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Improving the Pan American Health Organization's Vaccine Supply Chain

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The Pan American Health Organization (PAHO), serving as the regional office for the Americas of the World Health Organization, procures vaccines for 37 countries in Latin America and the Caribbean. To maintain a high coverage of basic vaccines, conduct regional campaigns to eliminate specific infectious diseases, and introduce new vaccines, PAHO continuously seeks to identify supply chain improvement opportunities. A team of researchers from PAHO and the School of Industrial and Systems Engineering at Georgia developed analytical tools to improve demand forecasting, transportation cost estimation, and bid award allocation. This work has assisted PAHO in achieving its goal of controlling costs while improving service to member countries.

Key words: Health care, vaccines, combinatorial auctions, bundle bidding, forecasting applications.

1. Introduction

The Pan American Health Organization (PAHO) is the regional office for the Americas of the World Health Organization. Through its Revolving Fund for Vaccine Procurement (RF), PAHO procures vaccines for 37 countries in Latin America and the Caribbean, including small island states and larger countries, from both large multi-national manufacturers and emerging suppliers in developing countries. Payments to suppliers are made from the capital in the fund, and countries in turn repay this money plus a 3% service fee upon vaccine delivery. In 2006, the level of expenditure on these purchases was approximately $160 million.

Since its inception in 1979, the RF has supported countries with the achievement of high coverage of basic vaccines and, from 1997, with the accelerated uptake of new vaccines including measles-mumps-rubella (MMR), pentavalent (DTP-HepB-Hib), and seasonal influenza. The RF has also supported successful polio eradication and measles elimination in the region through national vaccination campaigns requiring high volume procurement of the relevant vaccines. Through the RF support of procurement of the relevant rubella-containing vaccines, rubella elimination in the region is anticipated by 2010.

Each year, PAHO requests bids from suppliers for the vaccine products required by member countries. A summary of PAHO's current procurement process and the timeline is provided in Appendix A. PAHO strives to keep actual orders within 10 percent of the forecast quantity stated in the annual agreements made with suppliers and desires to have at least two suppliers for each vaccine whenever possible. The allocations to each supplier are determined manually and by consensus of a PAHO team, with members representing the quality, procurement, and immunization program interests. Agreements with suppliers are made for a term of one year. When evaluating bids, PAHO considers "landed price" (vaccine cost plus transportation cost), past performance and quality of suppliers, and special country requests. For example, certain countries prefer only to receive vaccines from specific suppliers; PAHO honors this preference.

The PAHO - Georgia Tech collaboration set out to identify opportunities for improvement throughout the vaccine supply chain and within the vaccine procurement process specifically. The primary outcomes of the project include:

- Assessment of demand forecast accuracy and recommendations for improvement.
- Improved estimates of the cost of transporting vaccines.
- Quantitative models for bid award allocation.
- Assessment of the benefits and the challenges of bundle bidding in vaccine procurement.

Vaccine procurement in the U.S. has been considered in the literature. Jacobson et al. (1999) and Jacobson et al. (2004) develop integer programming models to minimize the total cost of vaccines, clinic visits, preparation, and wastage given the available suppliers and the vaccination schedule recommended by the National Immunization Program of the Centers for Disease Control and Prevention. These studies consider multiple suppliers for the entire vaccination *schedule* rather than for each individual *vaccine*. Chick et al. (2006) consider the design of contracts to balance manufacturers' objectives of setting production volume and profitability with public health costs and benefits. There is a vast literature on combinatorial auctions, or problems in which buyers must select from among suppliers offering combinations of individual products; de Vries and Vohra (2003) provide a good survey.

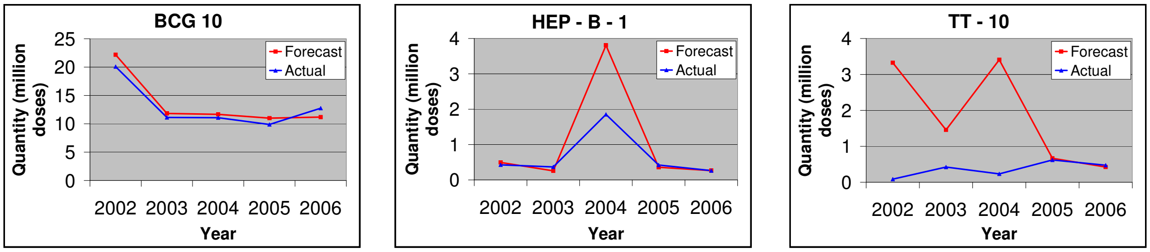
Our contribution is to extend the application of operations research methodologies to problems arising in vaccination for an entire region. We present an analysis of the accuracy of PAHO's forecasts and factors impacting this accuracy, as well as targeted recommendations for improvement. Because transportation costs are not included in the bids suppliers submit and therefore must be estimated, we assess the quality of the current transportation cost estimate and present new methods that perform better under multiple performance measures. Motivated by recommendations from a supply chain assessment performed by the Latin American Logistics Center (Latin America Logistics Center (2006)), PAHO desires to explore bundle bidding in which suppliers can submit bids for groups of vaccines rather than only individual vaccines. However, based on fears cited by other countries about the possibility that bundle bidding will reduce long-term supply security and unfairly favor large suppliers, PAHO seeks a quantitative assessment of the impacts of such practices. We develop mathematical models to explore the implications of bundle bidding. To our knowledge, we are the first to develop vaccine procurement models that incorporate bundle bidding and requirements for supplier diversity for individual vaccines. We show that these auctions can be designed in a way that is fair to suppliers and maintains supply chain security for PAHO.

2. Forecast Analysis

Forecasting is a challenge for PAHO because of the vast differences in the requirements, resources, and forecast methodologies of the member countries. As a result, PAHO often cannot meet its internal goal of keeping the difference between forecasted and order quantities within 10 percent. Large deviations between ordered and forecasted quantities hurt relationships with suppliers and may lead to higher prices in the long run. Of the 14 vaccines analyzed over the five-year period 2002-2006, the highest number of vaccines that hit the 10 percent target in a given year was five, which occurred both in 2004 and 2005. Table 12 in Appendix B presents the mean absolute percent error (MAPE) and the percent mean absolute deviation (PMAD) between forecasted and ordered quantities as well as the number of years (between 2002-2006) where a given vaccine's order quantity was within 10% of the forecast. Comparing forecasted and actual demand quantities placed each vaccine into one of three categories:

- Forecasted orders and actual orders appear almost the same throughout the five-year period (for example, BCG10 in Fig. 1(a)).
- Trends of the forecasted orders and actual orders are the same, but the quantities differ significantly at one or more points (for example, HEPB1 in Fig. 1(b)).

• Forecasted orders and actual orders appear not to have much agreement in more than two periods (for example, TT10 in Fig. 1(c)).



(a)BCG 10 (b)HEPB1 (c)TT10

Figure 1 Forecasted Demand and Actual Demand for BCG-10, HEB-B-1, and TT-10

To understand why forecasts for some vaccines are substantially better than others we investigated three potentially contributing factors:

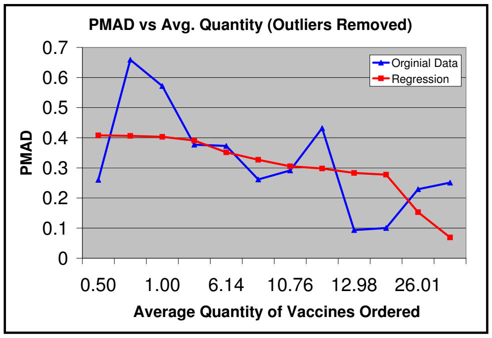
• Individual country forecasts,
• Total quantity ordered of a particular vaccine,
• Number of countries purchasing a particular vaccine.

In their study of PAHO's operations, the Latin America Logistics Center cited the reliance on individual countries in forecasting their own demand as one of the significant problems with PAHO forecasts (Latin America Logistics Center (2006)). PAHO collects individual country demand and aggregates those to arrive at regional forecasts. We investigated the extent to which individual countries vary in forecast accuracy for a particular vaccine over time. In doing so, we chose to look at the individual country forecasts for the three most poorly forecasted vaccines (TT 10, HIB 1, and HEP B 10) and the two best forecasted vaccines (BCG 10, MMR 10) as determined by the MAPE statistic (see Table 12 in the Appendix).

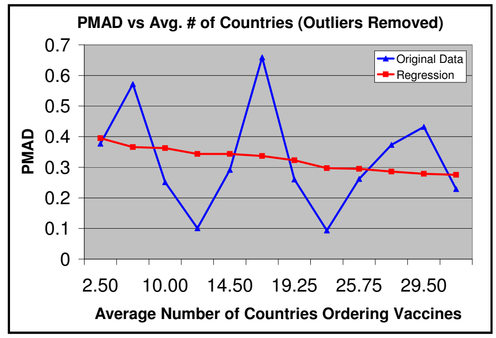
For each of these vaccines we looked at the forecasts and calculated PMAD for each country (which ordered or placed a forecast for that vaccine at least once) over the five year period of 2002-2006. For each vaccine, we classified the countries' forecasting performance as 'good', 'fair', 'bad', and 'very bad' for PMAD values 0-0.5, 0.5-0.8, 0.8-1, and above 1, respectively. The classification of the countries tended to vary, some more drastically than others, depending on the vaccine type. For instance, Venezuela had a value of 0.16 for MMR 10, 20.71 for TT 10, 1.55 for HIB 1, and 0.8 for HEP B 10. Ecuador had values of 0.80 for BCG 10, 5.6 for MMR 10, and 0.88 for HEP B 10. Montserrat had values of 0.397 for BCG 10, 0.25 for MMR 10, and 3.00 for TT 10. These variations in forecasting accuracy across vaccine type for each country indicate that while the particular country may have some effect on forecasting accuracy, the type of vaccine that is being forecasted also plays a significant role in how accurate the final predictions will be.

Note that there were quite a few occasions in which countries either submitted a '0' for quantity forecasted and then ordered a substantial amount, or they forecasted a substantial amount and then did not make any actual order. This behavior may have significant effects on overall demand forecasting, particularly when larger countries are guilty of the practice. It is telling that for the three most poorly forecasted vaccines this event occurred at least once in virtually every period, while this occurrence was much less frequent with the other two vaccines.

Next, we investigated whether there is a linear relationship between forecasting accuracy and two other variables, namely, the average quantity ordered of a vaccine and the average number of countries to order a vaccine. Figures 2(a) and 2(b) display the actual data compared with the linear regression. Hypothesis tests (detailed Appendix B) conclude with 95 percent confidence that there is not a linear relationship between our predictor and response variables.



(a)Average Quantity Ordered vs. PMAD



(b)Average Number of Countries Ordering a Vaccine vs. PMAD

Figure 2 Actual Data and Linear Regression

Our analysis of PAHO's forecasting suggests there are very few countries that consistently stand out as 'bad' forecasters when their performance is compared with the forecasting accuracy of all other countries. There are specific instances in which countries do perform well below the average of all countries for a given year, but we find no evidence of long run behavior to this end. This finding, coupled with little evidence of a linear relationship between vaccine forecast accuracy and either the number of doses ordered or the number of countries ordering a vaccine, leads us to the conclusion that forecast quality is vaccine-specific rather than depending on these other factors. There may be several reasons for some vaccines being more stable than others, including (i) the nature of the disease for which a particular vaccine is intended, (ii) the number of campaigns or promotions made for a particular vaccine at the country level, and (iii) the nature of the program for that vaccine (community-based or school-based). Specific strategies for improving demand forecasting based on the insights provided by this analysis are presented in the Recommendations section.

3. Transportation Cost Analysis

Vaccine transportation costs make up a significant portion of the total expenditure from the Revolving Fund. In 2006, they exceeded $5.5 million, or 5.6 percent of the total expenditure on vaccines. The PAHO - Georgia Tech collaboration sought to understand the factors affecting shipping costs as a means to achieve supply chain improvement. Moreover, we developed ways to incorporate more accurate shipping cost estimates into the bid award allocation process. In the following sections, we address these two topics.

3.1. Shipping Cost and Bid Award Allocation

It is clear from historical data that shipping cost to a given country varies with the supplier and with the vaccine being shipped, so decisions about bid allocations to suppliers should consider transportation costs. As a result of work done by the Latin America Logistics Center, PAHO began including transportation cost estimates in its bid award process for the 2006 purchasing year (Latin America Logistics Center (2006)). To do this, PAHO personnel calculated the average shipping cost as a percent of goods per shipment for each supplier-vaccine pair using shipping data from 2005. This factor (*supplier-vaccine scalar*) was used to inflate the quoted vaccine cost, resulting in a *landed cost* estimate for each supplier-vaccine pair, where landed cost was defined as the estimated cost per dose to purchase and ship a given vaccine from a particular supplier. This landed cost, rather than the nominal vaccine cost, was then used by PAHO immunization and procurement officials in determining which suppliers to award in the 2006 bid allocation process. This marked an important step toward considering total supply chain costs in bid allocation decisions.

Table 1 Example of Supplier Differences in Shipping Cost

Supplier	Vaccine	Country	Doses	Shipping Cost as % of Vaccine Cost
Supplier 1	MR10	Country A	500,000	2.132
Supplier 2	MR10	Country A	687,600	6.770

Table 2 Example of Vaccine Differences in Shipping Cost

Supplier	Vaccine	Country	Doses	Shipping Cost as % of Vaccine Cost
Supplier 2	MR10	Country A	687,600	6.770
Supplier 2	MEASLES10	Country A	500,000	17.608

Table 3 Examples of Country Differences in Shipping Cost

Supplier	Vaccine	Country	Doses	Shipping Cost as % of Vaccine Cost
Supplier 2	DT 10 ADULT	Country C	500,000	27.511
Supplier 2	DT 10 ADULT	Country D	500,000	45.145
Supplier 3	YELLOW FEVER 5	Country E	100,000	2.275
Supplier 3	YELLOW FEVER 5	Country F	100,000	5.804
Supplier 3	YELLOW FEVER 5	Country G	100,000	6.022
Supplier 3	YELLOW FEVER 5	Country H	100,000	7.942

Building upon this idea, we investigated the previous five years' shipping data to determine the extent to which not only supplier and vaccine affect transportation cost, but also how the destination country may play a role. Differences between suppliers may be due to the location from which each supplier is shipping or the strength of that supplier's agreements with freight forwarders. Vaccine-related differences may stem from different cold chain temperature requirements but also from packaging, which differs based on the presentation or the dose size. Country differences reflect the frequency, number, and freight capacity of flights into each country; the customs requirements of that country; and the volume being shipped to that country. It is clear that all three factors are important. The example in Table 1 shows that for similar quantities of the same vaccine being shipped to the same country, two different suppliers incur very different shipping costs. Further, the same supplier experiences different costs for different vaccines, as is illustrated in Table 2. Finally, Table 3 demonstrates the range of shipping costs possible for the same supplier-vaccine pair when destination countries differ. We note that shipment quantities are comparable in all of these instances. The importance of the country in estimating shipping costs is further emphasized by the fact that those countries to which shipping is the most costly (e.g., Caribbean islands) are also those which typically order the smallest quantities. It is not uncommon to experience shipping costs that are six to seven times the cost of goods for these destinations.

To incorporate the impact of the destination country on the landed cost, we developed a *country shipping scalar* for each of the member countries. We used these scalars to modify the landed cost estimates of supplier-vaccine pairs. These estimates were then implemented in the bid award allocation model, and this performance was compared to that of the supplier-vaccine landed costs.

3.2. Generating Country Shipping Scalars

We sought methods of estimating transportation cost that would demonstrate improved performance over the landed cost method but would still be simple to implement. In this section, we describe four sets of country shipping scalars developed and analyzed with these goals in mind. For each, the information required is readily available in PAHO's annual shipping report. Each scalar can be calculated using Microsoft Excel's regression and optimization capabilities, thus eliminating the need for sophisticated software. Before describing the scalars, we discuss metrics used to compare their performance.

There are multiple performance measures that can be used to assess the quality of transportation cost estimates. The choice of performance measure(s) depends on organizational goals. Each metric presented here has its benefits and drawbacks, so combining them provides a more complete picture of a scalar's usefulness. *Mean absolute deviation* penalizes both over- and under-estimation of transportation cost. Small values indicate that the difference between the predicted and actual transportation cost for individual shipments is, on average, small. *Mean absolute percent error* considers the error in the transportation cost estimate as a fraction of the actual transportation cost. Thus, an error of the same absolute value is penalized more when the total cost of the shipment is small than when it is large. Like the mean absolute deviation, the *sum of squared error* penalizes over- and under-estimation of costs. However, the penalty is quadratic rather than linear; large deviations are penalized more steeply than small ones. When using a scalar that minimizes the sum of squared errors, one may accept small deviations on many shipments over large deviations on a few shipments, unlike when using a scalar that minimizes mean absolute deviation. Finally, *net dollar error* indicates the difference between the total projected cost and the realized cost of transporting all vaccine shipments in a given year. Large negative values for this measure indicate substantial underestimation of transportation costs, which may result in budgetary challenges and difficulties in managing the limited capitalization of the Revolving Fund. Large positive values may also create difficulties. While small (either positive or negative) net dollar errors do not necessarily indicate accurate estimation of individual shipments, they do provide a picture of the overall budget impact of transportation cost.

We developed four sets of country shipping scalars and then used the performance measures just described to assess each scalar set. Specifically, the scalars are the *Min MAD* scalar, which is determined by solving an optimization model that minimizes the mean absolute deviation between the estimated and actual shipping costs for the shipments during a given year; the *Min MAPE* scalar, generated by minimizing the mean absolute percent error of the estimated cost of shipments; the *Regression* scalar, calculated by minimizing the sum of squared error in shipment cost estimation; and the *Regression No Outliers* scalar, in which anomalous data points were removed before performing the regression analysis. The performance summaries of the sets of scalars for the years 2003 to 2006 are given in Table 4, while the scalars themselves are detailed in Appendix B.

We considered each of the four performance measures as well as a rank aggregate to compare the different country shipping scalars with each other and with the current PAHO practice of using landed cost estimates. The results of this comparison are summarized in Table 4.

In columns 6-9 of Table 4, each of the transportation cost estimate methods is ranked for the respective performance measures (where rank 1 indicates the estimate that performs best for the measure and rank 5 that which performs worst). These ranks are then summed to create a rank aggregate score, which indicates the relative performance of a given estimate when all performance measures are considered. Those estimates with low rank aggregates perform fairly well on most measures; those with higher rank aggregates perform less favorably. The table illustrates that for each year, the various country shipping scalars outperform the current PAHO practice of landed cost estimates. Moreover, for the years considered, the *Min MAD* scalar consistently outperforms the others in the rank aggregate. This analysis indicates that it is possible to substantially improve the quality of the transportation cost estimates, with impact on budgeting, bid award allocation, and supply chain performance. Insights generated by a computational analysis of the impact of using the country shipping scalar on bid award allocations are detailed in the next section.

4. Bid Award Allocation Modeling

In this section, we discuss how to formally model the problem of bid award allocation, the annual task in which PAHO chooses the suppliers from which to purchase each of the vaccines required by the member countries. We first consider the current procedure and then we introduce bidding on

Table 4 Performance Summary of Transportation Cost Estimators

					Ranks				
Estimator	**MAD**	**MAPE**	**SSQ**	**Net $**	**MAD**	**MAPE**	**SSQ**	**Net $**	**RAS**
2003									
PAHO Estimate	0.1079	0.8982	96.38	677,016	5	2	5	2	14
Min. MAD	0.0907	0.9455	75.25	91,545	1	3	3	1	8
Min. MAPE	0.1026	0.5683	88.73	-1,702,411	4	1	4	5	14
Regression	0.0949	1.0112	71.03	-780,130	2	5	1	3	11
Reg. (No Outlier)	0.0952	0.9847	75.21	-790,458	3	4	2	4	13
2004									
PAHO Estimate	1.0676	0.5192	266,830.95	-860,138	5	3	5	5	18
Min. MAD*	1.0591	0.4849	266,814.21	-571,107	3	2	4	1	10
Min. MAPE	1.0525	0.4221	266,786.96	-831,515	2	1	3	4	10
Regression	1.0656	0.8788	266,216.51	822,490	4	5	1	3	13
Reg. (No Outlier)	1.0427	0.7131	266,696.34	764,979	1	4	2	2	9
2005									
PAHO Estimate	0.2934	0.5351	1,986.64	-935,284	5	3	5	3	16
Min. MAD	0.2457	0.4548	1,540.29	-562,199	1	2	3	1	7
Min. MAPE	0.2592	0.4363	1,728.68	-917,972	2	1	4	2	9
Regression	0.2656	0.5704	1,283.61	-1,060,325	4	5	1	4	14
Reg. (No Outlier)	0.2618	0.5523	1,334.67	-1,072,314	3	4	2	5	14
2006									
PAHO Estimate	0.4463	0.4478	7,589.30	-595,461	4	2	5	4	15
Min. MAD	0.4141	0.5393	7,043.10	-244,453	1	3	3	1	8
Min. MAPE	0.4245	0.3785	7,564.02	-569,312	2	1	4	3	10
Regression	0.4734	2.2488	4,658.08	1,178,365	5	5	1	5	16
Reg. (No Outlier	0.4283	1.2107	5,639.65	540,673	3	4	2	2	11

MAD=Mean Absolute Deviation; MAPE=Mean Absolute Percent Error; SSQ=Sum of Squared Error; Net $ =Dollar Value of Over- or Under-Estimation of Actual Transport Cost; RAS = Rank Aggregate Score. All performance evaluation done on actual shipping data for the respective years. *If the convergence value in Excel Solver is decreased, additional iterations will find scalars with a slightly lower MAD.

bundles of multiple vaccines rather than on individual items. Such bundle bidding allows suppliers to provide a discounted price for vaccines that might have positive synergies in their production or distribution processes. We develop mathematical models that can be used to solve the bid allocation problem optimally in the presence of vaccine bundles or complicating considerations, such as supplier diversification. We use an integer programming model for both the current process and the bundle bidding.

4.1. Current Bidding Process

If complex considerations, such as supplier diversification, are not taken into account the current bid allocation problem can be solved separately for each vaccine since each supplier submits bids for each vaccine independently. The optimal solution to this problem can be found simply by sorting the bids of suppliers in the increasing order of price per dose, and then allocating as much as possible to the first supplier. In the following sections, we demonstrate that the bid allocation problem with the presence of complicating constraints or bundles cannot be decomposed into subproblems, and finding the optimal allocations is not an easy task.

A mathematical model of the current bid allocation without complicating considerations and how it can be decomposed into separate models for each vaccine is presented in Appendix D.1.

4.2. Bundle Bidding

PAHO's challenge is to reduce costs while improving service to member countries. With the goal of encouraging affordable pricing, PAHO is considering a "bundling" approach in its international bidding process. Here, we define a bundle as a set of two or more vaccines offered together rather than as individual products. Suppliers may be able to cut costs by bundling vaccines due to synergies in the manufacturing process or shipping, which may lead to lower prices and savings for PAHO. For example, if two vaccines share common resources but have complementary demand patterns, this would help the manufacturer to smooth out production. Alternatively, if two vaccines have similar demand patterns and can be shipped together, this might result in lower shipping and handling costs. Offering bundles consisting of both new and well-established vaccines may also be a strategic move on the part of suppliers given the low margins on the older products (Thom (2007), Coleman et al. (2005)).

If bundle bidding is adopted at PAHO, the process for receiving and evaluating bids must change. Hence we have designed a new bidding process to simulate and analyze the effects of bundle bidding. In our proposed process, suppliers will continue to submit a production quantity and a price per dose for each individual vaccine in their portfolios. However, a supplier will also be able to create bundles of vaccines and submit discounted prices for the vaccines in the bundles. For example, a supplier may place bids for vaccines a and b separately with prices c_a and c_b and quantities q_a and q_b. In addition, that supplier may also create a bundle k with n_k vaccines that includes vaccine a and b with costs c_a^k and c_b^k. This means that if vaccine a and b are awarded to this supplier, PAHO can save $(c_a^k - c_a)$ per dose of vaccine a and $(c_b^k - c_b)$ per dose of vaccine b by selecting bundle k. It is possible that a supplier will put a lower limit on the amount supplied within a bundle to realize the savings due to synergies. (If a very small quantity is awarded, the supplier's economies of scale or scope may not be realized.) Therefore, suppliers will submit a lower bound on the required allocation amount for each of the vaccines in a bundle in addition to specifying the bundle prices. Hence, l_a^k and l_b^k will be the lowest quantities that PAHO can order within bundle k (with prices c_a^k and c_b^k) for the vaccines a and b that bundle. To summarize, for each bundle k created with vaccine set $B_k = \{\upsilon_1^k, ..., \upsilon_{n_k}^k\}$, suppliers will submit minimum quantities $L_k = \{l_1^k, ..., l_{n_k}^k\}$ and per-dose prices $C_k\{c_1^k, ..., c_{n_k}^k\}$ for the vaccines in the bundle. Note that single bids can also be considered as bundles with only one vaccine.

Unlike the current system in which suppliers bid on single vaccines, the bid award allocation problem for bundle bidding cannot be solved easily. This problem is not decomposable into subproblems since the prices of vaccines depend on the bundles selected and hence on the other vaccines' allocations. The allocation problem with vaccine bundles discussed here can be considered under the subject of combinatorial auctions. This is a specific class of problems in operations research wherein an organization (in this case, PAHO) requests bids from multiple suppliers for combinations of different products (here, vaccines). In PAHO's case, what operations researchers call the "combinatorial auction" is commonly referred to as the"bidding and allocation process," and we adopt the PAHO terminology throughout the remainder of this paper. Optimal solutions to problems of this type that are of realistic size cannot be found by any simple procedure. A mathematical model based on integer programming can be used to solve the bid award allocation problem with bundles. The model we developed is presented in Appendix D.2.

While the new bidding process proposed here allows increased flexibility over the current PAHO system, it does not capture all of the aspects of the allocation process. PAHO also wants to include the effects of the cost of transportation and supplier diversification in the allocation process. Transportation cost, as we have seen in the preceding discussion, is an important component of the overall vaccine supply chain cost. Moreover, it is important to PAHO to promote supplier diversity whenever possible to ensure availability of supply for the short and long term. In the following two sections we will discuss how PAHO can incorporate these factors into the mathematical program developed for finding the optimal allocations.

4.3. Bundle Bidding with Transportation Cost Considerations

In this section, we discuss how we can incorporate the cost of transportation into the bid award allocation problem. As described in the section on transportation cost analysis, PAHO adjusts the price per dose submitted by suppliers for vaccines based on the historical shipping data to generate a landed cost estimate. Since the demands of countries are aggregated when determining bid award allocation in the current system, this adjustment is based only on supplier-vaccine pairs. Landed costs can be incorporated into the bundling model in a straightforward manner.

As discussed previously, a better cost estimate can be obtained by considering shipment destinations in addition to origins and contents. To do this, we utilize the country shipping scalars introduced in the Transportation Cost Analysis section in conjunction with the landed costs to estimate per-dose shipping costs for each supplier-vaccine-country combination. In Appendix D.3, we present a mathematical model that considers these shipping cost estimates as well as the per-dose prices submitted by suppliers in bid award allocation. This model can be used to find the optimal bid allocation when shipping costs depend on supplier, vaccine, and country factors.

4.4. Bundle Bidding with Supplier Diversification

PAHO generally wants to work with more than one supplier for a given vaccine, if there exist bids from different suppliers for that vaccine. PAHO believes that requiring supplier diversification increases the reliability of the supply chain. However, supplier diversification may come at an increased cost, since an unfavorable bid may be accepted if there is only one other supplier offering a good price. The mathematical model presented in Appendix D.4 can be used for the bid award allocation problem with supplier diversification under bundle bidding.

4.5. Test Scenarios

Quantitative data on the discounts suppliers may be able to offer as a result of bundling are not available to date. Hence, to test the mathematical models and to explore the effects of bundling, we designed a computational study based on different hypothetical bid scenarios using the set of vaccines, suppliers, and supplier portfolios from 2006. In this analysis we tried to understand the effects of the following factors:

1. Size and nature (fixed or variable) of discounts,
2. Lower bounds on allocation quantities set by suppliers,
3. Bundle size (number of different vaccines included in a bundle),
4. Number of bundles submitted.

We examined whether bundling changes the bid award allocation, which suppliers benefit from bundling, and what other factors must be considered to keep the bid process fair. To examine these factors and their effects, we constructed four sets of test instances as follows:

Set 1: We generated 18 instances to cover all combinations of the following parameters. We considered 2%, 5%, and 10% fixed discounts (for any vaccine in a bundle). For lower bounds on acceptable quantities for vaccines in the bundle, we considered 25%, 50% and 75% of the maximum quantity submitted by each supplier. We set a limit of two or three vaccines per bundle. This means for each scenario with bundle size two (three) we generated *all* possible sets with two (two and three) elements for all suppliers.

Set 2: We generated 18 instances to cover all combinations of the following parameters. We kept the discount sizes and lower bounds same as in Set 1. However, instead of imposing a limit on the bundle size we limited the number of bundles allowed per supplier to be 10 or 50. For suppliers whose portfolio makes it possible for them to create more than the limiting number of bundles, we generated their bundles randomly from among all those they are capable of providing.

Set 3: We generated 6 instances to cover all combinations of the following parameters. We considered a variable discount which depends on the bundle size (number of vaccines in the bundle).

We use 5% as our base discount and any bundle with more than two vaccines had an additional 1% discount for each vaccine after the first two. That is, the discount parameter we used for this set is equal to (5+bundlesize-2)%. We kept the same lower bounds as before. We did not put a limit on the bundle size but limited the number of bundles allowed per supplier to be 10 or 50 as in Set 2.

Set 4: We generated 11 instances to examine the effects of limiting the number of bundles per supplier. We set the lower bound as 25% of the quantity submitted, and used a variable discounting scheme as described for Set 3. We did not put a limit on the bundle size but limited the number of bundles allowed per supplier to 3, 5, 8, 10, 12, 15, 20, 25, 30, 50, or 100.

In addition, we explored the effects of transportation cost under the current and proposed bidding processes. In these experiments, we assumed that the acceptable lower bound on quantity awarded for single vaccine bids is 25% of the quantity submitted by a supplier.

4.5.1. Test Results with No Transportation Costs and No Supplier Diversification. Tables 5 to 8 summarize the results for the instances described above solved by the bundle bidding model that does not consider transportation cost or supplier diversification. Optimal solutions are found for all instances. The time required to solve an instance ranges between 5 seconds to 15 minutes depending on the total number of bundles, and hence total number of binary variables. The description of the columns' contents are as follows:

A: Maximum bundle size allowed
B: Limit on number of bundles per supplier
C: Lower bound on the acceptable quantity as a percentage of quantity offered
D: Average discount
E: Total number of bundles
F: Total savings realized by PAHO if the proposed model is used
G: Percent of suppliers awarded at least one vaccine
H: Percent of vaccines supplied by more than one supplier (among the ones for which multiple suppliers placed bids)

Table 5 **Results for Set 1 instances**

Instance	A	B	C	D	E	F	G	H
1	2	-	25%	2.00%	319	1.80%	56.25%	28.57%
2	2	-	25%	5.00%	319	4.49%	56.25%	28.57%
3	2	-	25%	10.00%	319	8.99%	43.75%	19.05%
4	2	-	50%	2.00%	319	1.79%	56.25%	23.81%
5	2	-	50%	5.00%	319	4.48%	56.25%	28.57%
6	2	-	50%	10.00%	319	8.98%	43.75%	19.05%
7	2	-	75%	2.00%	319	1.53%	56.25%	23.81%
8	2	-	75%	5.00%	319	4.17%	62.50%	28.57%
9	2	-	75%	10.00%	319	8.62%	50.00%	19.05%
10	3	-	25%	2.00%	1663	1.80%	56.25%	23.81%
11	3	-	25%	5.00%	1663	4.49%	56.25%	23.81%
12	3	-	25%	10.00%	1663	8.99%	43.75%	23.81%
13	3	-	50%	2.00%	1663	1.79%	56.25%	23.81%
14	3	-	50%	5.00%	1663	4.48%	56.25%	28.57%
15	3	-	50%	10.00%	1663	8.98%	43.75%	19.05%
16	3	-	75%	2.00%	1663	1.53%	56.25%	23.81%
17	3	-	75%	5.00%	1663	4.18%	56.25%	19.05%
18	3	-	75%	10.00%	1663	8.64%	43.75%	19.05%
Average	**2.5**	-	**50%**	**5.67%**	**991**	**4.98%**	**52.78%**	**23.54%**

The first conclusion that we can derive by looking at the results in Tables 5, 6, 7, and 8 is that the biggest effect on savings with bundle bidding comes from the discounts. Of course, as expected, the larger the discount, the more PAHO can save. However, the size of the discount is not the only

Table 6 Results for Set 2 instances

Instance	A	B	C	D	E	F	G	H
1	-	10	25%	2.00%	80	1.50%	62.50%	33.33%
2	-	10	25%	5.00%	80	3.89%	62.50%	33.33%
3	-	10	25%	10.00%	80	8.27%	50.00%	42.86%
4	-	10	50%	2.00%	80	1.43%	62.50%	33.33%
5	-	10	50%	5.00%	80	3.84%	62.50%	33.33%
6	-	10	50%	10.00%	80	7.97%	56.25%	52.38%
7	-	10	75%	2.00%	80	1.00%	62.50%	38.10%
8	-	10	75%	5.00%	80	3.00%	68.75%	33.33%
9	-	10	75%	10.00%	80	6.51%	62.50%	57.14%
10	-	50	25%	2.00%	242	1.74%	56.25%	38.10%
11	-	50	25%	5.00%	242	4.38%	56.25%	38.10%
12	-	50	25%	10.00%	242	8.82%	43.75%	33.33%
13	-	50	50%	2.00%	242	1.70%	56.25%	33.33%
14	-	50	50%	5.00%	242	4.32%	62.50%	42.86%
15	-	50	50%	10.00%	242	8.70%	50.00%	33.33%
16	-	50	75%	2.00%	242	1.40%	56.25%	38.10%
17	-	50	75%	5.00%	242	4.00%	56.25%	42.86%
18	-	50	75%	10.00%	242	8.40%	50.00%	33.33%
Average	-	**30**	**50%**	**5.67%**	**161**	**4.49%**	**57.64%**	**38.36%**

Table 7 Results for Set 3 instances

Instance	A	B	C	D	E	F	G	H
1	-	10	25%	7.33%	80	12.95%	50.00%	66.67%
2	-	10	50%	7.33%	80	12.43%	50.00%	66.67%
3	-	10	75%	7.33%	80	10.15%	50.00%	66.67%
4	-	50	25%	7.18%	242	14.89%	37.50%	61.90%
5	-	50	50%	7.18%	242	14.21%	37.50%	61.90%
6	-	50	75%	7.18%	242	12.04%	43.75%	52.38%
Average	-	**30**	**50%**	**7.26%**	**161**	**12.78%**	**44.79%**	**62.70%**

Table 8 Results for Set 4 instances

Instance	A	B	C	D	E	F	G	H
1	-	3	25%	7.72%	33	12.55%	50.00%	66.67%
2	-	5	25%	7.31%	50	12.35%	43.75%	66.67%
3	-	8	25%	7.75%	68	14.82%	37.50%	57.14%
4	-	10	25%	7.33%	80	12.95%	50.00%	66.67%
5	-	12	25%	7.60%	90	14.63%	37.50%	61.90%
6	-	15	25%	7.60%	102	14.42%	37.50%	57.14%
7	-	20	25%	7.35%	122	14.82%	37.50%	57.14%
8	-	25	25%	7.29%	142	14.42%	37.50%	57.14%
9	-	30	25%	7.42%	162	14.89%	37.50%	61.90%
10	-	50	25%	7.18%	242	14.89%	37.50%	61.90%
11	-	100	25%	7.18%	400	14.89%	37.50%	61.90%
Average	-	**25**	**25%**	**7.43%**	**135.55**	**14.15%**	**40.34%**	**61.47%**

factor. As can be seen in Tables 5 and 6, PAHO may expect to save more when the set of bundles offered by suppliers covers a larger portion of the vaccine set demanded. For the instances in Set 1, we considered all possible vaccine combinations given a maximum bundle size (two or three). On the other hand, for the instances in Set 2, we limited the number of bundles that a supplier can offer. Even though we did not put a limit on the bundle size, since we used a fixed discounting parameter, we observed smaller savings. This is because not all vaccines are included in the bundles created and hence savings could not be observed for all vaccines considered.

Furthermore, we observe that for Sets 1 and 2, percentage of total savings is less than the average discount but for Sets 3 and 4 this percentage is much higher than the average discount. We conclude that in the later sets discounts depend on the bundle size and hence big suppliers offering very big discounts are preferred. That is, our model tries to select large bundles with larger discounts than average. So, the resulting savings is larger than the average discount realized.

Another parameter that affects savings realized is the lower bounds set by suppliers on vaccine quantities in bundles. We see that we expect to see less savings if we move from 25% to 75% when every other parameter is set constant. The effect is even larger for instances in Set 3 where only 10 bundles per supplier are allowed.

Instances in Sets 3 and 4 tell us that the allocations change when discounts depend on the number of vaccines in each bundle. It is a valid expectation that suppliers with large product portfolios are more likely to offer large bundles. Combining this with the assumption of large discounts coming with large bundles, we conjecture that bigger suppliers can offer greater discounts. As a result, if PAHO allows large bundles, these suppliers may increase their chances of being awarded a large allocation. This raises a fairness and reliability issue. For example, for the instances in Set 1, in the optimal solution, 53% of the suppliers were awarded at least one vaccine but only 24% of the vaccines were supplied from more than one supplier. On the other hand, if we consider Set 4, where there is no limit on bundle size and discount depends on the number of vaccines in a bundle, we see that only 40% of the suppliers are awarded something but approximately 62% of the vaccines were assigned to multiple suppliers. Furthermore, 61% of the vaccines offered by the largest supplier (having a portfolio with 19 vaccines) are awarded in the instances in Set 1 whereas this supplier is awarded all vaccines it is offered in Set 4.

Table 9 Effect of transportation costs on the current process without bundles

	NT		CT		PT	
Supplier	**Vaccine**	**Quantity**	**Vaccine**	**Quantity**	**Vaccine**	**Quantity**
1	2	1.61%	2	1.61%	2	1.61%
2	1	9.60%	1	9.60%	1	9.60%
3	1	0.51%	1	0.51%	1	0.51%
4	1	0.08%	1	0.08%	1	0.08%
5	5	25.86%	6	28.43%	6	28.43%
6	0	0.00%	0	0.00%	1	0.02%
7	0	0.00%	0	0.00%	0	0.00%
8	0	0.00%	0	0.00%	0	0.00%
9	2	0.04%	3	4.50%	3	4.50%
10	0	0.00%	0	0.00%	0	0.00%
11	2	4.37%	3	4.44%	3	4.42%
12	0	0.00%	0	0.00%	0	0.00%
13	11	16.50%	11	16.50%	11	16.50%
14	11	41.41%	8	34.31%	8	34.31%
15	0	0.00%	0	0.00%	0	0.00%
16	1	0.02%	1	0.02%	1	0.02%
Transp. Cost	$ 7.834 mil.		$ 6.011 mil.		$ 6.626 mil.	
Vacc. Cost	$ 152.849 mil.		$ 153.583 mil.		$ 153.586 mil.	
Total Cost	$ 160.683 mil.		$ 159.594 mil.		$ 160.212 mil.	

4.5.2. Test Results with Transportation Costs. We explored the effect of the transportation cost estimate on two scenarios. The first one is the scenario where no bundles are allowed and the second one is Instance 11 of Set 1 described above. Optimal solutions are found for these scenarios using the integer program proposed to handle transportation costs. For the no bundle scenario, an optimal solution is found within seconds. It took around 10 minutes to find the optimal solution for the bundling scenario. The results are summarized in Tables 9 and 10, respectively. Three cases are presented: no transportation costs are considered (NT), transportation costs are estimated with the current methodology (CT), and transportation costs are estimated with our proposed method (PT). In the NT case, we minimize the vaccine cost only. The transportation cost estimate is then calculated *a posteriori* for the resulting allocation using the proposed method with country shipping scalars. The PT results are generated using the per dose shipping cost determined by the MAD country shipping scalars. The Vaccine columns present the number of different

Table 10 **Effect of transportation cost: Instance 11 of Set 1**

	NT		CT		PT	
Supplier	**Vaccine**	**Quantity**	**Vaccine**	**Quantity**	**Vaccine**	**Quantity**
1	2	1.61%	2	1.61%	2	1.61%
2	1	9.60%	1	9.60%	1	9.60%
3	2	0.88%	2	2.42%	2	2.42%
4	1	0.08%	1	0.08%	1	0.08%
5	5	25.86%	6	28.43%	6	28.43%
6	0	0.00%	0	0.00%	2	0.63%
7	0	0.00%	0	0.00%	0	0.00%
8	0	0.00%	0	0.00%	0	0.00%
9	2	0.04%	3	4.50%	3	4.50%
10	0	0.00%	0	0.00%	0	0.00%
11	2	4.37%	3	4.44%	3	3.82%
12	0	0.00%	0	0.00%	0	0.00%
13	12	16.14%	12	14.61%	12	14.61%
14	11	41.41%	8	34.31%	8	34.31%
15	0	0.00%	0	0.00%	0	0.00%
16	0	0.00%	0	0.00%	0	0.00%
Transp. Cost	$ 7.931 mil.		$ 5.997 mil.		$ 6.571 mil.	
Vacc. Cost	$ 145.983 mil.		$ 146.724 mil.		$ 146.759 mil.	
Total Cost	$ 153.914 mil.		$ 152.721 mil.		$ 153.330 mil.	

vaccines awarded and the Quantity columns present the percent of the total quantity allocated to each supplier. We see that, even though transportation cost is small with respect to the cost of the vaccine, it has an effect on bid allocation when considered. That is, the number of vaccines awarded to some suppliers changes. More importantly, we see that the allocations also change when the transportation cost estimation method changes. This indicates not only the importance of including transportation cost estimates in bid award allocation decisions, but also of using an estimate that captures as much information (supplier, vaccine, and country) as possible. We also see that if we do not consider transportation costs (NT case), the resulting allocation may yield a smaller vaccine cost than the case where transportation costs are added (PT case) in the objective function. However, the total cost observed is higher since the resulting allocation in NT case generates a higher transportation cost. We note that although the CT column shows a lower transportation cost than that in the NT column, this is misleading because (as demonstrated earlier) the current method of estimating transportation cost is not as accurate as the proposed country scalar method.

4.5.3. Test Results with Supplier Diversification. In order to see the effect of supplier diversification, we have also tested the model discussed in the Bundle Bidding with Supplier Diversification section for some of the scenarios described above. Note that the model with supplier diversification has more binary variables than the previous two models. Hence, solving scenarios having large number of bundles optimally may be hard because of the computational time and memory requirements. However, in practice we expect that suppliers will offer fewer bundles than in our large test scenarios. Thus, the supplier diversification model can be a useful tool to analyze the effect of supplier diversification on cost.

In our experiment we set $K_j = 2$ for vaccines where more than one supplier exists and $K_j = 1$ for the rest in all scenarios tested. Namely, we want to choose more than one supplier for a vaccine if there exist multiple suppliers placing bid for that vaccine. Table 11 presents the results. We have run our model for the no bundle case, the first three scenarios in Sets 1 and 2, and the first eight scenarios on Set 4. Run times to find the optimal solution vary between 10 seconds to 30 minutes for these instances. Column ND gives the cost of optimal allocation for the case where supplier diversification is not required. Column WD presents the case where more than one supplier is required for those vaccines having offers from multiple suppliers. As expected, the cost of optimal allocation is higher with supplier diversification; however, the increase in cost is generally less than 0.2 percent. The highest difference is observed for the case where no bundles are allowed with 0.62

percent. In other words, the cost of imposing supplier diversity is lower when bundles are allowed in the bidding process. This means that bundling itself contributes to supplier diversification without it being explicitly required. The average increase in cost for the bundling scenarios tested is only 0.14 percent. On the other hand, the cost increase is larger for Set 4 instances where discounts within the bundle increase with bundle size. This is because large bundles can be offered by large suppliers, and without explicit supplier diversification only these suppliers will be awarded. To diversify in such cases, we should select bundles offered by other suppliers having smaller product portfolios and hence offering smaller bundles with smaller discounts.

Table 11 **Effect of supplier diversification (x 1,000,000)**

Scenario	ND	WD	Difference
No Bundle	$152.849	$153.796	0.62%
1-1	$150.100	$150.112	0.01%
1-2	$145.983	$146.009	0.02%
1-3	$139.111	$139.168	0.04%
2-1	$150.563	$151.128	0.38%
2-2	$146.897	$146.933	0.02%
2-3	$140.204	$140.255	0.04%
4-1	$133.661	$133.893	0.17%
4-2	$133.967	$134.199	0.17%
4-3	$130.196	$130.444	0.19%
4-4	$133.058	$133.298	0.18%
4-5	$130.486	$130.734	0.19%
4-6	$130.811	$131.068	0.20%
4-7	$130.196	$130.444	0.19%
4-8	$130.809	$131.049	0.18%

5. Recommendations and Future Work

The work done by the PAHO-Georgia Tech collaboration has already provided valuable insight into supply chain improvements for PAHO's vaccine procurement process. Here we present recommendations for PAHO and outline important opportunities for future work.

Forecasting is a critical component to PAHO's supply chain performance. The process relies heavily on the forecasts at the country level. To this end, we recommend that PAHO work towards improving individual country forecasts through:

- Better understanding of how national vaccination campaigns affect vaccine demand,
- Development of causal models for vaccines, in particular those that are most poorly forecast right now,
- Improved visibility of current inventory, including investigation of vendor-managed inventory
- PAHO-sponsored training in best-practice forecasting techniques at the country level,
- PAHO employment of a forecaster in each country (in particular in the largest countries),
- Possibly imposing penalties on countries that stand as outliers in a given period (for example, outside a 25% range from the average),
- Quantifying the cost of forecast inaccuracies to target other improvement initiatives.

These remedies are aimed at bringing consistency to the forecasting techniques at the country level, in addition to bringing a higher level of transparency to the process. PAHO is currently working on improving aggregate forecasting through rolling forecasts and causal forecasting, which is a step in the right direction. However, we believe that pursuing the actions recommended above will also help to remedy some of the forecasting issues.

Analysis of historical shipping data and the computational analysis with hypothetical bundling scenarios demonstrate the importance not only of including transportation costs in bid award allocation, but also of choosing a shipping cost estimate that reflects the influence of supplier, vaccine, and country. Based on our analysis, we recommend the following actions.

- In the short term, incorporate country scaling factors into the bid award allocation to more accurately capture true transportation costs and choose suppliers with these costs in mind.
- In the long term, move toward a bid award allocation procedure that chooses not only suppliers but also vaccines and their presentations based on total supply chain cost.

With these steps, PAHO will continue to improve operations throughout the vaccine supply chain.

In the light of the computational experiments, the team generated the following conclusions regarding the affect of bundle bidding.

- A mathematical model is needed to better capture the discounts made by suppliers with bundles.
- Savings realized increase as discounts increase.
- Savings are expected to increase as the percentage of vaccines included in a bundle increases.
- Low quantity limits set by suppliers yield higher savings.
- We expect that bundle bidding will be more advantageous for suppliers with large product portfolios than for those with small portfolios.
- Large bundles may yield large savings but this raises a fairness issue since only large suppliers can offer such bundles. It also affects the reliability of the supply chain. Limits on bundle sizes or explicit supplier diversification may solve the fairness or reliability problems.
- The cost of explicit supplier diversification is higher when no bundles are allowed. Namely, bundling contributes to supplier diversification.
- Supplier diversification is more expensive when large bundles with large discounts exist.
- The cost of explicit supplier diversification decreases as the total number of bundles and the number of suppliers offering bundles increase.
- Considering transportation costs in supplier selection changes the optimal bid allocation. Hence, an accurate transportation cost estimation is important.

This study has led to increased application of quantitative tools in PAHO's effort to provide service to its member countries. It demonstrated the importance of accurate forecasting and transportation cost estimation in PAHO's vaccine procurement process and provided methods that will contribute to PAHO's continuous improvement in these areas. In addition, we have generated important insights about the implications of bundle bidding. Future work includes incorporating quantitative measures of supplier reliability and total vaccination cost into a comprehensive vaccine procurement model for the region. These and other important opportunities for additional supply chain improvements at PAHO remain, but this work demonstrates the significant impact that operations research methodologies can have on challenges in public health.

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Appendix A: PAHO's Current Procurement Process

Here is the timeline for PAHO's procurement process:

- June: Countries report quarterly demand forecasts for the coming year for each vaccine in their schedule.
- August: PAHO requests and receives bids from suppliers based on the aggregated demand forecast; a bid includes the maximum quantity that can be supplied and a price per dose.
- October: PAHO makes agreements with suppliers; an annual agreement includes the anticipated quantity PAHO will order from a supplier and the price per dose (from the bid).
- Quarterly throughout the year:
  - —PAHO obtains updated requirements from countries.
  - —PAHO places firm orders with suppliers for specific vaccine, quantity, and destination.
  - —Suppliers ship to country and bill to PAHO.
  - —PAHO invoices country for cost of vaccine, transportation, and 3% service charge.

The forecasts are based on the estimates from different countries for their vaccine requirements, which partly follow from the national immunization schedules for those countries. For certain vaccines (for example, influenza), demand is seasonal. Identical vaccines come in multiple presentations, for example in single or multi-dose packaging or in liquid form or dried form requiring reconstitution. The appropriate presentation is impacted by demand forecasts. The advantage of the five-dose presentation is that it usually results in less wastage, whereas the shipping cost for the 10-dose presentation might be lower. Hence, depending on the total demand volume, one of these presentations, or a combination, might be desirable. PAHO considers different presentations separately in the forecasting and bidding process. The suppliers submit bids separately for each vaccine. While some suppliers may have enough capacity to satisfy the entire demand for a particular vaccine, others may not. In this case they submit a bid only for part of the demanded quantity.

Appendix B: Forecasting Analysis

Forecast Error Measures: Mean Absolute Percentage Error (MAPE) and Percent Mean Absolute Deviation (PMAD) are two measures of accuracy for a fitted time series value in statistics. More specifically,

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right| \qquad \text{and} \qquad PMAD = \frac{\frac{1}{n}\sum_{t=1}^{n}|A_t - F_t|}{\frac{1}{n}\sum_{t=1}^{n}A_t},$$

over n periods where t is the period, A_t is the observed value, and F_t is the forecasted quantity in period t.
Hypothesis Testing: We have used two sided hypothesis tests (with $\alpha = .05$) to identify if there exists a linear association between (i) PMAD and the average quantity ordered for a given vaccine and (ii) PMAD and the average number of countries ordering a vaccine. The tests returned 0.092 and 0.0473 as their p-values, respectively. Consequently, with a 95% confidence level we failed to reject the hypothesis that there are no linear relationships between our predictor and response variables.

Table 12 Forecasting Statistics and Demand Data for 14 Vaccines

Vaccine	MAPE	PMAD	10% BDD	Avg. Qty. Ordered	Avg. # of Countries
BCG 10	0.0914	0.0936	3	12,982,177	25.25
MMR 10	0.1176	0.1004	3	13,562,966	14.5
DT (Adult 10)	0.2417	0.2291	2	26,011,551	30.25
DPT/HEP B/HIB 1	0.2760	0.2617	1	8,611,956	25.75
MR 10	0.2823	0.2511	0	34,405,569	10
DT (Pediatric 10)	0.3220	0.2603	1	503,598	19.25
HEP B 1	0.3332	0.6591	1	666,134	16
DPT 10	0.3925	0.4320	1	11,511,774	29.5
MMR 1	0.4676	0.3732	1	6,135,984	27.75
YF 5	0.4719	0.2915	0	10,760,650	14.5
MR 1	0.5489	0.3770	1	2,223,530	2.5
HIB 1	0.6210	0.5718	1	997,976	9.25
HEP B 10	0.7846	1.1805	2	7,798,988	15.25
TT 10	10.7141	4.1048	1	367,487	4

10% BDD = The number of times, within a 5 year period, that the acutal vaccine order fell within a 10% range of the forecast.
Avg. Qty. Ordered = The average number of units ordered, among all countries, of this vaccine over a 5 year period.
Avg. # of Countries = The average number of countries, per year, that ordered this vaccine over a 5 year period.

Appendix C: Transportation Cost Analysis

Table 13 lists the individual country shipping scalars calculated for 2006 using the four methods: *Min MAD*, *Min MAPE*, *Regression*, and *Regression No Outliers*. Similar tables have been calculated for the years 2003-2005 as well.

Table 13 **2006 Country Shipping Scalars**

Country	Min MAD	Min MAPE	Regression	Reg. No Outliers
1 Anguilla	10.8351	10.8350	27.1003	27.1003
2 Antigua	1.3159	2.1417	4.0059	4.0059
3 Argentina	0.9521	0.9513	1.0051	1.0051
4 Bahamas	1.3228	1.3241	1.8630	1.8630
5 Barbados	1.4771	1.4772	2.5910	2.5910
6 Belize	2.1845	0.4465	2.8705	2.8828
7 Bermuda	2.9815	2.9812	3.8605	3.8605
8 Bolivia	1.5580	1.2554	1.8662	1.8662
9 Brazil	1.3553	0.8905	1.2699	1.2699
10 Brit. Vir. Is.	5.8713	5.8990	12.7660	12.7660
11 Cayman	2.2653	2.2628	3.5845	3.5845
12 Colombia	0.9275	0.9263	0.9808	0.9808
13 Costa Rica	1.2461	1.1126	6.6911	1.2804
14 Cuba	1.5455	0.7220	1.2103	1.2102
15 Dominica	2.2889	0.3899	2.7903	2.7938
16 Dom. Rep.	0.9985	0.9717	3.0981	3.0981
17 Ecuador	0.9070	0.9535	0.8670	0.8670
18 El Salvador	1.2654	1.1813	1.2860	1.2860
19 Grenada	1.8214	0.1554	2.8754	2.9094
20 GUT-IGSS	1.1958	1.1190	1.2865	1.2865
21 GUT-MOH	1.1262	1.0445	1.2108	1.2108
22 Guyana	1.7982	1.8005	2.6039	2.6039
23 Honduras	1.2741	1.1058	1.4357	1.4357
24 Jamaica	1.0566	0.9727	1.1870	1.1870
25 Montserrat	10.1996	11.4324	16.0816	16.0816
26 Net. Antilles	2.9536	2.9593	7.7973	7.7973
27 Nicaragua	1.2689	1.1597	2.2549	2.2549
28 Panama	1.0350	1.0347	1.2332	1.2332
29 Paraguay	1.4254	1.3598	1.4099	1.4099
30 Peru	1.0529	1.0188	1.1410	1.1410
31 St. Kitts	4.7933	3.2897	10.9786	10.9786
32 St. Lucia	2.7261	2.1443	5.0465	5.0465
33 St. Vincent	14.1886	0.5648	144.3323	60.4851
34 Suriname	2.2887	2.2860	2.4609	2.4609
35 Trinidad	1.4485	1.1727	2.0300	2.0300
36 Turks and Caicos	2.7326	2.7271	2.7208	2.7208
37 Uruguay	1.5211	1.3252	2.4387	2.4387
38 Venezuela	0.9890	0.9660	1.0007	1.0007

Scalar values equal to 1.0000 indicate that no shipments were made to the given country in that year.

Appendix D: Bid Award Allocation Models

The integer programming models for solving the bid award allocation problem are detailed below.

D.1. Bid Allocation Models for the Current Bidding Process

Notation:

N : set of vaccines and $n = |N|$
M : set of suppliers and $m = |M|$
D_i : total demand for vaccine i
S_{ij} : amount of vaccine i offered by supplier j
c_{ij} : price per dose of product i if supplied by j
l_{ij} : the lowest amount of vaccine i that supplier j accepts to supply
x_{ij} : amount of vaccine i supplied by supplier j
y_{ij} : $\begin{cases} 1 & \text{if supplier } j \text{ supplies vaccine } i \\ 0 & \text{otherwise} \end{cases}$

$$\text{Minimize} \quad \sum_{i=1}^{n}\sum_{j=1}^{m} c_{ij}x_{ij} \tag{1}$$

$$\sum_{j=1}^{m} x_{ij} \geq D_i \qquad \forall i \in N \tag{2}$$

$$x_{ij} \leq S_{ij} \qquad \forall i \in N \quad \forall j \in M \tag{3}$$

$$x_{ij} \geq l_{ij}y_{ij} \qquad \forall i \in N \quad \forall j \in M \tag{4}$$

$$y_{ij} \in \{0,1\} \qquad \forall i \in N \quad \forall j \in M \tag{5}$$

In the above formulation there does not exist constraints that connect variables for different vaccines. Hence the overall problem can be decomposed into n subproblems , which can than be solved separately and efficiently for each vaccine i.

D.2. Bid Allocation Model for Bundle Bidding

The following model can be used to determine allocations in the case of bundles. We consider single bids as bundles with only one vaccine.

Notation:

N : set of different vaccine configurations needed and $n = |N|$
M : set of suppliers and $m = |M|$
K_i : set of bundles for supplier j and $k_j = |K_j|$
D_i : total aggregate demand for vaccine i
S_{ij} : maximum amount of vaccine i that can be supplied by supplier j
c_{ij}^k : cost of vaccine i if supplied by j within bundle k
l_{ij}^k : minimum amount of vaccine i that can be supplied by supplier j within bundle k
x_{ij}^k : amount of vaccine i awarded to supplier j within bundle k
y_j^k : $\begin{cases} 1 & \text{if bundle } k \text{ of supplier } j \text{ is selected} \\ 0 & \text{otherwise} \end{cases}$

$$\text{Minimize} \quad \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{k_j} c_{ij}^k x_{ij}^k \tag{6}$$

subject to

$$\sum_{j=1}^{m}\sum_{k=1}^{k_j} x_{ij}^k \geq D_i \qquad \forall i \in N \tag{7}$$

$$\sum_{k=1}^{k_j} x_{ij}^k \leq S_{ij} \qquad \forall j \in M \; i \in N \tag{8}$$

$$l_{ij}^k y_j^k \leq x_{ij}^k \qquad \forall j \in M \; i \in N \; k \in K_j \tag{9}$$

$$x_{ij}^k \leq S_{ij} y_j^k \qquad \forall j \in M \; i \in N \; k \in K_j \tag{10}$$

$$y_j^k \in \{0,1\} \qquad \forall j \in M \; k \in K_j \tag{11}$$

D.3. Bundle Bidding Model with Transportation Cost Considerations

Additional Notation:

H : set of countries and $h = |H|$
R_i^l : requirement of vaccine i for country l
t_{ij}^l : cost of shipping a dose of vaccine i from supplier j to country l
z_{ij}^l : amount of vaccine i shipped to country l by supplier j

$$\text{Minimize} \quad \sum_{j=1}^{m}\sum_{i=1}^{n}\sum_{k=1}^{k_j} c_{ij}^k x_{ij}^k + \sum_{j=1}^{m}\sum_{i=1}^{n}\sum_{l=1}^{h} t_{ij}^l z_{ij}^l \tag{12}$$

subject to

Constraints (8), (9), (10), (11) and

$$\sum_{l=1}^{h} z_{ij}^l \leq \sum_{k=1}^{j} x_{ij}^k \qquad \forall j \in M \; i \in N \tag{13}$$

$$\sum_{j=1}^{m} z_{ij}^l \geq R_i^l \qquad \forall i \in N \; l \in H \tag{14}$$

$$z_{ij}^l \geq 0 \qquad \forall j \in M \; i \in N \; l \in H \tag{15}$$

D.4. Bundle Bidding Model with Supplier Diversification Considerations

Additional Notation:

K_i : number of suppliers desired for vaccine i

$$w_{ij} : \begin{cases} 1 & \text{if vaccine } i \text{ is supplied by supplier } j \\ 0 & \text{otherwise} \end{cases}$$

$$\text{Minimize} \quad \sum_{j=1}^{m}\sum_{i=1}^{n}\sum_{k=1}^{k_j} c_{ij}^k x_{ij}^k \tag{16}$$

subject to

Constraints (7), (9), (10), (11) and

$$\sum_{k=1}^{k_j} x_{ij}^k \leq S_{ij} w_{ij} \qquad \forall j \in M \; i \in N \tag{17}$$

$$w_{ij} \leq \sum_{k=1}^{k_j} x_{ij}^k \qquad \forall j \in M \; i \in N \tag{18}$$

$$\sum_{j=1}^{m} w_{ij} \geq K_i \qquad \forall i \in N \tag{19}$$

$$w_{ij} \in \{0,1\} \qquad \forall j \in M \; i \in N \tag{20}$$

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