a package being less than the sum of its parts) usually by using different languages for specifying mutual exclusivity between bids (Sandholm 2002a, b; Fujishima et al. 1999; Nisan 2000; Hoos and Boutilier 2001).

Expressiveness leads to economically improved allocations of the items because bidders do not get stuck with partial bundles that are of low value to them, as demonstrated, for example, in auctions for bandwidth (McMillan 1994, McAfee and McMillan 1996), for transportation services (Sandholm 1991, 1993, 1996; Caplice and Sheffi 2003), for pollution rights, for airport landing slots (Rassenti et al. 1982), and for carrier-of-last-resort responsibilities for universal services (Kelly and Steinberg 2000).

However, package bids and exclusivity constraints form too impoverished a language for real-world sourcing. While any mapping from bundles to real numbers can be expressed in that language in principle, real-world preferences in sourcing cannot easily or concisely be expressed in it. Starting in 1997, CombineNet tackled this challenge and generalized the approach to expressive competition, with the language constructs discussed above. Approaches similar to CombineNet's have been adopted, but only for less complex (orders of magnitude smaller and less expressive) events (Hohner et al. 2003, Metty et al. 2005).

CombineNet, Expressive Bidding, Expressive Competition, Expressive Bid Taking, REV, ClearBox, Combinatorial Exchange Description Language, and CEDL are trademarks of CombineNet, Inc.

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