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Budget consideration in the Antigen Bundling Problem (ABP)

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Abstract
Globalizing the vaccine affordability problem can allow to have robustness in case there are budget drops. Previous research has dealt with the Antigen Bundling Problem (ABP) which is a mathematical formulation which tries to optimize benefits for both customers and manufacturers in terms of vaccine distribution. This problem assumes a coordinated market with pooled procurement which reduces the prices of vaccines and increases affordability. This works expands previous research by incorporating uncertainty in the budgets of markets. This uncertainty is represented by a drop in the reservation price. Experimental results suggest that as market segmentation increase, the dropping reservation prices have less of an impact on the system. However, this may not translate the same way for the manufacturers. This study examines the results of having budget reductions and the advantages and disadvantages of market segmentation in terms of the model.

1. Introduction

One of the most effective ways of preventing the spread of infectious disease and reducing mortality while promoting national economic growth and reducing poverty, is the use of vaccines [1, 2] which prepare the immune system for future attacks of microbes. According to the World Health Organization (WHO) immunization coverage by vaccines has improved in the last few years and five factors have been identified to achieve results that will increase this coverage. One of the factors to promote more coverage of vaccines is access to all vaccines in all places at all time [3]. According to Plahte, currently the limiting factors of vaccination access are related to the difference in income countries have and the manufacturers. Vaccines that are very expensive are not affordable to by low and middle income countries. This results in limited demand for these vaccines that incur a very high research and development cost for manufacturers. This in fact results in higher prices [4]. The costs of these vaccines might be so high that no country wants to buy them, making them unsustainable to produce for the manufacturer [5]. So, a problem that starts small locally unaffordable, becomes global issue since the vaccine is not produced for anyone.

A way to counteract these problems is using combination vaccines which offer multiple antigens in a single shot, providing an opportunity to increase accessibility and simplify logistic problems. To increase efficiency in accessibility even more, the procurement mechanism must offer better prices. To do this vaccine manufacturers offer tiered pricing and buyers must rely on pool procurement to improve the negotiating leverage [6].

This project consists on an \ABP model first proposed by Proaño et al. [7] and then expanded by Mosquera [6]. It consisted on a hypothetical vaccine market where a monopsonistic entity provides decisions about procurement that improves the implementation of a coordinated procurement system, in which both pooled procurement and tiered-pricing are implemented. In Mosquera they analyzed how the increase of reservation price would change the solutions [6]. This project has the objective to understand the effect of budget reduction in different markets that will impact negatively the reservation price.

2. Literature Review

In terms of vaccine pricing the literature can be divided in different parts including affordability, the way to price, the type of market and assumptions taken. This work is an expansion of the model presented in Mosquera's thesis and Proaño's et al work which provide a wide literature review in terms of vaccine affordability and tiered pricing in coordinated markets [6, 7]. This work will present a summary of those reviews and then focus on one of the assumptions both authors do to run their model.

Vaccine pricing models focus on having either only monovalent vaccines (vaccines with only one antigen) [8-12], combinatorial vaccines (vaccines with more than one antigen) [13, 14], or a combination of both [7]. These models run on a set of assumptions including how the market is regulated. The literature proposes that having a monopsonoistic entity to regulate the market can help with assumptions that will both simplify the mathematical model and have better results for all parties associated with the vaccine allocation model [15]. To have an even greater effect in terms of effectiveness, Proaño et al explain how bundle pricing from e-commerce can used to increase the affordability of the vaccines [7]. However, as Mosquera mentions, the model built in Proaño et al assumes that the reservation prices of markets are deterministic. In the new model, Mosquera explores what would happen if reservation prices had an uncertainty. To explore this area he calculated a reservation price based on the different countries Gross National Income (GNI) that composed a specific market and added a degree of uncertainty [6]. An assumption that is made in both Mosquera and Proaño et al model is that the countries in all the markets will accept the schedule given by the entity. This means that the countries in each of those markets have enough budget to accept the price given, which might not always be the case.

The literature has suggestions regarding how to calculate budget and reservation prices, but very few studies unite these two topics together. Current focus is on the reservation price of the customer the literature presented in this paragraph is related to the Willingness to Pay (WTP). According to Löffler there are two methods of obtaining the WTP of the customer. The first method consists on directly asking the customer what is his WTP for a specific product, while the second method consist on indirectly calculating WTP depending on either customer or product information. Löffler concludes that albeit direct prices being somewhat easier to obtain, the customer can often lie about these values and thus are more unreliable and provide a worse solution than indirect methods [16]. Miller et al. compares various indirect and direct methods of calculating WTP and concludes that all methods including hypothetical ones such as Choice-Based Conjoint analysis (CBC) provide a good approximation of benchmark calculations of WTP. However, he agrees that methods with incentive such as the Incentive CBC (ICBC) produces much better estimation of WTP [17]. The ICBC can be compared to the bundle strategy used in our model. Most of these indirect methods do not include the budget or wealth of the customer or country. However, in different utilization functions in the literature there is a relationship between budget and WTP [18-20]. In Grassi's research, it is explained how is unfair to linearly relate budget (ability to pay) with the customer's WTP since it will mean that a person who is poor will be less willing to pay for any service or product than a person who is rich. Even though she agrees that WTP should be calculated independently from ability to pay, Grassi concludes that in the no-borrowing scenario a person that does not has the ability to pay for a product will not buy the product making the WTP effectively 0 [21]. This information is used in this paper to assume that reservation prices will drop randomly for certain markets at certain levels.

3. Motivation

Two approaches were used to address the objective of analyzing vaccine pricing when different countries reduce their budget. Both approaches in this thesis assume that the reservation price of a market will drop. The first approach assumed that only a few bundles of a market will drop in price while the second approach assumed all bundles of a market will drop in price. Both represent realistic scenarios where countries decide to lower their vaccine coverage or drop a specific vaccine form their schedule which will affect the schedule of the entire market. This study wants to understand what are the effects of dropping reservation price and what are the advantages or disadvantages for both consumers and producers of vaccine depending on the type of market systems analyzed. These results can be used to determine political and ethical decisions about vaccine pricing policies and distribution.

4. Glossary

- TSS: Total Social Surplus. Addition of total customer surplus and manufacturers profit
- TCS: Total Customer Surplus. Savings from buyers procuring vaccines at prices lower than their reservation price
- TP: Total Profit. Revenue minus cost to recover annualized R&D at a given Minimum Accepted Rate of Return (MARR)
- Reservation Price: Highest/lowest price the buyer/seller would be willing to pay/sell for a product or service
- Antigen: Toxin or other external substance that induces an immune response in the body
- Bundle: Collection of antigens in one single vaccine
- Monopsony: market structure wherein buyer interacts with many would-be sellers of a product

5. Model

The objective of this model is to maximize TSS which is the addition of TCS and TP. As Proaño suggest, the same result can be obtained by multiplying the reservation prices of the vaccines times the number of bundles of that vaccine and then subtracting the annualized capital recovery of a bundle if that bundle was created. This formulation allows for a much simpler model where prices of vaccines are not initially in the objective. The constraints of this model allow the following:

- Bundle prices must same price or cheaper than single pricing
- All markets meet their antigen demand but do not exceed the maximum amount recommended per dose
- Manufacturers make profit and demand is elastic.
- Linearization constraints and the support of the other models developed by Proaño were the lower and upper bound of prices can be calculated to estimate the best values for both customer surplus and manufacturers prices.

Indices:

$na: number\ of\ antigens$
$nm: number\ of\ market\ segments$
$nb: number\ of\ bundles$
$np: number\ of\ vaccine\ producers$

Main Sets:

$B: sett\ of\ bundles - vaccines$
$A: set\ of\ antigens\ used\ for\ immunizing\ the\ entire\ vaccine\ market$
$M: set\ of\ market\ segments$
$P: set\ of\ vaccine\ produceers$

Secondary Sets:

$A_1(b): set\ of\ antigens\ provided\ by\ bundle\ b \in B$

$A_2(m)$: $set\ of\ antigens\ required\ by\ market\ m \in M\ in\ its\ immunization\ schedule$

$B_1(a)$: $set\ of\ bundles\ that\ supply\ antigen\ a \in A$

$B_2(p)$: $set\ of\ bundles\ supplied\ by\ produce\ p \in P$

Q_b: $set\ of\ group\ of\ vaccines\ made\ by\ producer\ of\ b \in B$

$that\ combined\ offer\ the\ same\ antigen\ prorection\ as\ b$

N_{Q_b}: $set\ of\ bundles\ included\ in\ Q_b$

Parameters:

R_{bm}: $reservation\ price\ of\ bundle\ b \in B\ in\ market\ segment\ m \in M$

λ_m: $Average\ Number\ of\ children\ born\ in\ market\ segment\ m \in M\ in\ a\ year$

C_b: $capital - recovery\ annuity\ required\ for\ covering\ the\ production\ and\ development$

$cost\ of\ bundle\ b \in B$

d_{am}: $number\ of\ doses\ of\ antigen\ a \in A\ requred\ to\ provide\ full\ immunity$

$to\ a\ child\ in\ a\ market\ segment\ m \in M$

D_{bm}: $maximum\ number\ of\ doses\ of\ bundle\ b \in B\ that\ can\ be\ administered\ to\ a\ child\ in$

$market\ m\ in\ M\ to\ avoid\ over - immunization$

S_b: $maximum\ number\ of\ doses\ of\ a\ bundle\ b \in B\ that\ can\ be\ supplied\ by\ its\ manufacturer$

k_b: $producer\ of\ bundle\ b \in B, and\ k_b \subset P$

ϕ: $constant\ used\ in\ elasticity\ constraint\ to\ capture\ concavitu\ and\ convexity\ of\ demand$

$name_b$: $bundle\ name$

gni_m: $expected\ gross\ national\ income\ per\ capita\ for\ market\ segment\ m \in M$

Variables:

X_{bm}: $number\ of\ doses\ of\ bundle\ b \in B\ bought\ by\ market\ m \in M$

Y_{bm}: $price\ per\ dose\ of\ bundle\ b \in B\ in\ market\ m \in M$

$$\gamma_b f(x) = \begin{cases} 1, & bundle\ b \in B\ is\ produced \\ 0, & o.w. \end{cases}$$

Objective function and Constraints

$$Maximize \sum_{b\in B}\sum_{m\in M} R_{bm}X_{bm} - \sum_{b\in B} C_b\gamma_b \tag{1}$$

$$R_{bm} - Y_{bm} \geq \sum_{t\in Nq} (R_{tm}\gamma_t - Y_{tm}), \qquad \forall\ b \in B, m \in M, q \in Q_b: |Q_b| \geq 1 \tag{2}$$

$$\sum_{b \in B1(a)} X_{bm} * D_{bm} \leq d_{am}\lambda_m, \qquad \forall\, a \in A, m \in M \tag{3}$$

$$\sum_{m \in M} X_{bm} \leq S_b \gamma_b, \qquad \forall\, b \in B \tag{4}$$

$$\sum_{m \in M} Y_{bm} X_{bm} \geq C_b \gamma_b, \qquad \forall\, p \in P, b \in B: k_b == p \tag{5}$$

$$X_{bm} \leq D_{bm}\lambda_m \left(1 - \left(\frac{Y_{bm}}{R_{bm}}\right)^{\phi}\right), \qquad \forall\, b \in B, m \in M \tag{6}$$

$$Y_{bm} \geq Y_{bn}, \qquad \forall\, b \in B, m \in M, n \in M: gni_m \geq gni_n \tag{7}$$

$$Y_{bm} \leq R_{bm} * g_b \tag{8}$$

6. Effects of dropping reservation price in different markets

This section provides an analysis of the case where budgetary restrictions are considered by dropping reservation prices. When considering budgets, the literature often uses utility functions. According to these functions the reservation price will be negatively affected by how much the budget is restricted. However, utility functions are subjective, and calculating the utility of a specific vaccine to a market is extremely difficult. A way to avoid subjectivity is explore a wide array of scenarios where an assumption is made that a reduction in budget corresponds to a reduction in reservation prices. To do this a design of experiments was performed where the data related to reservation price was changed in each experiment. The baseline reservation prices for each vaccine were calculated according to the recommendations of Mosquera. The following table presents the factors considered and the levels each factor will take.

Table 1: General Factorial Design for Budget Uncertainty

Factor	**Levels**
Market segments	2, 4, 8, and 12
Drop in reservation price for a vaccine	unif(1%, 20%) and unif(21%, 40%)
Market impacted by drop in reservation price	1 … “Market segments”
Replications: 20	

Since the model is deterministic and variance needs to be considered to run our experiment, the following was done randomly: the reservation price of vaccine bundles was dropped. The randomness refers to the uniform probability distributions shown in Table 1. For example, if the experiment was running in the first scenario then all vaccine bundles will have their reservation price reduced by a random percentage drawn from uniform distribution (1%, 20%). In all cases this drop will happen in only one market, so the reduction in this example would only occur in market 1 of a 2-market system. This first scenario would then be re-run another 19 times for a total of 20 runs per scenario. Before running our experiment, a baseline experiment was run where reservation price was not reduced. This baseline experiment allows us to see the true impact of a reduction in reservation price. The results of the baseline experiment were consistent with the results of Mosquera, which was the targeted results.

The results of our experiment in Figure 1 below show that as the market segments increase, TSS increases for the baseline as well as in the face of reduced reservation price. The key piece of information shown below, is that the gap between the reduced reservation price scenarios v. the baseline scenarios decreases as market segments increase. Furthermore, increasing the reduction of reservation price has a smaller relative impact on total social surplus when the market segments increase.

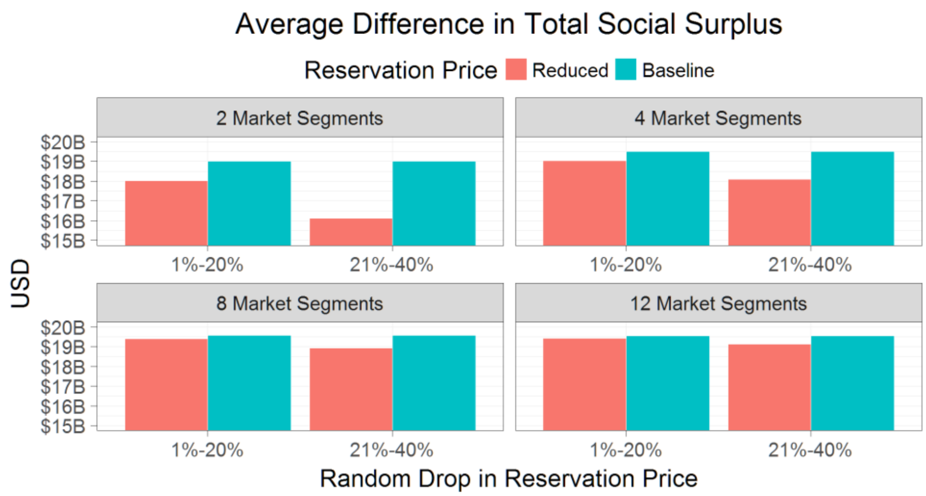

Figure 1: Total Social Surplus v. Reservation Price & Market Segments

We decided to compare TP and TCS in terms of their market values where:

$$Provider\ Market\ Value = \frac{TP}{TP + TCS}$$

$$Consumer\ Market\ Value = 1 - \ Provider\ Market\ Value$$

The results of our experiment in Figure 2Figure 3 below show that as the market segments increase, the provider market value decreases and the consumer market value increases. This means that the benefits in total social surplus shown in Figure 1 are being enjoyed by the consumers as the market segments increase. An interesting piece of information shown below is that increasing the reduction of reservation price has little to no impact on provider and consumer market values, relative to the baseline.

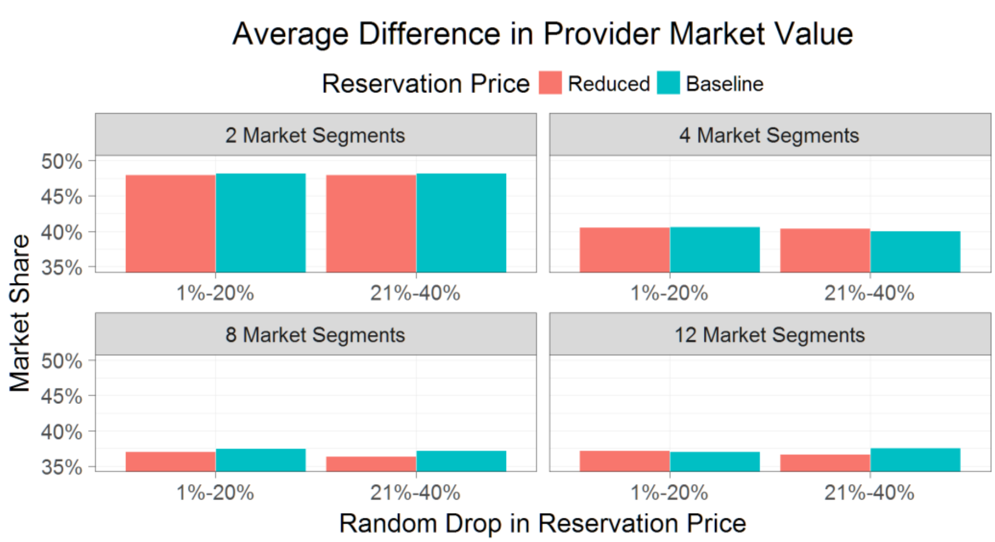

Figure 2: Provider Market Share v. Reservation Price & Market Segments

The results of our experiment in Figure 3 below show the similarity of the solution schedule for each scenario of our experiment compared to its baseline counterpart. The information below tells that the total selling quantity of each vaccine bundle to each market is stable in the face of reduction in reservation price. The lower bound selling price of each vaccine bundle to each market is not stable in the face of reduction in reservation price, where it gets more different as market segments increase. The upper bound selling price of each vaccine bundle to each market is stable in the face of reduction in reservation price.

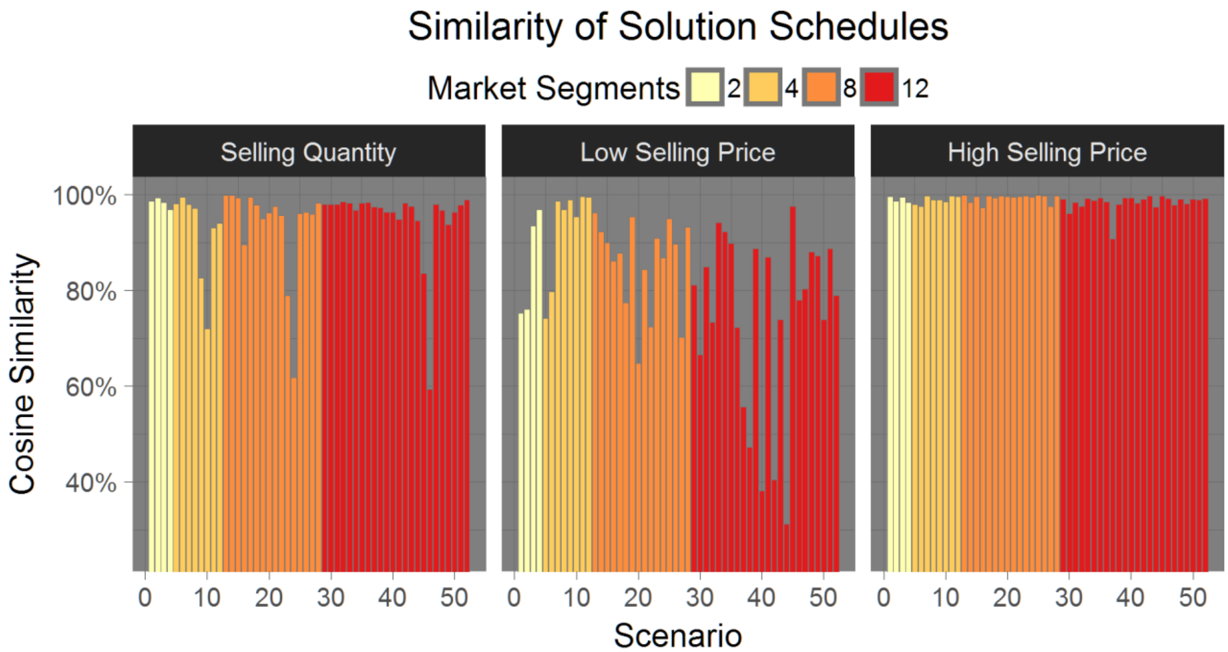

Figure 3: Solution Similarity between our Experiment and Baseline Experiment

7. Conclusions and Future Work

As expected when reservation prices drop, there is a negative impact in TSS, TCS and TP. However, as market segmentation increase, TSS and TCS become less affected by the reservation price drop. TP follows a similar pattern when the baseline is compared to the scenario where the budget was dropped. However, producers do not make as much profits when market segmentation is increased. Even though consumers still make profits and TSS is increased, there is a risk that producers do not participate in a system where there are many markets since the profits are decreased even when their risk is larger.

Future work will concentrate on how to group countries into different markets so that TSS is increased and the negative impact of a budget drop is decreased. Another part of this research wants to explore what happens when budget uncertainty is reflected into the number of children that need to be vaccinated. This would allow the budget uncertainty to be reflected on the country level because the number of children that need to be vaccinated per country is known.

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