A Combinational Auction Improves School Meals in Chile

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Chile's school system is using mathematical modeling to assign catering contracts in a single-round sealed-bid combinational auction. The Chilean state spends around US$180 million a year to feed 1,300,000 students from low income families, making this one of the largest state auctions. To improve the quality of the assignment in the auction process, we constructed an integer linear programming model to decide contract awards optimally among different concession holders. The model completely changed the nature of the process in three crucial aspects. First, it gave transparency and objectivity to the complete process, generating competition among firms. Second, it allowed the companies to build flexible territorial bids to include their scale economies, leading to efficient resource allocation. Finally, the model indeed found an optimal solution, which is not easy because the assignment problem was NP-complete with more than 10,000 binary variables. This new methodology improved the price-quality ratio of the meals with yearly savings of around US$40 million—equivalent to the cost of feeding 300,000 children during one year.
(*Games/group decisions: bidding/auctions. Government: agencies.*)

Chile is a developing country with 15 million inhabitants and an education system consisting of 14,000 schools distributed throughout the country's 13 geographic regions. As much as 91 percent of school coverage is financed wholly or partly by the state, which includes providing education to children from poor families—30 percent of all children under 18 live below the poverty line. A key element in turning the goal of equal opportunities into a reality is compensating for the social deficits suffered by children and young people who come from socioeconomically vulnerable sectors. Chile does this through welfare programs that provide complementary meals, with a view to lowering school absenteeism and dropout rates and improving school performance, supported by other programs in the health, housing, student and recreation sectors (Henríquez 1999).

The National School Assistance and Scholarship Board (JUNAEB) is a public service operating in the education sector with responsibility for providing these assistance programs. One of its key objectives is to provide meals for pupils during the school day (including breakfast, lunch, tea, and supper, as the case may be)—a service delivered cost-free to school children across the country.

JUNAEB's yearly program budget amounts to

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US$150 million, of which US$138 million are spent on the school meals program to feed around 1,200,000 school children at the primary and secondary levels. This covers the regular meals program plus a vacation program and various reinforcement programs run by the Education Ministry.

In 1980, JUNAEB decided to contract out catering services to external firms through competitive auctions for the different school districts. At that time, only three companies participated in the bidding process, but the number of participants rose to 30 during the 1990s, and currently stands at 26.

JUNAEB has major bargaining power over concession holders, given the huge volume of meals it demands. It also has wide experience in this field, and thus it manages catering programs for its sister organizations, JUNJI and INTEGRA, which are responsible for meal services in Chile's preschools. These two institutions provide for a further 126,000 children from an annual budget of US$46 million. As a result JUNAEB has overall responsibility for food purchases amounting to US$184 million per year, providing meals for about 1,326,000 children in all.

Every year, it puts out contracts to tender to provide catering services for one-third of the country's schools during the following three years. The total sum involved in the auction is on the order of US$180 million, making it one of the largest state auctions in the country.

The auction of school meal services is administered by one institution (JUNAEB), but as it serves JUNJI and INTEGRA as well, the process needs to reconcile the interests of all three institutions. A further complication is that, although the auction involves providing a daily meals service over a three-year period, it is subject to several quite variable scenarios arising from the length of the contract involved. For example, the number of school meals to be provided can vary; so can the food structure of the different meals, as new nutritional requirements come into force. The beneficiaries of the meals service vary widely also (their ages range from two to 24 years old), so the auction process needs to include a wide variety of meals and food services.

Another key issue in this auction is the synergies that firms have if they operate in several geographical regions because of economies of scale. Economies of scale arise for various reasons, such as the use of common infrastructure for neighboring regions, volume discounts on input purchases, efficiency in transport, and efficiencies in staffing.

Despite the large sums of money involved and the complexity of the problem, until 1997 JUNAEB awarded contracts using subjective and quite rudimentary criteria. Essentially the firms presented a technical project for the meals service and a group of bids, each one with its price. What a technical project should be was not clearly defined. Each firm had the freedom to present the project it wanted. For example, a firm could offer meat twice a month and vegetables 10 times a month, while another firm could offer meat and vegetables six times a month. JUNAEB evaluated the technical projects and assigned a grade to each. Finally, it applied a succession of filters based on the technical grade to eliminate lower-quality bids, reducing the size of the feasible space in an iterative way. The prices didn't play a major role; JUNAEB's only concern in this respect was to assign a set of winning bids within the budget. The solution obtained, as well as the incentives, were clearly not appropriate.

Until 1997, JUNAEB awarded contracts using subjective and rudimentary criteria.

As a matter of fact, the auction process had important problems. First, as the technical projects for the meals service didn't have clear definitions, JUANEB's evaluation of them was a completely subjective procedure. This made it easy for bidders to exert inappropriate pressures on the officials administering the process. In this type of negotiation, contracts should be awarded using objective methods to ensure transparency. Second, as prices were not a key factor, bidders didn't have incentives to be more efficient to reduce their costs. Therefore, the result was that JUNAEB paid a lot of money for low-quality products.

Given these major problems, in 1997, the JUNAEB board and a team of researchers from the University of Chile designed and implemented a new mechanism for auctioning the school meals service. The principal changes introduced in the new mechanism were (1) standardizing the technical project for the meals service, with JUNAEB defining what it wants from the firms, and (2) keeping firms that satisfy these technical requirements in the bidding process to compete on price. The format of the new bidding process complies with World Bank recommendations to guarantee transparency: first JUNAEB defines technical hurdles to ensure that bidders satisfy minimum requirements, and then it awards contracts on the basis of price. JUNAEB can control service quality by setting high technical barriers.

Consequently, the JUNAEB nutritionist team defined a variety of products that the competing firms must price—for example, an 850-calorie lunch for secondary school students, for which it specifies nutritional requirements and the frequency of such foods as meat, fish, and vegetables.

For the purpose of the auction, JUNAEB divides the country into roughly 90 school districts or territorial units (TUs). On average, each of the country's 13 administrative-geographic regions is divided into seven TUs. The new auction mechanism allowed bids for groups of TUs, so firms could take advantage of their particular scale economies. This possibility led to what is known as a combinational auction. To assign the contracts optimally among the different bidders, we constructed a linear programming model with binary variables.

We developed and implemented the new auction mechanism, which assigns the contracts in a single-round, sealed-bid combinational auction. We first used the mathematical model in 1997 only as a decision-support system for decision makers. Given the successful application, JUNAEB decided to completely implement the new mechanism from then on, and it used it successfully in the auctions of 1999, 2000, and 2001. In these cases, JUNAEB informed the firms about the new mechanism, provoking a substantial change in their competitive behavior. In 1998, there was no auction process.

The introduction of mathematical tools was decisive in generating a clean, transparent and competitive auction process. The bidding process also captured the firms' scale economies by permitting bids for combinations of TUs. Finally, the model allowed an optimal allocation of resources. It was thus possible to auction the school meals service in the best way possible—a key objective, since what is at stake is the quality of meals provided to around 1,300,000 Chilean children, many of whom depend on school meals as the basis of their nutrition.

A Combinational Auction

The country is divided into TUs. JUNAEB holds auctions for school catering services in one third of these districts each year, with contracts lasting for three years.

Each bid specifies the coverage of a group of TUs. Firms can present as many bids as they wish, with each bid being accepted or rejected in its entirety. For example, if a company presents a bid covering five TUs, JUNAEB accepts or rejects the complete package and cannot accept the bid in three out of the five TUs bid for. Usually firms submit many bids, ranging from small ones for a single TU to large ones covering several.

> This saving amounts to some US$40 million a year, equivalent to feeding 300,000 children during one year.

Because JUNAEB allows bids covering packages of TUs, firms can take advantage of the economies of scale available for providing a large number of services. They can usually submit a bid covering districts X and Y together that is lower than the sum of separate bids for the same two TUs.

In other areas like this one, when several properties are auctioned, a bidder may be willing to pay a higher price for a property if she or he also wins another group of properties than if she or he won only the one property. Therefore, authorities might encourage bidders to take advantage of the synergies they have by permitting bids for combinations of assets.

If combinational bidding is not allowed, bidders may face "exposure risk" (Rothkopf et al. 1998). Suppose a bidder has a synergy in a group of assets. If combinational bidding is not allowed, the bidder could make an unsuccessful attempt to acquire the group of assets and pay more for the individual assets than they

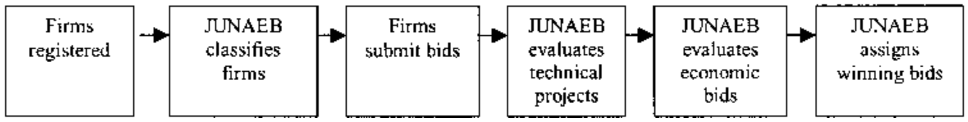

Figure 1: The new auction process consists of six main activities carried out in a strict chronological sequence to meet a schedule. First, firms interested in participating in the auction are registered. Then JUNAEB classifies them according to their capacities. The companies submit their bids, including a technical project and the economic bids. JUNAEB evaluates the technical projects, and firms that satisfy all the requirements compete on price through their respective economic bids. Finally, JUNAEB assigns the winning bids, using the mathematical model.

are worth to her or him. Alternatively, the bidder may be unwilling to risk bidding above the sum of her or his individual valuations and, consequently, may not be able to obtain the combination for which the synergy makes her or him the efficient recipient.

The sale of multiple properties in an auction is a very active field of current research (Klemperer 1999). However, as Kelly and Steinberg (2000) point out, even though tremendous advantages may be obtained by permitting combinational bids in different kinds of auctions, actually few auctions permit combinational bidding. The principal reason is that combinational bidding leads to a very difficult computational problem. In general, the auctioneer's problem of determining the optimal set of bids to be assigned is NP-complete.

In some applications, combinational bidding has been allowed and the problem of determining the set of winning bids has been solved using integer linear programming. Letchford (1996) describes an auction of school-bus contracts in which operators were permitted to submit group bids with a discount premium if certain contracts were awarded simultaneously. The size of the problem was small (201 individual bids and three group bids), and it was efficiently solved in a commercial package. Keskinocak and Tayur (2000) mention the application of a single-round, sealed-bid combinational auction that The Home Depot used for contracting carrier capacity. Carriers could submit bids that allowed them to incorporate their synergies when operating a group of lanes.

Baird (1984) describes the case of a tendering system used to reduce fishing catch levels, in which fishers presented bids corresponding to the price they should be paid to cease fishing a determined amount of fishes. Using a mathematical programming approach, they found the bids, which combined with others, would led to the required reduction at an overall minimum cost.

As far as we know, apart from the application we describe and mentioned above, a combinational auction has not been used successfully for many real-world problems.

The New Auction Process

The new auction process begins when JUNAEB calls for expressions of interest and registers the interested firms (Figure 1).

JUNAEB then evaluates the interested parties from a managerial, technical, legal, and financial point of view, ruling out those that do not satisfy minimum reliability standards and assessing the capacities of those that do.

JUNAEB classifies the firms that satisfy the reliability standards based on two characteristics:

—Their financial and operating capacity, placing them in five categories according to the maximum number of TUs they could serve, and

—Their technical and managerial evaluation, for which firms are given an overall performance rating, which is used in the mathematical assignment model.

Following this, JUNAEB publishes a call to tender with the ground rules for bidding. Potential concession-holders (currently about 26) then submit their bids electronically on diskette. Electronic submission is convenient for all firms and helps JUNAEB input the data for the assignment model. JUNAEB gives each diskette a code and deposits the bidder's name-code relation with a notary so the evaluators will remain ignorant of bidders' identities until the moment they award the contract. Each firm presents a technical project for meals service and its economic bid.

The technical project is based on requirements clearly established by JUNAEB, including the following:

—Nutritional requirements for the different meals,

—Food structure for the various meals (breakfast, lunch, tea, and supper) and the frequency (or minimum and maximum presence) of certain foods, and the minimum variety required in the meals provided,

—Minimum quality characteristics of the inputs,

—Operating conditions, such as hygienic standards, supplies, food-handling practices, and supervision, and

—Infrastructure, such as furniture, equipment, and crockery.

Firms don't have any freedom in defining the technical project. They only declare how they will satisfy the requisites established by JUNAEB. Then, JUNAEB assesses whether each firm satisfies those requirements. Firms that successfully come through these hurdles remain in the bidding process and compete on price through their respective economic bids.

Each economic bid a firm makes specifies a coverage of between one to eight TUs, depending on the upper limit allowed by its classification. Firms can make as many bids as they wish, with each bid to be accepted or rejected in its entirety. When JUNAEB accepts a firm's bid, the firm must provide all meal services in the corresponding TUs.

In each bid submitted, firms must quote prices on 168 items, corresponding to the products the JUNAEB, JUNJI, and INTEGRA nutritionist teams define. Because these agencies provide many different services, there are 30 meal types, each providing a defined number of calories. For example, meal B350 is a breakfast for primary school children containing 350 calories; meal M1000 is a lunch for secondary school children containing 1,000 calories.

For each meal, nutritionists have specified three food structures using different possible food combinations to provide the calories required in each meal. These food structures vary in quality, thereby enabling JUNAEB to price a variety of products, some of which are better than others. The objective is to give the highest possible quality to all TUs within the budget.

Therefore, each product is a meal that the JUNAEB team has fully specified, establishing the number of calories it provides, its nutritional content, and how often it must include particular foods. Firms have to quote a price for each of these products in every bid they submit. They quote prices for the 100-percent-demand level, that is, when they actually provide the planned number of meals. Firms set a higher price per meal if demand falls to 80 percent, and a higher price still if demand falls to 60 percent. This reduces the risk firms would face if they were to provide fewer meals than the planned number because of teacher strikes, epidemics, or other unforseen events. This permits them to quote a lower price for the basic 100-percent-demand level, which is the most likely scenario. On the other hand, firms can offer discounts if the level of demand exceeds 104 percent in the event that the number of students increases or the school day is lengthened, for example. They express this discount as a uniform percentage per meal.

In developing countries, state-run social programs absorb a large part of the national budget.

An economic bid thus includes

—The TUs being applied for,

—Prices corresponding to three food structures (**Type-A scenarios**) for each of 30 meal types, and

—Prices for each of the meal/food structures for three demand levels, plus a discount for an increase in demand (**Type-B scenarios**).

Taking into account the different meals, food structures, and demand levels, the firms provide a total of 168 prices (Table 1). Some combinations do not exist.

The total cost of a bid for a given food structure and demand level depends on the number of meals of each type to be provided in each TU. The JUNAEB nutritionist team specified two different mixes of each meal type to be provided in each TU; these are known as master plans (**Type-C scenarios**).

Master Plan 1, for example, specifies that for territorial unit X, 20,000 B250 meals are to be provided each day, 15,000 B700 meals, and so forth; Master Plan 2 requires 20,000 B250 meals and 15,000 B800s, and so

Bid N°: 110
Firm's Code: 1234
TU Applied: 505—506—507—0—0—0—0—0
% discount per meal if demand level exceeds 104 %: 1,5

Demand Level	B250	B350	B700
	Food Structure 1		
100—80	$138,63	$157,63	$362,37
80—60	$154,03	$175,14	$402,63
<60	$184,84	$210,17	$483,16
	Food Structure 2		
100—80	$143,63	$160,73	$377,32
80—60	$159,59	$178,59	$419,24
<60	$191,51	$214,31	$503,09

Table 1: This is part of the single economic bid form that firms have to fill out for every bid they submit. Firms must include the corresponding territorial unit (TU) codes and prices for each meal (B250, B350, and so forth) and each food structure (1, 2, or 3), according to the corresponding demand bracket (100–80 percent, 80–60 percent, or less than 60 percent). In addition, the firm must indicate the discount per meal it will offer if the level of demand rises above 104 percent.

forth. Generally speaking, Master Plan 2 contains meals with a higher number of calories than Master Plan 1, some of which are not provided under the current meals program. For example, Master Plan 2 includes 1,200-calorie lunches for a certain segment of secondary school students, whereas Master Plan 1 provides 1,000-calorie lunches for the same segment. For a given master plan, and knowing the 168 prices and the TUs covered in a given bid, one can calculate the total cost of the bid for each food structure and demand level. This requires multiplying the unit prices of each product by the quantities specified in the master plan and adding up the total. This data is the input for the mathematical assignment model.

Mathematical Assignment Model

We choose a combination of bids in consideration of two different objective functions: (1) to minimize the cost for JUNAEB alone, and (2) to minimize the cost for the three institutions together (**Type-D scenarios**).

In each case, we use two cost vectors (**Type-E scenarios**). The first corresponds to the costs obtained from the prices the firms offer in their economic bids. The second modifies these costs by incorporating the overall performance ratings JUNAEB gave the bidding firms, based on its evaluations of their technical and managerial capabilities.

We build the performance of the firm into the objective function by reducing linearly the prices the firms bid by the performance factor of the firm. In this way, we give the bids of top-rated firms an advantage compared to those of firms with lower performance ratings. We use linear weights because they are very easy to explain to the firms. In future processes, we should be able to use a more sophisticated method (conjoint analysis) to weight the performance factor in the objective function.

The factor JUNAEB obtains from the technical and managerial evaluation is quite objective. Half of it corresponds to the firm's performance on past contracts with JUNAEB, if any. JUNAEB uses regular quality controls to measure performance. JUNAEB obtains the other half by analyzing the firm's current managerial situations, using the ISO 9000 quality norm, a widely recognized and reliable standard. In this way, JUNAEB assigns a performance factor to each firm and informs it before it submits the bids. Firms can appeal their performance factors, making the whole process very transparent.

In addition to the main constraint of the model, which is to choose a combination of bids to cover all TUs, we consider some additional constraints:

—To avoid excessive concentration, which would make the program vulnerable, we set an upper limit on the number of TUs to be assigned to any one firm. Each firm has a different limit, depending on its financial and operating capacity.

—Along the same lines and to encourage diversification in the system, we also set a limit on the minimum number of firms that will be awarded contracts (**Type-F constraints)**.

—To facilitate supervision and control, JUNAEB sets an upper limit on the number of firms to be assigned to each geographic region (**Type-G1 constraints)**.

—On the other hand, so that each region has a minimum number of firms operating in it that can respond to contingencies, we set a lower limit on the number of firms awarded contracts in each region. Then, if a firm fails in its obligations for some reason, another firm operating in the same region can take its place temporarily and maintain service (**Type-G2 constraints**).

—We consider only bids above a predetermined price, so as to eliminate unrealistically low bids. Firms that underestimate their costs may be able to win the bidding process by submitting very low value bids but then be unable to comply with the contract, a problem that JUNAEB prefers to avoid (**Type-H constraints**).

We perform sensitivity analysis on the optimal assignment by including and omitting each of these restrictions (F, G, and H) in order to quantify the monetary cost of each. The only restriction JUNAEB always imposes is the upper limit on the number of TUs per firm. Apart from this, we consider different scenarios that include different food structures (A), different demand levels (B), the two master plans (C), the two objective functions (D), and the performance factor (E). By mixing all possible variations (some of which did not exist in reality) we generated 704 scenarios for analysis (Table 2).

Scenarios Analyzed

Variations	Description	Number of Alternatives
A	Different food structures	3
B	Demand levels (100%, 104%, 80%, and 60%)	4
C	Two master plans	2
D	Objective function (JUNAEB alone or all three institutions)	2
E	With or without considering firms' performance rating	2
F	With or without lower limit on number of firms	2
G	With or without limit on number of firms per region	2
H	With or without rejecting bids falling below minimum price	2
Total		704

Table 2: We analyzed various scenarios corresponding to the mixes shown, generating 704 instances of the model.

To find the optimal assignment for each scenario, we formulated the problem as a linear programming model with binary variables. We defined a binary decision variable for each bid, where the decision is to accept the bid or reject it. We also defined auxiliary binary variables, corresponding to the restrictions limiting the number of firms per region and the number of firms in the winning assignation.

The resulting model can be viewed as a set-covering problem with additional constraints. The set-covering problem is a known NP-complete problem, and the additional constraints certainly do not reduce its complexity since they can be redundant in a worst-case scenario (Garey and Johnson 1979). Thus, our assignment problem is NP-complete, so it belongs to the most difficult class of combinatorial problems. In the 1999 auction, firms made 4,500 bids, while in the 2000 auction, firms made 12,000 bids. Therefore, the models had 4,600 and 12,100 binary variables, respectively.

We had 704 instances of the model to solve, and given the tight deadlines for doing this, we had to solve each instance in a short time. Because one percent of optimality could be approximately US$2 million, we needed to find optimal solutions or, in the worst case, solutions with a gap of 0.01 percent.

To strengthen the linear relaxation of the model's formulation to deal with the combinatorial complexity of the problem, we added some cutting planes used in knapsack and packing problems. Also, for some instances we delinked a set of restrictions. We used this formulation in the most difficult instances with good results.

We programmed the model in FORTRAN 90 and solved it using the CPLEX program on a Pentium III computer. We solved all 704 instances of the model in three minutes on average. The most difficult instances took almost an hour.

We were able to solve these large instances in practice in a short time for several reasons. The model has three NP-complete combinatorial subproblems: a multiknapsack problem, an uncapacitated location problem, and a set-covering problem (Appendix). First, the packing cuts dealt effectively with the complexity introduced by the multiknapsack subproblem (Crowder et al. 1983). Second, the delinked formulation dealt effectively with the uncapacitated location problem (Balakrishnan et al. 1989). Finally, the number of objects covered (TUs) was fixed and fairly small (around 30). Therefore, around 15 bids or binary variables were active in optimal solutions, making the structure of the problem much easier than would be suggested a priori by the 12,000 binary variables. We describe the linear integer programming model and these enhancements in detail in the Appendix.

Solution and Implementation

By solving the different instances of the model, we found optimal solutions for the various scenarios, and the JUNAEB Contract Award Commission was able to evaluate different scenarios along with the quality and robustness of their solutions. For example, we calculated the total cost of enhancing the quality of meals by comparing the value of the objective function at the optimum solution for each alternative food structure (A).

We also calculated the cost of providing new types of meals of higher caloric value by analyzing the optimal solutions for the two master plans (C). By comparing the optimal solutions for the two alternative objective functions (JUNAEB alone or the three institutions jointly), we calculated the cost to JUNAEB of including JUNJI and INTEGRA in the bidding process (D). We also computed the cost of the optimal solutions corresponding to JUNAEB and the amount corresponding to the other two institutions. These figures are critical because they show the respective institutions whether the costs are within their budgets or they need to request an increase from the government.

Operations research practitioners can play a key role in this area.

We also found the cost of making a less risky assignment by using firms with higher qualifications or performance ratings (E). We also computed the additional cost of the solution generated by limiting the minimum number of firms in the assignment so as to diversify the assignment (F), the cost of restricting the number of firms per region (G), and the cost of rejecting bids below the predetermined minimum price (H).

One of JUNAEB's objectives was to implement a robust solution for the different scenarios under analysis. To insure that it did, we assessed the consistency in the behavior of the optimal solution for the 100-percent-demand scenario compared to demand at 80 percent, 60 percent, and 104 percent of the budgeted level (B). We also wanted information on how robust a given solution is with respect to the different food-structure alternatives, given that JUNAEB can undertake an assignment with one structure but may change it the following year.

For each instance of the model, we constructed a solution report (Table 3). To facilitate the JUNAEB Contract Award Commission's analysis, we constructed statistical data tables for the solutions to the different instances of the model. For example, we constructed a table to help it analyze the performance of the optimal solution for a given instance under other different scenarios. The commission could then see how robust the solution was.

In the 1999 auction, the chosen assignment included nine firms, each making a single bid, with a total annual system cost of US$60 million (US$45 million for JUNAEB). Comparing the solutions of different instances of the model was extremely helpful. For example, JUNAEB decided it was worth paying more to use firms with better performance ratings. A total cost increase of just four percent allowed it to use firms that were on average 40 percent better qualified, which was considered highly advantageous. In addition, the solution obtained was optimal for the 100-percent-demand level, but it was also seen to be extremely robust for other levels of demand and even for other food structures (a deviation of under 0.1 percent from the optimum in the other scenarios).

In the 2000 auction, JUNAEB chose 11 firms as winners, one with three bids, one with two, and nine with a single bid. In both years, this whole auction process, including evaluating scenarios and calculating the statistics, had to be carried out in the space of one week, given the legal deadlines permitted in the process.

Results and Conclusions

JUNAEB's use of mathematical modeling in the bidding process to award school meal contracts, along with other managerial enhancements, yielded a number of major improvements. We compared the auction for 1999 (when the new process started in 1997 was in full use) and the one it replaced, used in the 1995 contract award (before the new process), and found a substantial improvement in the nutritional quality of the meals provided and in the food structure, as well as in

PARAMETERS

A. Food Structure:	1	
B. Demand Level:	80–100%	
C. Master Plan:	1	
D. Objective Function:		JUNAEB
E. Firms' Performance Rating:		CONSIDERING
F. Minimum Number of Firms:		WITHOUT LIMIT
G. Number of Firms per Region:		WITH LIMIT
H. Predetermined Minimum Price:		WITHOUT LIMIT

COSTS

Total JUNAEB + JUNJI + INTEGRA =	29149.1 MM	(under budget:	303.1 MM)
Total JUNAEB =	21238.1 MM	(under budget:	899.2 MM)
Total JUNJI =	5512.2 MM	(under budget:	−249.5 MM)
Total INTEGRA =	2398.9 MM	(under budget:	−346.6 MM)

WINNING BIDS

Firm	Bid	#TUs	Total $MM	JUNAEB $MM	JUNJI $MM	INTEGRA $MM	TUs							
765	422	5	4466.3	3457.1	455.4	553.8	902	903	904	905	906			
959	440	2	1764.0	990.5	641.4	132.1	1331	1339						
896	30	2	2295.1	1515.6	622.7	156.8	401	402						
896	198	3	3271.4	2056.0	864.6	350.7	1332	1334	1336					
855	45	2	2083.0	1859.8	132.6	90.6	907	909						
559	33	3	2404.0	1898.9	297.7	207.4	505	508	901					
388	127	6	4880.7	3934.7	687.4	258.6	403	404	405	501	1335	1333		
241	1604	8	6800.4	4556.5	1728.7	515.3	502	503	504	506	507	510	511	1201
190	30	1	1184.2	968.9	81.7	133.6	908							
Total			29149.1	21238.1	5512.2	2398.9								

Table 3: This solution report for an instance of the model describes the parameters of the instance of the model. Then, it shows the total cost of the assignment and the cost for each institution (in Chilean pesos). Finally, it shows the winning bids, giving the code of the firm, the number of its bid, the number of territorial units (TUs) in the bid, the total cost and the cost for each institution and, finally, the codes of the TUs in the bid.

the infrastructure of the meals service and the labor conditions of the food handlers in the schools (Table 4). These improvements increased total costs by 24 percent (in real terms), but the average price of a meal rose only 0.76 percent. Price trends would have predicted an increase of at least 22 percent to obtain this higher quality. This saving amounts to some US$40 million a year, equivalent to feeding 300,000 children during one year. (Each auction covers one third of the country and the resulting contracts last for three years, so JUNAEB conducts one auction each year. The auctions compared (1995 and 1999) awarded contracts over the same TUs.)

By using mathematical modeling to assign contracts, JUNAEB made great improvements and saved a significant amount of money for the following reasons:

(1) The new auction process is objective and transparent, with few chances for firms to exert inappropriate pressures on the decision makers. JUNAEB has standardized the criteria for meal service (the technical project), and firms compete on prices. The mechanism makes JUNAEB's decisions more objective, and the model results obtained are entirely replicable and can be demonstrated publicly whenever necessary.

(2) The process is fair and impartial and a reliable method of awarding a contract, forcing firms to compete and to increase their efficiency and productivity. Also, the performance factor, based on JUNAEB's evaluations, can benefit firms with a history of good performance. Therefore, firms have improved their management, raised the quality of their service, and

Nutritional Input–Nutrients (Meal B700)

1995 Auction (Without Model)	1999 Auction (with Model)
Fats: maximum 30%	Fats: maximum 10%*
Sucrose: not specified	Sucrose: maximum 25 g.*
Vitamin C: 19.8 mg.	Vitamin C: 45 mg.*
Calcium: 264 mg.	Calcium: 400 mg.*
	(*): In accordance with dietary recommendations

Food Structure

1995 Auction	1999 Auction
Dairy products: 50% milk once a week, and milk substitute containing 30% milk four times a week	Dairy products: 50% milk four times a week, and milk substitute containing 30% milk once a week
Meats: minced meat four times per month (20 g.)	Meats: minced meat six times per month (40 g.)
Fruit: four times per month	Fruit: fresh fruit six times per month, and twice in preserve or dried form.
Salad: optional	Salad: six times per month (60 g.)
Bread: optional	Bread: three times a week at breakfast
Biscuits: optional	Biscuits: once or twice a week

Infrastructure

Main additional infrastructure in schools compared to 1995:
Fridge/freezer
Fume extraction canopy
Stainless steel/tiled sink
Lights
New crockery at start of program

Situation of Food Handlers

Situation of food handlers improved in the following respects compared to 1995:
Real wages increased by 41.5%.
All have taxable bonuses.
Quarterly Labor Directorate certification required of being in compliance with labor market and pension fund obligations.

Table 4: A comparison of 1995 and 1999 auctions in terms of nutritional quality, food structure, infrastructure of meal services, and labor conditions of food handlers in the schools shows the significant improvements generated by the new auction process.

reduced their prices, and they still make profits. In fact, firms' average profit on sales increased from 3.2 percent in 1995 to 4.9 percent in 1999. Average return on equity rose from 28 percent in 1995 to 38 percent in 1999, indicating the increase in investment made by the firms.

(3) The new mechanism allows firms to make bids to cover packages of TUs. In this way, they can take effective advantage of scale economies, such as transportation savings and volume discounts.

(4) In each scenario, JUNAEB obtains the least-cost bid combination that satisfies all the restrictions. Given the large number of bids involved and the difficult combinatorial structure of the problem, it could not have done this manually; moreover, if it had done so, it probably would have lost a significant amount of money. In fact, if an assignment chosen manually turned out to be two percent inferior to the optimal solution, which could easily happen without an appropriate solution tool, the loss would amount to US$3.5 million, equivalent to providing a year's meals to 25,000 children.

(5) The mathematical model makes it possible to obtain optimal solutions rapidly for the different scenarios. We believe the statistical data tables constructed from the different instances of the model were a great

help in finding the best solution, especially at the meeting of the JUNAEB Contract Award Commission. With the information presented, the commission could evaluate the costs and benefits of each scenario, determining the cost of the different assignments for each of the participating institutions, as well as the cost to JUNAEB of including JUNJI and INTEGRA in the auction. We also calculated the costs of imposing operating restrictions, of enforcing a minimum price for the bids, and of using better quality firms. We also calculated the cost of providing menus with better food structure and greater caloric value, as well as the robustness of the solution obtained with respect to different food structures and demand levels.

As a result of using the mathematical model, the solution assignment has an optimal price-quality ratio that is robust to different scenarios, which is highly important in a problem of this complexity that concerns such large sums of money.

The reasons the new auction process improved the price-quality ratio fall into two categories: First are those related to changes in the competitive and bidding behavior of the firms (points (1), (2), and (3)). Second are those related to the analytical capabilities of the mathematical model (points (4) and (5)). Comparing the 1995 and 1999 auctions, we estimate that both effects saved about US$40 million. In the 1997 auction, however, the commission relied on the analytical capabilities of the model, but the firms didn't know about it and, consequently, didn't change their competitive behavior. So in comparing the 1997 auction with the 2000 auction, we isolate the effect of the change in the competitive behavior of the firms and quantify the savings related to it, which amounts to US$23 million. Therefore, we can say roughly that 60 percent of the impact of the new process (23 out of 40) derives from the change in the firms' competitive behavior and the other 40 percent can be attributed to the analytical capabilities of the model.

The clearest evidence of the success of this application is its continued use. After using it in 1997 for the first time, JUNAEB used it again in 1999, 2000, and 2001 and intends to use it in all future auctions. Over the years we have improved the methodology. For example, we enhanced the model's outputs, improving the comparison among different scenarios. In addition, JUNAEB used the same methodology in three auctions for contracts to supply spectacles, amounting to US$2 million each.

Our work is an example of a successful application of operations research in a field that has major social impact. In developing countries, state-run social programs absorb a large part of the national budget, but key decisions are often based on very precarious criteria. Sophisticated decision-making tools can be used for such problems, even when they have never been used before.

We believe operations research practitioners can play a key role in this area, so it is essential to disseminate information about the potential of mathematical tools for decision making among executives in state institutions. These tools give decision makers better analytical capabilities and a deeper understanding of their problems, and perhaps more important, mathematical tools for decision making can provide transparency and encourage competition. These are key issues in achieving efficiency and improving the allocation of resources, which can directly improve the quality of many people's lives.

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APPENDIX
Mathematical Model Parameters

R: set of geographic regions in the country.

I: set of territorial units.

K: set of participating firms.

J: set of bids submitted.

c_j(*foodstr, demandlev, masterpl, O.F.*): cost of bid j for a given food structure, demand level, and master plan, depending on the objective function used (JUNAEB or all three institutions).

$POND_k$: weight assigned to firm k, according to its overall performance rating. If the evaluation is made ignoring qualification, the weight is set at 1.

$e(j)$: firm presenting bid j.

$u(j)$: set of territorial units included in bid j.

$oer(k, r)$: set of bids presented by firm k that include TUs belonging to region r.

$MAXunifir(k)$: maximum number of TUs acceptable for firm k. This limit depends on the size of the firm and varies between one and eight.

$MINfirass$: minimum number of firms acceptable in the assignment. The limit is set between nine and 11.

$MINfirreg(r)$: minimum number of firms acceptable in geographical region r. The limit varies between regions but is usually around two.

$MAXfirreg(r)$: maximum number of firms acceptable in geographical region r. This varies from region to region but is usually around four.

Variables

$$X_j = \begin{cases} 1 & \text{accept bid } j \\ 0 & \text{reject bid } j \end{cases} \quad \forall j \in J,$$

$$Y_{kr} = \begin{cases} 1 & \text{firm } k \text{ will serve TU in region } r \\ 0 & \text{firm } k \text{ will not serve any TU in region } r \end{cases}$$

$$\forall k \in K, \forall r \in R,$$

$$Z_k = \begin{cases} 1 & \text{firm } k \text{ has one or more bids accepted} \\ 0 & \text{firm } k \text{ has no bids accepted} \end{cases}$$

$$\forall k \in K.$$

Objective Function

Minimize total cost of assignment for a given food structure, demand level, and master plan, depending on the objective function used (JUNAEB or all three institutions) and on whether or not a firm's overall performance rating is considered in the assignment.

$$\min \sum_{j \in J} c_j(foodstr,\ demandlev,\ masterpl,\ O.F.) \cdot X_j \cdot POND_{e(j)}.$$

Constraints

(1) All territorial units must be covered.

$$\sum_{j: i \in u(j)} X_j \geq 1 \quad \forall i \in I.$$

(2) Limit on number of territorial units assigned to each firm.

$$\sum_{j: e(j) = k} X_j \cdot |u(j)| \leq MAXunifir(k) \quad \forall k \in K.$$

(3a) Calculation of variables Y_{kr}.

$$Y_{kr} \leq \sum_{j: j \in oer(k,r)} X_j \quad \forall k \in K, \forall r \in R.$$

(3b) Calculation of variables Y_{kr}.

$$\sum_{j: j \in oer(k,r)} X_j \leq |oer(k, r)| \cdot Y_{kr} \quad \forall k \in K, \forall r \in R.$$

(4a) Calculation of variables Z_k.

$$Z_k \leq \sum_{r \in R} Y_{kr} \quad \forall k \in K.$$

(4b) Calculation of variables Z_k.

$$\sum_{r \in R} Y_{kr} \leq |R| \cdot Z_k \quad \forall k \in K.$$

(5) Limit on number of firms per region (optional).

$$MINfirreg(r) \leq \sum_{k \in K} Y_{kr} \leq MAXfirreg(r) \quad \forall r \in R.$$

(6) Minimum number of firms in assignment (optional).

$$\sum_{k \in K} Z_k \geq MINfirass.$$

(7) Integrability of the variables.

$$X_j,\ Y_{kr},\ Z_k \in \{0,1\}.$$

Constraints (1) define a classic covering problem, where the TUs are the elements to be covered and the bids are the covering elements. Constraints (2) constitute a multiknapsack problem. Constraints (3) make it necessary to activate variables Y only when the corresponding X variables have been activated, which is the structure of uncapacitated location problems. Constraints (4) have the same structure using variables Y and Z. Constraints (5) and (6) are general bounds for variables Y and Z, respectively. The resulting model is a combination of known NP-complete problems.

The total number of instances in the model to solve was 704, and the time available to do so was short, so each instance had to be solvable quickly. Accordingly and given the combinatorial complexity of the problem, we built additional constraints into the model to strengthen the linear relaxation of its formulation.

We first added the following cutting planes:

$$\sum_{(j: e(j) = k) \wedge (|u(j)| > MAXunifir(k)/2)} X_j \leq 1 \quad \forall k \in K.$$

Because of the limit on the maximum number of TUs that can be assigned to each firm (constraint (2)), we can select at most only one of the bids of a firm that covers more than half of this maximum, showing the validity of the cuts. These cutting planes are not a linear combination of constraints (2), so they strengthen the linear relaxation of our model. These types of cutting planes are widely and effectively used in formulating and solving knapsack or packing problems (Crowder et al. 1983, Nemhauser and Wolsey 1988).

In addition, for some instances, we delinked restrictions (3b) in the following way:

$$X_j \leq Y_{kr} \quad \forall j \in oer(k,r),\ \forall k \in K,\ \forall r \in R.$$

This strengthening technique, frequently used in uncapacitated location models, leads to an expanded model with a better linear relaxation than the original one, but it makes the model bigger. When solving the linear relaxation, this formulation gives a more integral solution than the original in relation to variables Y. The coefficient $|oer(k,r)|$ in (3b) allows small values of Y_{kr} and still satisfies the constraint. The delinked formulation forces larger values of variables Y to activate the corresponding variables X. Thus, fewer iterations are required in the branch-and-bound stage, but each iteration takes more time because the model is larger. We used this expanded formulation in the most difficult instances with good results. Balakrishnan et al. (1989) and other authors they cite report similar results.

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Ricardo Halabi Caffena, National Director, JUNAEB, writes: "The National School Assistance and Scholarship Board (JUNAEB) is a national agency in charge of distributing meals to 1,200,000 children in Chile's primary and high schools. This program is essential since most of these children come from low-income families. The service is provided by external firms, which are awarded contracts through yearly bidding. The total yearly costs of the meals are about US$180 million, considering two additional institutions which also participate in these programs.

"Before 1997 the system had important imperfections. The contracts were awarded through a discussion process supported by very rudimentary mathematical tools. The imperfections of the system not only made it difficult to find good solutions on its own but also allowed the competing firms to make improper pressures on the system, driving the prices up.

"In 1997, to improve the situation, Lysette Henríquez, who had recently been appointed as head of the JUNAEB, called a group of researchers at the Industrial Engineering Department of the University of Chile and contracted them to develop a mathematical model and a computational system to support the auction process. The system was based on the notion of assigning bids to firms so as to minimize the global costs, while satisfying a complex set of operational constraints. These included limiting the number of regions any firm could work on and a minimum and maximum number of firms assigned to each region. Also, a set of possible meals was evaluated to find the most adequate within the budget.

"The results of implementing this system were dramatic. The new procedure completely changed the character of the auction process. Being compelled by the objectivity of the model, the firms had to stop any type of pressures and compete on the merits of their proposals. After some initial resistance, the system changed the culture of the firms, which, due to the competition, became more efficient and structured.

"The system also allowed reaching best solutions and evaluating different scenarios, opening options that JUNAEB had not considered before. Based on these very good results, the system was improved and used also in the next auction process in 1999 and is presently being implemented for the 2000 bidding. It is going to be used in all future auction processes.

"The evaluation of the 1999 process (using the mathematical model) compared to the pre-model approach of 1995 allowed us to obtain for practically the same average price per meal (an increase of less than 1 percent in real terms) improvements in the quality of the food and the service worth an estimated US$13 million per year. This sum is equivalent to feeding daily meals to an additional 115,000 children yearly.

"The work was carried out by professionals of JUNAEB, headed by Lysette Henríquez, with Cristián Martínez, who worked in a team effort with the group from the University of Chile headed by Professor Rafael Epstein, with Jaime Catalán and Gabriel Weintraub."