Entity Distribution

Bruno Alves Maciel, Ruben A. Proano

December 10, 2019

Abstract

Your abstract.

1 Introduction

International organizations such as Gavi, the Vaccine Alliance [1] and UNICEF negotiate and finance the procurement of vaccine for low-income countries. These organizations recognize vaccines as a cost-effective health care intervention [1] in low income countries, where savings due to their proper use can be 16 times higher than the costs of treating preventable illnesses, even without considering quality of life changes [2]. However, the World Health Organization (WHO) estimates that 9.5 million children worldwide remain without access to vaccines despite their benefits. Under a larger study to analyze how to ensure global vaccine affordability, we hypothesize that vaccine access is partially affected by the lack of coordination in the global vaccine market among buyers, and the asymmetric power relationship between them and large vaccine producers. In the current global vaccine market, countries buy vaccines directly from producers or intermediaries, or buy together via pool procurement mechanisms, such as the Pan American Health Organization (PAHO) Revolving Fund, or through GAVI's financial support [3]. These pool procurement mechanisms are referred to in this study as coordinating entities as they make vaccine procurement decisions for the countries receiving their support.

Under the hypothetical scenario where we can design which countries should be served by different coordinating entities, in this study, we explore the effect on vaccine affordability for low-income countries of optimally assigning countries to different coordinating entities. While considering the different goals and restrictions driving such assignments, we aim to ensure that the global vaccine market is as profitable and affordable as possible profitable and affordable to ensure a sustainable global vaccine market. Our framework assumes that all coordinating entities can effectively make high-quality procurement to any of its assigned countries via an optimization approach. Hence, there is no difference in quality among the coordinating entities. It is also assumed that the coordinating entities in this study are non-cooperative and each of them corresponds to a monopsonistic entity proposed by Proano et. al [4] that makes vaccine procurement plans via an optimization-based process. Each of the coordinating entities relies on an optimization based approach to determine vaccine procurement quantities and prices that maximize the total social surplus (total welfare) for each entity's cohort of countries. The optimization based approach follows a four stage process: "stage 0" determines which countries, grouped in markets, should be assigned to each coordinating entity; "stage 1" maximizes total social surplus by determining which vaccines each coordinating entity buys and in which quantities; "stage 2" and "stage 3" use the resulting quantities resulting from "stage 1" to determine vaccines prices (the lowest profitable prices) that result in the most affordable procurement plans and the most profitable prices per dose (the highest affordable prices), respectively, that maintain the optimal total social surplus determined in "stage 1".

This paper complements a preliminary study where we determined that cooperation among coordinating entities increases both affordability and profits for the global vaccine market. However, by increasing the number of non-cooperative coordinating entities, and under the lowest profitable prices, affordability of target low-income countries can be increased at the expense of profits for vaccine producers. In our general parent original study we considered the effect of three experimental factors: (1) the order in which coordinating entities negotiate with vaccine producers, considering that vaccine supplies are limited; (2) the number of non-cooperative coordinating entities in the global vaccine market; (3) The policy producers use to recover their fixed cost investments.

Table 1: Problems tested to determine best criteria when grouping countries.

ID	Problem Name	Description of the objective criteria
O1	Benchmark	Markets are ranked by the average GNI of their countries and are greedily assigned to the entities, so that each entity coordinates an equal number of markets.
O2	Equalize RP	Markets are assigned to entities so that potential dollar value of the markets coordinated by the entities are as closed as possible.
O3	Equalize Population	Markets are assigned to entities so that the number of children cared by the entities are as close as possible.
O4	Strong LICs	Markets are assigned to entities so that the potential dollar value of the markets coordinated by the entities with at least one low-income country (LIC) are as high as possible.
O5	Big LICs	Markets are assigned to entities so that the aggregated children population for entities with at least one LIC are as high as possible.
O6	Isolated HICs	Markets are assigned to entities so that the potential dollar value of the markets coordinated by entities with at least one LIC are as high as possible, without including the contribution of markets with high-income countries (HICs).
O7	Closed HICs	Markets are assigned to entities so that the children population under entities with at least one LIC market are as high as possible without including the population of markets with HICs.
O8	Strong HICs	Markets are assigned to entities so that potential dollar value of the markets coordinated by entities with at least one HIC are as high as possible.
O9	Big HICs	Markets are assigned to entities so that children population for entities with at least one HIC are as high as possible.

In this study, we focus on "stage 0", the problem of assigning countries (grouped in market segments) to coordinating entities. We explore a set of likely optimization problems to represent "stage 0"; these problems differ from each other primarily on the objective criteria of the market segment assignments. The output of the assignment for each objective criteria is use as input for stages 1, 2 and 3. The objective criteria of the proposed market-to-entity assignment problems to represent "stage 0" are shown in Table 1. A benchmark assignment problem is included, in which countries are ranked by their GNI per capita, grouped in market segments of similar population, and then these market segments are greedily assigned to coordinating entities, so that each supports an equal number of market segments.

2 Methodology

At "stage 0" we assign countries to coordinating entities by solving each of the proposed optimization problems described in Table 1 under a fixed pre-determined set up of the three experimental factors and under randomized reservation prices. We generate 50 random instances for each problem representing 'stage 0'. In each repetition, the maximum price the reservation price is randomized between 90% and 110% of their base values.

In this study, the fixed experimental set up consists of: (1) 194 countries grouped into 12 market segments based on their income per capita; (2) coordinating entities procuring vaccines sequentially following an order based on an descending average GNI per capita of the markets they represent; (3) producers not adjusting their expected fixed costs as they close deals with the coordinating entities. The baseline reservation prices for each vaccine in a market were estimated based on the procedure proposed by Mosquera []. The groups of markets assigned to entities, resulting from solving 'stage 0' for any random instance of reservation prices are then used as inputs to solve stage 1 of the optimization-based process to determine which vaccines should be produced, and how much of each is bought by each market. Finally, we solve stages 2 and 3 to determine the

Table 2: Metrics used to compare the proposed scenarios.

ID	Metric	Description	Expression
M1	Total Customer Surplus (TCS)	Savings from procuring vaccines across all market segments of all coordinating entities.	$\frac{\left(\sum_{m\in M}\sum_{b\in B}(R_{bm}-Y_{bm})X_{bm}\right)}{MV}$
M2	Market Value (MV)	Total monetary value in the vaccine market. Sum of all customer savings and all profit.	$TCS + \sum_{e\in E}(X_{bm}Y_{bm} - C_b g_b)$
M3	TCS/MV	Customer surplus at the lowest possible prices across all coordinating entities divided by market value.	TCS/MV
M4	TPF/MV	Total profit at the highest possible prices across all coordinating entities divided by market value.	$\frac{\left(\sum_{m\in M}\sum_{b\in B}Y_{bm}X_{bm}-g_bC_b\right)}{MV}$
M5	TSS/MV	An aggregate indicator of the savings obtained by all countries relative to the prices they were willing to pay and the profits obtained by all vaccine producers.	$\frac{\left(\sum_{m\in M}\sum_{b\in B}R_{bm}X_{bm}-g_bC_b\right)}{MV}$
M6	Customer Surplus in specific market segments	Customer surplus obtained in each of the four traditional market segments in which the vaccine market is separated: high-income countries, upper-middle-income countries, lower-middle-income countries and high-income countries.	$\frac{\left(\sum_{m\in TM}\sum_{b\in B}(R_{bm}-Y_{bm})X_{bm}\right)}{MV}$
M7	Revenue obtained from specific market segments	Revenue obtained from all the countries in each of the four traditional market segments in which the vaccine market is separated: high-income countries, upper-middle-income countries, lower-middle-income countries and high-income countries.	$\frac{\left(\sum_{m\in TM}\sum_{b\in B}Y_{bm}X_{bm}-g_bC_b\right)}{MV}$

range of prices that maximize surplus for the procurement quantities resulting from stage 1.

The performance of the instances solved for each of the problem representations for "stage 0" is summarized via the metrics described in Table 2. These metrics are expressed relative to the total dollar value of the vaccine market (i.e., the total amount of money available for vaccine procurement in each random instance) , which is necessary given that random reservation prices change the scale of customer savings and profit.

2.1 Formulation

The formulations for "stage 0" are represented as a max-min problems where their objectives change depending on the problem criteria listed in Table 1. To describe these problem formulations we rely on the following notation:
Sets:

B: set of vaccines

M: set of markets (each market is a group of countries)

E: set of coordinating entities, order in descending average GNI per capita of their market segments

Parameters:

R_{bm}: Reservation price of vaccine $b \in B$ for countries in market $m \in M$. Maximum price per dose that market $m \in M$ is willing to pay for vaccine $b \in B$

l_m: Average birth cohort per year of countries in market $m \in M$

C_b: Annualized R&D and production fixed cost necessary to produce vaccine $b \in B$, considering a desired rate of return

gni_m: Average gross national income (GNI) per capita among countries in market $m \in M$

G_{LIC}: Income threshold per capita, under which countries in a market segment are considered low-income countries

G_{HIC}: Income threshold per per capita, above which countries are considered high-income countries

Variables:

K: lower bound use in the characterization of the different problems described in Table 1, which are max-min problems. The values and units taken by this variable are function of integrating the constraints (5 to 10) to characterize the different "stage 0" assignment problems.

Z_{em}: Binary variable taking a value of 1 if market $m \in M$ is assigned to entity $e \in E$, or 0 if otherwise

X_{bm}: Quantity of vaccine $b \in B$ to be purchased by country $m \in M$. Decision variable for "stage 1".

Y_{bm}: Price paid for vaccine $b \in B$ in country $m \in M$. Decision variable for "stages 2" and "stage 3".

g_b: Binary variable indicating whether $b \in B$ is being produced or not

s_e: Binary auxiliary variable.

2.2 Stage 0

Each of the nine problems described in Table 1 are generated by a particular combination of the expressions (1 to 14). The objective (1) and constraints (2), (3), and (4) are common to all "stage 0" problem representations. The objective (1) maximizes the lower bound K. Restriction (2) guarantees that at least a country is assigned to each entity. Restriction (3) enforces that each market segment is assigned to exactly one entity. Restriction (4) ensures that all entities have markets assigned by decreasing GNI per capita.

To represent problem O2, inequality (5) is added to (1 to 14); the added constraint makes K the lower bound on the highest total cost that countries assigned to any entity are willing to pay.

Similarly, problem O3 is characterized by adding restriction (6) to (1 to 14). The added constraint makes K the lower bond the population served by any entity.

To represent problem O4, (7), (11) and (12) are added to the common set of expressions making K represent the lower bound on the highest total cost of entities that coordinate at least one low-income market.

Similarly to characterize problem O5, (8), (11) and (12) are added to the common set of expressions to make K the lower bound on the population served by the coordinating entities that support at least one market with low-income countries.

For characterizing problem 06, we integrate constraints (9), (11) and (12) to the common set of expressions in order to make K the lower bound on the total costs of the entities with at least one market with low-income countries, excluding entities with high-income markets.

Problem O7 is requires (10), (11) and (12) to be used in conjunction of the common set of expressions. Problems O8 and O9 require (7), (13) and (14), and (8), (13) and (14) to be used together with the common set of expressions, respectively. Restrictions (11) and (12) force the binary variable s_e to be 0 if no low-income countries are assigned to a coordinating entity e.

Restrictions (13) and (14) force the binary variable s_e to be 0 if no high-income markets are assigned to the coordinating entity e.

$$\max_{K} \quad K \tag{1}$$

$$\text{s.t.} \quad \sum_{m \in M} Z_{em} \geq 1 \qquad \forall \; e \in E \tag{2}$$

$$\sum_{e \in E} Z_{em} = 1 \qquad \forall \; m \in M \tag{3}$$

$$\sum_{m \in M} \sum_{b \in B} Z_{em} gni_m \leq \sum_{m \in M} \sum_{b \in B} gni_m Z_{(e-1)m} \qquad \forall \; e \in 2..||E|| \tag{4}$$

$$K \leq \sum_{m \in M} \sum_{b \in B} Z_{em} R_{bm} \qquad \forall \; e \in E \tag{5}$$

$$K \leq \sum_{m \in M} Z_{em} l_m \qquad \forall \; e \in E \tag{6}$$

$$K \leq s_e \left(\sum_{w \in M} \sum_{b \in B} Z_{ew} R_{bw} \right) + (1 - s_e) M \qquad \forall \; e \in E \tag{7}$$

$$K \leq s_e \left(\sum_{w \in M} Z_{ew} l_w \right) + (1 - s_e) M \qquad \forall \; e \in E \tag{8}$$

$$K \leq s_e \left(\sum_{w \in M : gni_w \leq G_{HIC}} \sum_{b \in B} Z_{ew} R_{bw} \right) + (1 - s_e) M \forall \; e \in E \tag{9}$$

$$K \leq s_e \left(\sum_{w \in M : gni_w \leq G_{HIC}} Z_{ew} l_w \right) + (1 - s_e) M \qquad \forall \; e \in E \tag{10}$$

$$\sum_{m \in M : gni_m \leq GNI_{LIC}} Z_{em} \geq 2 - ||M||(1 - s_e) \qquad \forall \; e \in E \tag{11}$$

$$1 \geq \sum_{m \in M : gni_m \leq GNI_{LIC}} Z_{em} + 1 - ||M|| s_e \qquad \forall \; e \in E \tag{12}$$

$$\sum_{m \in M : gni_m \geq GNI_{HIC}} Z_{em} \geq 2 - ||M||(1 - s_e) \qquad \forall \; e \in E \tag{13}$$

$$1 \geq \sum_{m \in M : gni_m \geq GNI_{HIC}} Z_{em} + 1 - ||M|| s_e \qquad \forall \; e \in E \tag{14}$$

$$\tag{15}$$

3 Results

3.1 Outputs

There are patterns visible in the resulting assignments for specific criteria. O4 groups all low-income markets with the high-income markets in Entity 1 (the one that negotiates first). When high-income markets are excluded in O6, all markets except high-income ones are joined together in a coordinating entity, but the sum of the prices that those market segments are willing to pay is still smaller than that of each individual high-income market segments. The same distribution is observed in O7, justifying those results being omitted from subsequent figures.

Figure 1 shows TSS/MV, TCS/MV and TPF/MV with an overall view of the system. Figures 2, 3, 4 and 5 focus on specific market segments, showing savings and revenue in each scenario. The solid lines in figures 1 to 5 show the performance for benchmark market-to-entity assignment.

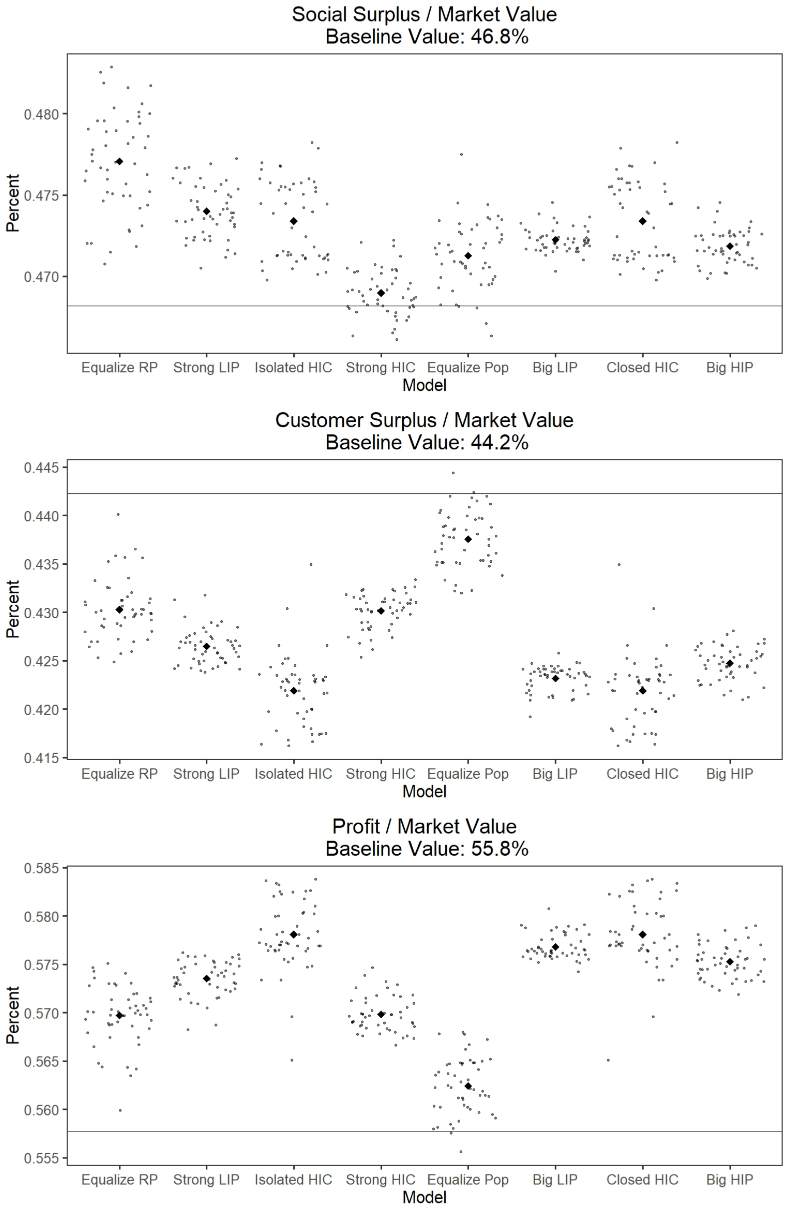

Figure 1: Comparison between $\frac{TSS}{MV}$, $\frac{TCS}{MV}$, and $\frac{TPF}{MV}$ across different criteria.

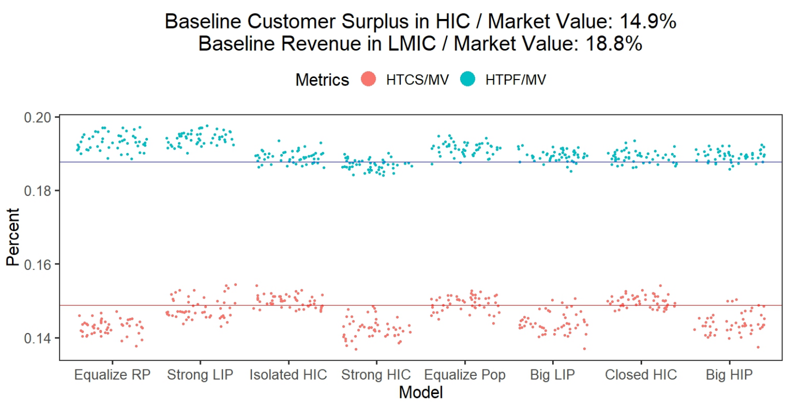

Figure 2: Comparison between M6 and M7 across different criteria for high-income countries.

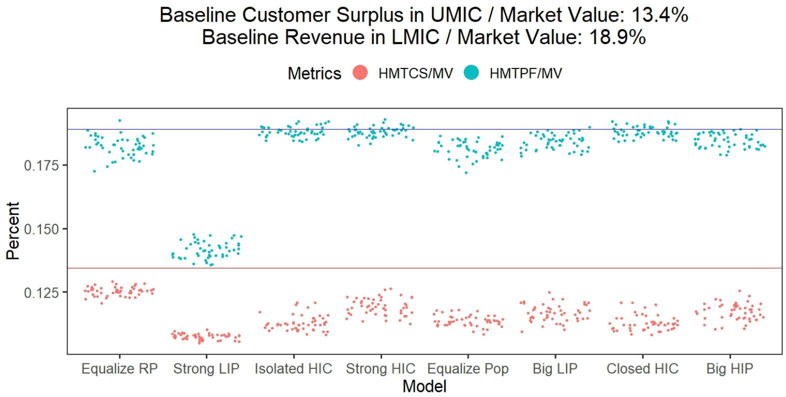

Figure 3: Comparison between M6 and M7 across different criteria for higher-middle-income countries.

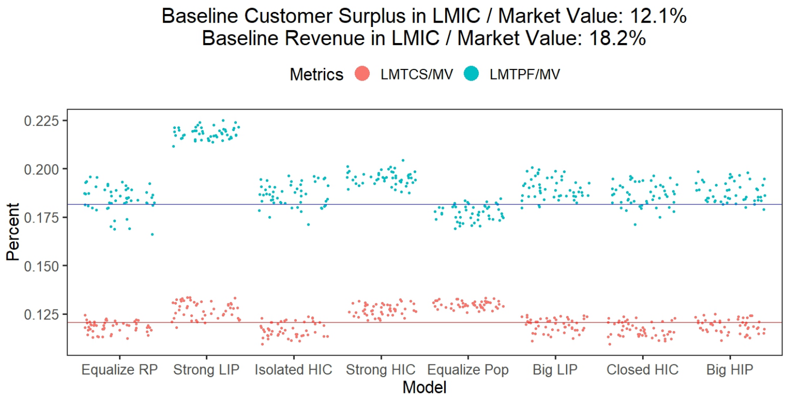

Figure 4: Comparison between M6 and M7 across different criteria for lower-middle-income countries.

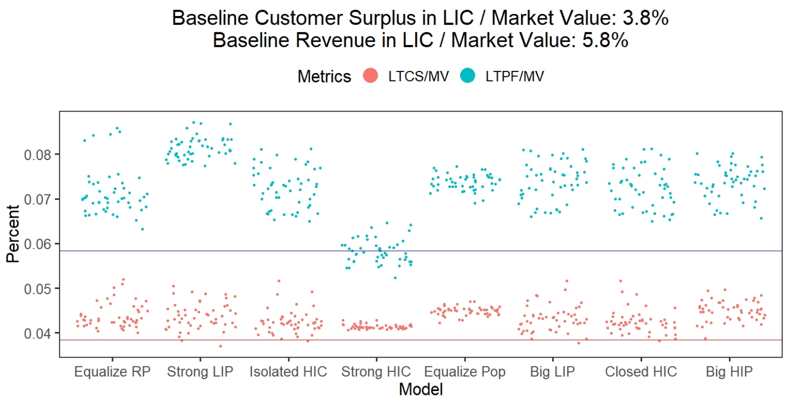

Figure 5: Comparison between M6 and M7 across different criteria for low-income countries.

3.2 Discussion

All proposed criteria perform better than the benchmark scenario in terms of social surplus, for the lowest profitable prices. However, when looking at the customer surplus with the savings that markets obtain overall, we see instead a decrease in performance. As the improvement in profit for vaccine producers is greater than the decrease in savings, the resulting surplus is positive, as shown in figure 1.

However, Figure 5 shows that the savings of low-income countries also improve in all considered scenarios. The decrease in overall customer surplus derives mainly from upper-middle income countries, which are impacted in affordability. Low-income countries are also responsible for the increase in profitability.

4 Conclusion

The trends seen in section 3 suggest that low-income countries benefit from negotiating in conjunction with higher-income countries. Savings for low-income countries are improved, while upper-middle-income countries perform worse. This arrangement is also beneficial to vaccine producers. This means that any of the proposed criteria can be used to mitigate the diminished profits seen in previous experiments when not all agents in the vaccine market cooperate. Those results also suggest that coordinating entities such as Gavi that limit their services to low-income countries might obtain better savings if some higher-income countries were included as well. The increase in profits might be an incentive for the countries to join the coordinating entities, given that the few producers that supply most of the vaccines operate from high-income countries. Even if high-income countries cannot be convinced to participate, "stage 0" characterizations O6 and O7 show that affordability and profits can still improve as long as upper-middle income countries cooperate. In order to minimize impact to high-income and lower-income countries, criteria O3 (equalizing the population across different coordinating entities) can be adopted to still offer improvements to low-income countries and vaccine producers.

References

[1] Gavi, the Vaccine Alliance. Cost-effective. https://www.gavi.org/about/value/cost-effective/, n.d. [Online; accessed 12-Dec-2018].

[2] Sachiko Ozawa, Samantha Clark, Allison Portnoy, Simrun Grewal, Logan Brenzel, and Damian G Walker. Return on investment from childhood immunization in low-and middle-income countries, 2011–20. *Health Affairs*, 35(2):199–207, 2016.

[3] World Health Organization. Brief 12: The vaccine market - pooled procurement, 2010.

[4] Ruben A Proano, Sheldon H Jacobson, and Wenbo Zhang. Making combination vaccines more accessible to low-income countries: The antigen bundle pricing problem. *Omega*, 40(1):53–64, 2012.