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Impact on affordability and profit of non-cooperative procuring entities on a hypothetically coordinated global vaccine market

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This study considers a hypothetical global vaccine market where multiple coordinating entities negotiate on behalf of countries with different purchasing powers. Each entity makes optimal procurement decisions that aim to improve affordability for a group of countries while improving profitability for producers. This study analyzes the effect of cooperation among coordinating entities on the affordability and profitability of a hypothetically coordinated vaccine market by controlling the number of non-cooperative coordinating entities, the number of market segments used for tier pricing, how fixed production costs are recovered, and the procuring order among coordinating entities. This paper relies on a three-stage optimization process that solves in sequence an MIP and two LP problems to determine ideal procurement plans and the price ranges per dose that maximize savings and profit for the plan. We establish that the order in which the coordinating entities negotiate with vaccine producers and the policies used to recuperate the cost of their fixed investments can affect profitability and affordability. We show that low-income countries can save more while satisfying their demand by negotiating through entities handling smaller groups of countries, while upper-middle and high-income countries increase their affordability by procuring through entities with larger groups of countries. A procurement order that prioritizes coordinating entities by ascending average income of the countries they support improves both affordability and profits. Furthermore, lowering the prices of vaccines with unsold supply during a sequential procurement process leads to financial losses for the producers without a substantial improvement in affordability.

Key words: vaccines, welfare, affordability, Operations Research, market design

1. Introduction

Vaccines are credited for saving more than 2 million lives every year [1]; they are among the most cost-effective healthcare interventions, as treating ill patients are many times more expensive than preventing those diseases through immunization [2]. Whitney et al. [3] estimates that in the US alone, vaccines saved over $1.38 trillion dollars in total societal costs between 1994 and 2013.

Phase	Country GNI (US$)	Co-Finance Policy	Annual Increase
1	$\leq$ 1,045	0.20	None
2	$\geq$ 1,045 and $\leq$ 1,580	$\frac{\text{total contribution in previous year}}{\text{total costs in previous year}}$,	15%
3	> 1,580	15% greater than in the last year of previous phase	Linear costs increase to 100% of costs in 5 years

Table 1 Phases of Gavi's co-financing policy according to GNI described in [5].

Classification	Abbreviation	Lower Country GNI Limit (US$)	Upper Country GNI Limit (US$)
High income	HIC	12,055	-
Upper middle income	UMIC	3,896	12,055
Lower middle income	LMIC	996	3,896
Low income	LIC	-	995

Table 2 World Bank classification for countries based on income [7].

The global vaccine market consists of countries that procure vaccines to satisfy their immunization needs from a limited set of producers. Typically high- and upper-middle-income countries purchase vaccines on their own. Other countries buy vaccines through pool procurement mechanisms, where they pool financial resources to buy vaccines as a group and take advantage of economies of scale [4], as it is done for Latin American countries through the Pan American Health Organization (PAHO)'s Revolving Fund. Alternatively, the United Nations Children's Fund (UNICEF) procures vaccines for 73 low- and low-middle-income countries who are eligible to receive financial support from donors such as Gavi.

Pooled procurement is also beneficial for vaccine producers. For example, UNICEF-Gavi secures low vaccine prices by offering a more stable and predictable demand for vaccine manufacurers [5], facilitating their production and fostering their ability to use tier pricing to push vaccine products [6]. Table 1 illustrates Gavi's co-financing policy for its member countries.

Through the use of tiered pricing, producers set different price levels depending on the buyer's income level [6]. Traditionally, vaccine producers have grouped countries as high-, upper-middle-, lower-middle-, or low-income countries based on The World Bank country classification (see Table 2). Producers may also have different tier pricing levels for different vaccines. Reselling low-priced vaccines to higher income countries is usually not feasible in the vaccine market, due to regulations, restrictions on cold-chain logistics, and differences in the immunization schedules.

Despite the positive effect of tiered pricing and pooled procurement, vaccines are not always available and affordable, especially for low-income countries. WHO [8] claimed that 19.5 million infants did not have access to essential vaccines in 2016, with 60% of them concentrated in ten low- and middle- income countries [8]. This lack of affordability is due to multiple reasons including the following: the vaccine supply by volume, is highly concentrated in a limited number of producers [2]; the monetary value of the vaccine market is concentrated on sales to high-income countries; (3) logistics factors affect vaccine distribution and increase costs; (4) fragility of healthcare systems to support immunization programs, and (5) political turmoil disrupting immunization campaigns and low national health investments. By 2018, for example, 80% of the entire vaccine supply by volume was produced by five large vaccine producers [8] and vaccine purchases by high-income countries generated 82% of the dollar value of the vaccine market, despite representing only 20% of the global demand by volume [9].

This paper extends a global hypothetically coordinated vaccine market proposed by Proano et al. [10], where for a single procurement period exercise (a single vaccine tender), a monopsonistic entity simultaneously maximizes affordability and profit, recommending optimal vaccine procurement quantities and their pricing ranges through an optimization-based three-stage approach. This study instead evaluates the impact of having multiple coordinating entities procuring vaccines on behalf of small groups of countries, where there is no cooperation among those entities. Similarly, the study determines procurement decisions aiming to clear all antigen demands for a single period. Results are contrasted to those obtained by considering a fully cooperative market that has a single entity.

Having coordinating entities develop procurement plans for smaller groups of countries can provide additional attention to each country's needs and ensure procurement practices that are aligned with regional healthcare priorities. However, smaller coordinated markets may also hamper the countries' opportunities to ensure savings by limiting the effect of economies of scale and inducing negotiating asymmetries between smaller buyers and large producers. For example, if procurement must clear antigen demand in a procuring cycle, the order in which entities buy vaccines for their countries can affect pricing decisions for late buyers, as producers can have incentives to link price discounts to push product.

In this study we consider a global vaccine market that buys vaccines to clear its demand once a year, and we investigate the effect on affordability of controlling three relevant factors: (1) the number of coordinating entities in the hypothetically coordinated global vaccine market, (2) the order those coordinating entities follow to buy vaccines, and (3) whether producers push their products by offering discounts on vaccines whose supply has been partially sold.

We assume that the hypothetical vaccine market consists of multiple coordinating entities, each serving a predetermined set of countries. Similarly to the framework proposed by Proano et al. [10], each entity aims to maximize affordability and profit by optimizing total social surplus. The entities group the countries they serve in a different number of market segments to take advantage of tier pricing. The entities aim to determine the optimal amount of vaccines to be bought for each market segment in their cohort of countries, as well as the range of prices per dose that maximize their cohort's total social surplus. We assume that each coordinating entity has a sense for the willingness to pay for any available vaccine by the countries in its cohort.

Additionally, we assume that the investment costs to manufacture vaccines are annualized and only charged for vaccines that are effectively sold. Manufacturers aim to recover during the procurement period the annualized fixed cost over that time interval. The annualized costs include a desired return on investment, high enough to cover the research and fixed costs of all vaccine products in the producer's portfolio over the product life-cycle. Furthermore, this paper assumes that producers mitigate the risk of not selling their entire supply for a vaccine by offering economies of scale via linear price functions. Profits for producers correspond to the aggregated difference between vaccine revenue from sales and any annualized fixed costs in the procuring period.

Without loss of generality, the vaccine negotiation process is assumed to happen once per year for each coordinating entity. Under a market with non-cooperative coordinating entities, we assume that producers can follow two policies to recover their annualized fixed costs: (1) offering discounts on vaccines whose supply was partially sold to other entities, or (2) offering no discounts.

The presence of coordinating entities in the vaccine market results in a procuring sequence during the one-year procurement period. This procuring sequence is ordered based on the income per capita of their country members. This study explores procuring orders based on ascending and descending average income per capita. Countries that require external donations for procuring vaccines are assumed to receive funds regardless of their affiliation to their coordinating entities (i.e., the effect of donations is reflected on the maximum prices they are willing to pay for a vaccine dose - reservation prices).

Under this setup, this study aims to answer the following questions:

Q1: How does vaccine affordability for target low-income countries and profits for producers in a non-cooperative coordinated vaccine market compare to those in a cooperative scenario?

Q2: What is the effect of market segmentation on the group of countries served by each entity?

Q3: What is the effect on affordability for target low-income countries and on profit of the number of coordinating entities procuring on behalf of countries?

Q4: How does the entity procuring order affect affordability and profits?

Q5: Can affordability and profits improve if producers adjust their prices as they close deals with coordinating entities during the negotiation sequence?

To address these research questions, we modify and extend the mathematical model proposed by Proano et al. [10] to compare scenarios in which a varying number of coordinating entities interact, not only to represent non-cooperative entities but also when entities work together as a single entity. We vary the order in which coordinating entities negotiate, the policies used by the producers to recuperate their investment, and the overall number of market segments into which the countries are grouped.

The rest of this paper is organized as follows. Section 2 reviews relevant literature on vaccine pricing and group buying. Section 3 describes the mathematical model and the three-stage optimization process, the experimental framework, and the performance metrics used in this study. Section 4 describes the data used in the study. Finally, Section 5 offers a discussion of the experimental results and relevant extensions.

2. Literature Review

In this section we review literature on group buying and mathematical modeling on vaccine pricing, leading to the seminal study from which this study extends. Although there is abundant literature on general group buying and its effects on tiered pricing [11, 12, 13, 14], we are unaware of studies considering group buying for vaccines. Vaccine pricing studies that rely on mathematical programming models have focused on the introduction a new vaccine into a single market [15, 16, 17]. Other studies question the mechanisms through which vaccines are sold, and how those affect affordability [18, 19, 20, 21]. Additionally, the literature also offers no consensus on how to price vaccines based on a cost-benefit analysis [22, 23, 24, 25, 26, 27]. Finally, Proano et al. [10] uses mathematical programming models and a three-stage optimization-based process to explore pooled procurement and tier pricing in a hypothetically coordinated global vaccine market, Section 2.1 further describes Proano et al. [10], as it offers the basis for this study.

Frontieres [18] discusses how the GNI-based tiered pricing does not guarantee higher affordability on its own, and might instead limit access to vaccines that become prohibitively expensive when jumping from low-income prices to lower-middle-income prices. This criticism is supported by Moon et al. [19], claiming that tiered pricing may overburden middle-income countries in an unsustainable manner while incentivizing producers to focus on the higher profits obtained from high-income markets.

Game theory models have also been used to address vaccine pricing decision problems [15, 16, 17]. Those approaches can find solutions that balance the needs of multiple market agents. Although these studies consider different vaccines as options for a single consumer to choose from, most of these studies have focused their attention on the impact caused by the introduction of new vaccines in a single market, ignoring the implications of potential buyer coordination.

Robbins et al. [17] uses a game theory model to frame the US vaccine market as an oligopoly of asymmetric producers in a Bertrand competition where each producer can supply the entire market. Consumers attempt to purchase enough doses of all the antigens for which there is demand in their country. The framework is offered as a mathematical approach to capture oligopolistic market interactions that in the US market suggests a different pricing strategy for combination vaccines.

When considering a global market in which manufacturers would be able to offer their products around the world, quality differences between vaccines that immunize against the same diseases may not be among the most relevant factors affecting demand. Proano et al. [10] proposes an optimization-based methodology to model pricing coordination between different market segments and producers when a single coordinating entity acts as a decision-maker that aims to improve affordability and profit simultaneously.

Other studies approach vaccine pricing through mathematical programming models[28, 29, 30, 31], assuming a central planner for the US market without considering supply limitations. Additional studies have focused on determining how combination vaccines fit on the overall schedule for the US market also under a central planner [32, 33, 34, 35].

Regarding group buying literature, studies rely on pool procurement to affect affordability and profit. Group buying studies typically assume economies of scale in the market, unlimited supplies, and consider a single product, producer, and mediator, often in the form of a website that charges membership fees to allow customers to access price discounts [11, 12, 13, 14]. These assumptions are used in modeling frameworks that capture the relationship between the purchased quantity and the price and the benefit of joining a coordinating entity. Those assumptions may not adequately fit the characteristics of the vaccine market, which has no membership fees as a way to access discounted prices. In a global vaccine market, countries need to meet other criteria to be eligible to belong to a group, such as being part of a geographical region or having economic indicators below a certain threshold.

Hu et al. [11] assumes that a set of customers can be coordinated into group buying entities negotiating online deals with a single seller. The study deals specifically with the issue of sequencing buyers, as the negotiating order can affect whether or not there is enough demand to justify the deal. Hu et al. [11] relies on game theory to model the interaction between customers and the seller, considering a sequence of discrete interaction periods, in which several customers may choose independently. Buyers from Hu et al. [11] have the option of not satisfying their demand or choosing outside sources not represented in the model.

Under a general coordinated group-buying framework, Yang et al. [12] studies the conditions that might make it more advantageous for sellers to serve each participating coordinating entity in a given market. The study assumes that the seller can obtain other business in case the entities refuse to negotiate and that there is a single seller whose decisions affect the market.

Chen and Roma [13] models group-buying through a three-step process involving producers, retailers, and buyers. Retailers can choose whether to cooperate with a group-buying entity or not. Assuming a linear demand, Chen and Roma [13] suggests that group-buying might be more advantageous to smaller, less powerful retailers than to bigger ones. It is assumed that retailers operate for profit, and would never cooperate.

Anand and Aron [14] consider group-buying mechanisms for a monopoly on web-based transactions under uncertain demand. There is uncertainty in the valuations customers make on products, and prices are assumed to be unknown. This uncertain demand in vaccine market due to population changes is low, as the birth rates of most countries tend to be stable during a year [36]. Any variations on purchased quantities are more likely to come from changes in available budgets, existing stockpile levels, reaction to outbreaks, logistical issues, and political instabilities.

Several studies have focused on Gavi, as an existing coordinating entity for the vaccine market, and on the impact on countries when they are no longer eligible for its aid [5, 37, 38]. Saxenian et al. [37] relies on the experience of some of the countries studied in Le et al. [5] to evaluate the readiness of 16 countries if they stop receiving financial assistance from Gavi by 2018, as they graduate according to Table 1. The incremental financial load on graduating countries may provoke these countries to cancel or scale down immunization programs and face issues with their vaccine supply [37], potentially decreasing their coverage levels. For instance, Ukraine reduced the incidence of Hepatitis B while supported by Gavi, but after its graduation from Gavi its immunization coverage plummeted in just two years [39]. Furthermore, those that exceeded the eligibility threshold can no longer request aid for any new vaccines, as was the case with Cuba and Ukraine.

2.1. Antigen Bundling Pricing Problem

Proano et al. [10] proposes the Antigen Bundling Pricing (ABP) problem, which considers that countries grouped as market segments (HIC, UMIC, LMIC, LIC) to procure vaccine products from multiple vaccine producers via a trusted intermediary. The procurement of these market segments is assumed to be coordinated by a single entity, which aims to guarantee that the negotiated prices ensure a desired profit level for the vaccine producers, and also the highest affordability to vaccine buyers. The model enforces tier-pricing by ensuring that low-income countries pay lower prices than higher-income countries while negotiating the same vaccine. Additionally, the ABP enforces that market segments buy vaccines at prices below their average reservation price for each vaccine in each market. Furthermore, the ABP also enforces a non-linear price elasticity.Proano et al. [10] shows that it is possible to price vaccine more affordably for all coordinated markets segments (including high-income markets) when the supply of combination vaccines are made available to all market segments. Additionally, Proano et al. [10] shows that the total social surplus (total welfare) is a consequence of the choice and volume of vaccines procured. While the study illustrates the benefits of pool procurement, it assumes that a single entity coordinates the entire global market and recommends optimal vaccine prices and purchase quantities. It also assumes that all vaccines are tier-priced based on a global vaccine market divided into four market segments based on their income per capita. The ABP is solved in three stages. First, a mixed-integer non-linear program maximizes total social surplus and determines optimal procuring quantities; then such quantities are used as inputs for two linear programming models that compute the high and low prices per dose that maintain the optimal total social surplus.

Considering a hypothetically coordinated vaccine market with a single entity, Mosquera [40] extends Proano et al. [10] to evaluate the effect on profits and affordability when grouping countries into a varying number of market segments (2, 4, 8, 12), and considering uncertain vaccine reservation prices and different rates on the producers return of investment. Mosquera [40] concludes that separating the countries into more market segments improves the affordability of low-income countries while decreasing the profits of vaccine producers. However, by increasing the number of market segments in which low- and low-middle-income countries are grouped while decreasing the number of market segments for upper-middle- and high-income countries, one could focalize savings without affecting manufacturers' profit and not making vaccines increasingly expensive for high-income countries (vaccines remain priced below each market's reservation price). Mosquera [40] also shows that uncertainty in reservation prices and the return on investment rates do not have a significant effect on affordability.

3. Methodology

This study proposes the Group Vaccine Allocation (GVA) model, a mathematical programming model that extends the Antigen Bundling Pricing (ABP) problem proposed by Proano et al. [10]. We integrate the GVA into a multi-stage experimental approach to test the influence on affordability and profit of four factors: (F1) the order in which multiple coordinating entities procure vaccines (entity priority), (F2) the type of policy adopted by the producers to recover annualized R&D fixed costs (annuity recovery), (F3) the number of coordinating entities, and (F4) the number of market segments in which countries are grouped. Each factor has multiple levels, and for each combination of levels, random experimental instances result from randomizing reservation prices for each vaccine in each market segment. For each of these instances, the GVA problem is solved in three stages. The first stage determines which vaccines to produced and the quantities to be bought by countries grouped in market segments, a second stage determines a lower bound on prices for the vaccines to be procured, and a third stage determines their upper bound. The former prices correspond to the most affordable and least profitable vaccine prices per dose, while the latter corresponds to the least affordable and most profitable prices. The reservation prices on each vaccine at each market segment serve as an upper bound for the high and low vaccine prices per dose. Without loss of generality, the GVA is solved for a single-year procurement cycle, where all countries in a global market are served by coordinating entities that make procurement decisions on their behalf.

3.1. GVA: Group Vaccine Allocation Model

After sorting the coordinating entities in a given procurement order, for each entity and the markets in which its countries have been grouped, GVA iteratively solves a sequence of three optimization models. The GVA determines optimal procurement plans and price ranges for each coordinating entity in the global market that cover the vaccine demand by keeping vaccine prices per dose below their reservation prices (Proano et al. [10]), while simultaneously maximizing profit to the manufacturers. For each coordinating entity, the first stage determines which vaccines and in which quantities should be bought for countries grouped in market segments under its support. The second stage uses the recommended procurement quantities as inputs to determine prices that maximize affordability for vaccine buyers, while the third stage uses these procurement quantities as inputs to determine dose prices that maximize the producers' profits. As a result, GVA determines a vaccine procurement plan and the range of prices per dose that maximize savings for the buyers and profits for the vaccine producers (i.e., the total social surplus, as defined in Proano et al. [10]). The following notation and formulation describe the GVA:

<u>Sets:</u>

- B: set of vaccines
- A: set of antigens offered by immunization
- M: set of market segments in which countries are grouped
- P: set of vaccine producers
- E: set of coordinating entities
- A^1_b: set of antigens offered in a dose of vaccine $b \in B$
- B^1_a: set of vaccines offering antigen $a \in A$
- B^2_p: set of vaccines manufactured by a producer $p \in P$
- Q_b: Set of vaccines that together offer the same antigen protection as vaccine $b \in B$, and are made by the same producer
- N_q: sets of all Q_b vaccines that offer the same antigen protection as $b \in B$

<u>Parameters:</u>

- R_{bm}: Reservation price of vaccine $b \in B$ in market segment $m \in M$. 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 in market $m \in M$
- C_b: Annualized fixed cost for R&D and production necessary to produce vaccine $b \in B$, considering a desired rate of return
- d_{am}: Annual antigen demand for $a \in A$ per child to fully immunize the child in market segment $m \in M$ according to the immunization schedule in the market

D_{bm}: Maximum number of doses of vaccine $b \in B$ allowed per child in market segment $m \in M$ to avoid over-immunization

S_b: Total supply of vaccine $b \in B$ per year

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

α: Scaling factor that allows vaccine prices to increase when a quantity smaller than the total capacity of a vaccine is purchased among all market segments

θ: Scaling factor that indicates the level of prices above the reservation price after which vaccine demand becomes null. $0 \le \theta \le 1$, no vaccine b will be bought if vaccine price is above θR_{bm}

u_b: Minimum price paid for a dose of vaccine $b \in B$

γ: Relative importance of maximizing the profit for producers. $0 \le \gamma \le 1$

ψ: Relative importance of ensuring the antigen demand is met. $0 \le \psi \le 1,\ \gamma + \psi = 1$

η: Scaling factor that ensures unnecessary vaccines are not produced.

Variables:

X_{bm}: Quantity of vaccine $b \in B$ to be purchased by market segment $m \in M$

Y_{bm}: Price paid for vaccine $b \in B$ in market segment $m \in M$

g_b: Binary variable indicating whether $b \in B$ is being produced (i.e., $g_b = 1$) or not(i.e., $g_b = 0$)

3.1.1. Stage 1 Problem

$$\max_{X,Y,g}\ \gamma\left(\sum_{b\in B}\sum_{m\in M} R_{bm}X_{bm} - \sum_{b\in B} C_b \frac{\sum_{m\in M} X_{bm}}{S_b}\right) - \psi \sum_{a\in A}\sum_{m\in M}\left(d_{am}l_m - \sum_{b\in B1_a} X_{bm}\right) - \eta \sum_{b\in B} g_b \quad (1)$$

$$\text{s.t.}\quad Y_{bm} + (1-g_b)\sum_{t\in N_q} R_{bm} \ge \sum_{t\in N_q} Y_{tm} \qquad \forall\ b\in B,\ q\in Q_b:\ ||Q_b|| \ge 1 \quad (2)$$

$$\sum_{m\in M} X_{bm} \le S_b g_b \qquad \forall\ b\in B \quad (3)$$

$$Y_{bm} \ge \left(\frac{(S_b g_b - X_{bm})\alpha + S_b g_b}{S_b}\right)\frac{C_b}{S_b} \qquad \forall\ b\in B,\ m\in M:\ S_b > 0 \quad (4)$$

$$Y_{bm} \le \theta R_{bm} g_b \qquad \forall\ b\in B,\ m\in M \quad (5)$$

$$Y_{bm} \ge g_b u_b \qquad \forall\ b\in B,\ m\in M \quad (6)$$

$$\sum_{b\in B1_a} X_{bm} \le d_{am} l_m \qquad \forall\ a\in A, m\in M \quad (7)$$

$$X_{bm} \le D_{bm} l_m \qquad \forall\ b\in B,\ m\in M \quad (8)$$

$$X_{bm} \ge 0 \qquad \forall\ b\in B,\ m\in M \quad (9)$$

$$g_b = \{0,1\} \qquad \forall\ b\in B \quad (10)$$

In Stage 1, the Mixed Integer Programming model described above determines all procurement quantities, X_{bm}, of vaccine b in market m that maximize profit for producers and affordability for the market segments assisted by a given coordinating entity at a particular experimental iteration (i.e., the Total Social Surplus for the markets associated with the coordinating entity). The formulation differs from the model proposed by Proano et al. [10] since, under a non-cooperative scenario, cannot guarantee that prices are such that they cover the annualized fixed costs for the producers. In the non-cooperative scenario revenue results from a subsequent negotiation between each producer and the coordinating entities; hence, the annualized fixed cost can only be met after all the negotiations have taken place. Additionally, the GVA model considers that price decreases linearly as procurement quantities increase, and that failing to meet demand is possible by intensively penalized.

Since we aim to increase affordability for target low-income countries, the objective function in stage 1 (1) simultaneously maximizes total social surplus, and through penalty multipliers, minimizes gaps in meeting vaccine demands and not covering setup cost for vaccine producers. The total social surplus contribution considers the fraction of the annualized fixed R&D costs relative to the number of vaccines bought by the coordinating entity in the current iteration $\left(\frac{\sum_{m\in M} X_{bm}}{S_b}\right)$. The objective also minimizes the gap between the vaccine purchases and the demand in the market segments the entity coordinates at the current iteration. The penalty function $\left(\psi \sum_{a\in A, m\in M}\left(d_{am}l_m - \sum_{b\in B1_a} X_{bm}\right)\right)$ in objective (1) allows for small gaps in meeting the demand that otherwise would render the problem infeasible. The last term in (1) minimizes the number of vaccine types used in the procurement plan.

Restriction (2) guarantees that the price negotiated for a combination vaccine is higher than the aggregated price of combining other vaccines from the same producer to offer similar antigen protection to the combination vaccine.

Restriction (7) guarantees that the coordinating entities do not buy more vaccines than their demand. Constraint (3) restricts the amount purchased of each vaccine to the supply available from its producer.

Restriction (4) expresses the elasticity relationship between order quantity and price. If the entire supply of a vaccine is bought, the price should be such that will to cover the annualized fixed costs (that is, $Y_{bm} \geq \frac{C_b}{S_b}$). When selling less than their total supply, this constraint adjusts vaccine prices based on the remaining supply to increase the revenue needed to cover fixed costs. The difference between the total vaccine supply and the amount that has been bought up to when it is an entity's turn to buy increases a vaccine price by a factor α, so that $\frac{(S_b g_b - X_{bm})\alpha + S_b g_b}{S_b} \geq 1$. Therefore, the constraint adjust prices depending on the remaining available supply. Restriction (5) guarantees that the negotiated prices do not exceed a ϕ factor over the reservation prices for each vaccine in each market segment. Restriction (6) forces prices per dose to be above a pre-established minimum price. Restriction (8) prevents that the optimal vaccine procurement of each vaccine in a market results in over-immunization.

3.1.2. Stage 2 Problem

$$\begin{aligned} \underset{Y}{\text{Max}} \quad & \text{TCS:} \sum_{b\in B}\sum_{m\in M}\left(R_{bm}-Y_{bm}\right)X^*_{bm} \\ \text{subject to} \quad & \text{Restrictions (2)} - (6) \end{aligned} \tag{11}$$

In Stage 2, a Linear Programming model maximizes the savings that countries can obtain by procuring vaccines at prices lower than the average reservation prices in their market segments, considering the vaccine quantities resulting from the solution of the Stage 1 problem as inputs. The Stage 2 problem establishes a lower bound on vaccine prices that that can still ensure that producers achieve the optimal total social surplus from Stage 1. Given that profits can only be calculated once all coordinating entities complete their negotiations and all prices are already known, the model in this stage enforces constraint (4) to determine the prices that facilitate securing a desired return on investment for an entity when it is its turn to procure.

3.1.3. Stage 3 Problem

$$\begin{aligned} \underset{Y}{\text{Max}} \quad & \text{TPF:} \sum_{b\in B}\sum_{m\in M} Y_{bm}X^*_{bm} - \sum_{b\in B} C_b g^*_b \frac{\sum_{m\in M} X^*_{bm}}{S_b} \\ \text{subject to} \quad & \text{Restrictions (2)} - (6) \end{aligned} \tag{12}$$

Stage 3, also a Linear Programming model, maximizes profits for the vaccine allocations resulting from Stage 1. This LP problem establishes an upper bound on the vaccine prices that maintain the optimized social surplus resulting from problem 1, without exceeding the reservation prices by beyond tolerance of θ.

It is assumed that all market segments can purchase all vaccines. Table 3 summarizes the constraints enforced at each stage of the GVA for an entity and a problem instance.

Without loss of generality, restriction (6) sets a minimum vaccine price per market US$0.20 [5, 41]. The constraint forces prices for a given vaccine to be at least the minimum price in all markets served by the coordinating entity when at least one entity is buying the product. This minimum price can be adjusted to reflect a minimum price per vaccine per market.

Under a scenario where coordinating entities do not cooperate, vaccine producers cannot guarantee that the annualized R&D and production fixed costs are fully recovered, since vaccine quantities sold to all markets are not realized at the same time. Thus under a non-cooperative scenario, decisions are unveiled iteratively for each coordinating entity without having a full picture of the purchases made, or to be made, by other coordinating entities. Under a non-cooperative scenario, no market agent knows the orders placed by all entities until the end of the last iteration. This additional risk for the producers, of not meeting their return on investment, may result in higher prices per dose.

Stage	Variables	Objective Function	Constraints
1	X_{bm}, Y_{bm}, g_b	(1)	(2), (7), (3), (4), (5), (6), (8)
2	Y_{bm}	(11)	(7), (3), (4), (5), (6)
3	Y_{bm}	(12)	(7), (3), (4), (5), (6)

Table 3 Expressions and constraints used in each problem associated with stages of the model.

This behavior is captured by the price-elasticity constraint (4). Producers can incentive coordinating entities to buy their remaining vaccine supply by following an adjusted fixed cost recovering policy; the portion of the annuity C_b is reduced after each iteration when part of the supply of vaccine b has been acquired.

While in a coordinated market it is possible to estimate profit, this approach is not feasible in a non-cooperative framework, since it is not trivial to determine how much of the annuity should be attributed to each coordinating entity. The approach proposed in the objective function (12) follows a similar pattern as (4) and considers that the costs are proportional to the fraction of the supply sold. Notice that during the procurement exercise, total profits cannot be estimated until all entities have completed their procurement; for this reason, during the experimentation, we also report on the actual revenue per vaccine. Finally, all vaccines produced for one coordinating entity remain available for the subsequent procurement.

By computing for each vaccine the highest and lowest acceptable prices per dose in stages 2 and 3 of the model, we also estimate the risk that producers do not meet their desired return on investment when all entities have made their procurement plans. When a vaccine yields a negative profit even at the highest acceptable prices in the optimal procurement plan, producing such a vaccine by itself does not result in a sustainable investment. Similarly, if the profit is positive even at the lowest prices in the optimal procurement plan, the vaccine is guaranteed to do financially well. In any other scenario, it will depend on the producer's ability to negotiate prices closer to the highest acceptable ones to enhance product profitability. In the GVA, the profit aggregates the revenue from the sales to all entities, and subtracts the annualized fixed costs for all vaccines produced; maximizing this aggregated profit allows for the more profitable vaccine those that result in losses, as long as the producer obtains an overall profit.

3.2. Framework

We design experimental scenarios by controlling four key factors: (F1) the number of market segments in which 194 countries can be grouped; (F2) the number of coordinating entities facilitating procurement in the global market; (F3) the order followed by the entities in negotiating their procurement plans; and (F4) by whether producers adjust or not their minimum prices to recover their return on investment. The procurement order of the coordinating entities can be ascending

Factors	Levels						
F1: Number of market segments	2		4		8		12
F2: Number of coordinating entities	1	2	3	4	6	8	12
F3: Coordinating entities procurement order	Ascending income				Descending income		
F4: Fixed cost recovering policies	Adjusted				Invariant		

Table 4 Experimental factors and levels

or descending based on the average GNI per capita of the countries served by each entity. Table 4 summarizes the experimental scenarios tested to answer the research questions.

For factor (F1), we grouped 194 countries into 2, 4, 8, or 12 different market segments based on the similarity of their GNI. The market segments are then assigned to coordinating entities based on their average income per capita so that all entities make decisions for an equal number of market segments per experimental scenario.

Factor (F2), allows the number of non-cooperative coordinating entities to vary in six levels (1,2,3,4,6,12). Considering the equal distribution of market segments per entity, if number of market segments is 12, the numbers of markets per entity decreases (12, 6, 4, 3, 2, and 1), as the number of entities increases (1, 2, 3, 4, 6, and 12), respectively. The maximum number of entities that can be used per experimental scenario is equal to the number of market segments, for 8, 4, or 2 in the scenario.

The case when a single coordinating entity represents all market segments serves as a benchmark scenario.

For factor (F3), the procurement order of the coordinating entities was sorted by either the ascending or descending average GNI of the market segments served by the coordinating entity.

For factor (F4), producers follow either an 'adjusted' or 'invariant' pricing policy. As stated earlier, producers estimate a minimum price per vaccine dose considering the annualized fixed R&D production costs that must be recovered. With an 'adjusted' policy, if revenue has already been obtained by selling vaccine doses to different coordinating entities, the producers determine minimum bounds on the vaccine prices that help meet the annualized fixed costs yet to be recovered. In the 'invariant' policy, at the beginning of the procuring cycle, producers estimate the minimum price bound to recover the entire annualized fixed costs and do not modify their estimations during the procurement sequence.

The combination of levels for the four factors results in 60 experimental scenarios. For each scenario, we randomize the reservation prices of each vaccine at each market from 90% to 110% of their historical baseline reservation prices. Vaccines that have not been purchased by a specific market had their reservation prices estimated as a function of the income of each market segment, as well as of the historical price of other vaccines offering similar antigens, as described in Mosquera

[40]. For each experimental scenario, we generated one thousand replications and solved the three-stage optimization GVA problem for each instance and coordinating entity, following the process described in Algorithm 1.

Algorithm 1 Solution Procedure

for $e \in$ `Set of coordinating Entities` **do**
  Solve the GVA model for e.
  Define which vaccines to produce
  Define vaccine quantities sold to each market segment
  Define upper and lower price bound per vaccine dose.
  for $b \in$ `Set of Vaccines to be bought` **do**
    if `Adjusted policy` **then**
      Annuity to be met for $b \leftarrow$ Annuity to be met for b - revenue obtained from selling $b \in B$ to $e \in E$
    Adjust supply of $b \leftarrow$ Quantity of b purchased by e
Generate output metrics.

3.3. Output Metrics

Across the experiment scenarios, we monitor the profits for producers, savings for countries grouped into market segments, and the aggregate measure of those two values, which corresponds to the total social surplus. Savings for a vaccine correspond to the difference between the reservation prices in each market segment, and its optimal prices, respectively. Given that the price countries are willing to pay is randomized for each experimental scenario, the dollar value of the global vaccine market is also random. Hence we normalize our metrics over the Market Value of each experimental instance. We also track the number of producers who do not cover annualized fixed costs for the vaccines they produce, as well as the number of times in which a market segment does not satisfy all of its vaccine demand. The number of unvaccinated children is monitored relative to the total population at each experimental scenario.

The proposed metrics help illustrate how affordable vaccines are in each experimental scenario while keeping track of the savings of each market segments. Similarly, we monitor how much profit producers obtain, and if individual producers facing negative profits. Table 5 summarizes the set of metrics used in this study.

Metric	Description	Mathematical Expression
Total Customer Surplus (TCS)	Savings received from the vaccine procurement of all market segments of all coordinating entities	$\sum_{e\in E}\sum_{b\in B}\sum_{m\in M}(R_{bm}-Y_{bm})X_{bm}$
Market Value (MV)	The total monetary value in the vaccine market. Sum of all customer savings and all profit.	$TCS+\sum_{e\in E}(X_{bm}Y_{bm}-C_b g_b)$
TCS/MV	Total customer surplus across all entities as a fraction of the market value, at the lowest vaccine prices.	TCS/MV
TPF/MV	Total profit across all entities as a fraction of the market value, at the highest vaccine prices.	$\sum_{e\in E}\left(\frac{\sum_{b\in B}\sum_{m\in M}(X_{bm}.Y_{bm}-C_b g_b)}{MV}\right)$
TSS/MV	Total social surplus across all entities as a fraction of the market value	$\sum_{e\in E}\left(\frac{\sum_{b\in B}\sum_{m\in M}(X_{bm}.R_{bm}-C_b.g_b)}{MV}\right)$
UD_{am}	Unsatisfied demand for antigen $a\in A$ in market segment $m\in M$. Difference between antigen demand and vaccine volume supplying the antigen in a given market	$d_{am}l_m-\sum_{b\in B1_a}X_{bm}$
unimmunized children	Number of combinations of times some antigen demand goes unmet in any market and entity.	$\sum_{e\in E}\sum_{m\in M_e}\sum_{a\in A}(1:UD_{am}\geq 0)$
% of unsatisfied antigen demand	Percentage of antigen demand across all antigens, markets and coordinating entities that is not covered in a given scenario.	$\frac{\sum_{e\in E}\sum_{a\in A}\sum_{m\in M_e:UD_m\geq 0}UD_m}{\sum_{e\in E}\sum_{a\in A}\sum_{m\in M_e}d_{am}l_m-\sum_{b\in B1_a}X_{bm}}$
Net result from producer p (NR_p)	Difference between the annualized fixed costs of vaccines manufactured by a producer p and the revenue obtained by producer from vaccine sales across all markets and coordinating entities.	$\sum_{b\in B}C_b.g_b-\sum_{e\in E}\sum_{m\in M_e}X_{bm}Y_{bm}$
Producers with financial losses	Number of producers whose revenue is not enough to cover the return on investment for the vaccine products they sell.	$\sum_{e\in E}\sum_{p\in P:NR_p\geq 0}1$
% of losses relative to annuity	Percentage of the annualized costs that are not covered by revenue obtained from sales to all markets and entities per scenario	$\frac{\sum_{p\in P:NR_p\geq 0}NR_p}{\sum_{b\in B}\sum_{m\in M}X_{bm}.Y_{bm}}$

Table 5 **Variables used as performance metrics and their explanations.**

4. Results

This study considers a vaccine market consisting of 14 producers offering 52 vaccine products to satisfy 6 different antigen demands (see Table 6); 194 countries are grouped by their GNI per capita into market segments for tier-pricing purposes. Rather than having only the usual 4-tier market segmentation (i.e., high-income, upper-middle-income, lower-middle-income and low-income countries based on the World Bank classification [7]), we group countries in either 2, 4, 8 or 12 market segments (see Table 7). Consequently, each vaccine has a different reservation price per market segment, depending on the selected segmentation of the global vaccine market. Without loss of generality, in this study all variations of diphtheria-tetanus-pertussis vaccines and all polio vaccines offer the same type of antigens, and are represented by DTP and IPV, respectively.

Metrics collected for each of the 60 experimental scenarios are compared with a benchmark in which all market segments receive procurement recommendations from a single coordinating entity. Hence, there is a different one-entity benchmark for each number of market segments in which

Producer	Vaccine	Antigens
1	6	HepB
	41	DTP, HepB and Hib
2	20	IPV
3	1	DTP
	7	HepB
	32	DTP and HepB
	42	DTP, HepB and Hib
4	2	DTP
	43	DTP, HepB and Hib
5	8	HepB
	14	Hib
6	3	DTP
	9	HepB
	15	Hib
	21	IPV
	25	MMR
	29	V
	33	DTP and HepB
	38	DTP and IPV
	44	DTP, HepB and Hib
	49	DTP, HepB and IPV
	51	DTP, HepB, Hib and IPV
7	10	HepB
	45	DTP, HepB and Hib
8	11	HepB
	16	Hib
	26	MMR
	30	V
	39	HepB and Hib
	40	MMR and V
9	17	Hib
	35	DTP and Hib
10	46	DTP, HepB and Hib
11	4	DTP
	18	Hib
	22	IPV
	27	MMR
	31	V
	36	DTP and Hib
	50	DTP, Hib and IPV
	52	DTP, HepB, Hib and IPV
12	5	DTP
	12	HepB
	19	Hib
	23	IPV
	28	MMR
	34	DTP and HepB
	37	DTP and Hib
	47	DTP, HepB and Hib
13	13	HepB
14	24	IPV

Table 6 Vaccines produced by each manufacturer and the antigens they offer. (Hib= Haemophilus influenzae type B, DTP= Diphtheria-Tetanus-Pertussis, Hep=Hepatitis (A or B), V=varicella, MMR=Measles-Mumps-Rubella, IPV= inactivated polio

countries have been grouped (i.e., 2, 4, 8, or 12). The benchmark mimics a system in which there is no need to follow any procurement order, nor adjust the recovery of the annualized fixed costs.

For clarity and brevity, and without loss of generality, this section primarily contrasts the results collected for experimental scenarios with countries grouped in 12 and 4 market segments. Results for scenarios with 2 and 8 market segments are available in Appendix **??**, and ratify the trends described in this section.

First, Figure 1 illustrates the Total Social Surplus as a fraction of the dollar value of the global market ($\frac{TSS}{MV}$) for each experimental instance. Figures 2 and 3 illustrate respectively the Total Customer Surplus ($\frac{TCS}{MV}$) and Total Profit ($\frac{TPF}{MV}$) for the set of vaccine prices that maximize savings (high prices) and profit (low prices), respectively, for the procurement plans that offer the highest $\frac{TSS}{MV}$ for each experimental instance.

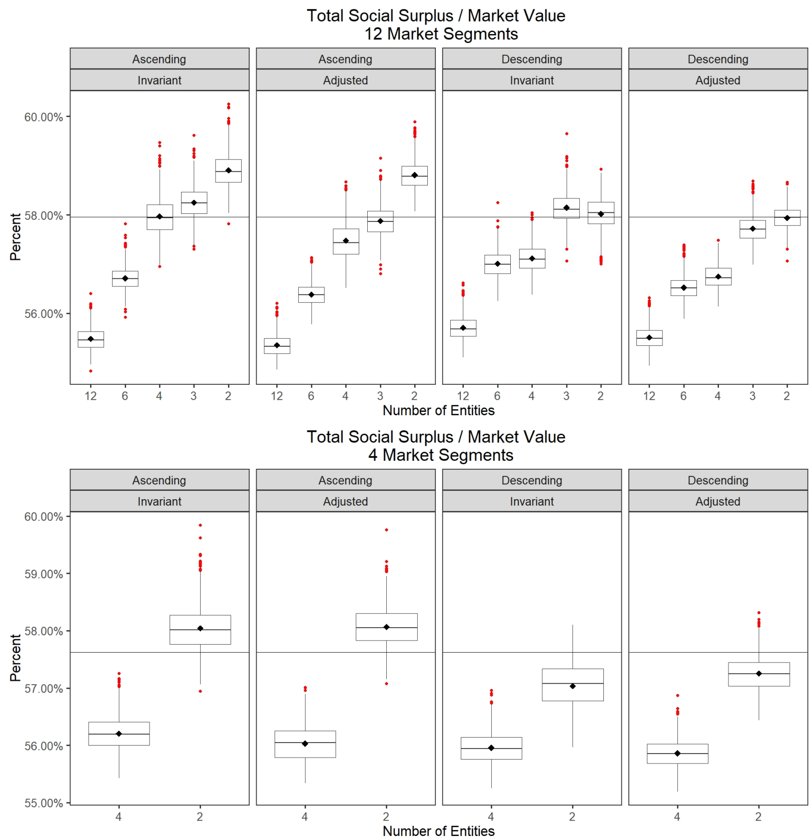

Figure 1 **Aggregated $\frac{TSS}{MV}$ in the global vaccine market for experimental scenarios with 12 and 4 market segments, for a varying number of coordinating entities, different procurement priorities orders, and different choices for the fixed cost recovery policy. For all scenarios, $\frac{TSS}{MV}$ increases as the number of entities decreases. Other factors have smaller impact.**

Figures 4, 5, 6 and 7 illustrate the $\frac{TCS}{MV}$ at high and low prices for countries that under the World Bank classification are considered low-income (LIC), lower-middle-income (LMIC), upper-middle-income (UMIC), and high-income (HIC). Similarly, Figures 8, 9, 10 and 11 illustrate the revenue as a fraction of the MV at high and low prices for the market segments of interest. The revenue from sales is used as a proxy for the TPF to facilitate comparison given that for scenarios with more than one market entity, the allocation of profit to each entity cannot be made until the end of the procurement cycle.

Figure 1 shows that total social surplus ($\frac{TSS}{MV}$) increases as the number of coordinating entities decreases, or equivalently, as the number of market segments handled by each entity increases (since the number of market segments is equally distributed by the number of entities in each experiment.) The $\frac{TSS}{MV}$ when countries are grouped into 4 market segments show similar trends with two exceptions: the $\frac{TSS}{MV}$ is not always better than the benchmark when the number of market segments per entity is one, and when the procuring order is based on 'ascending' income. These results illustrate that the $\frac{TSS}{MV}$, and hence the global market's aggregated affordability and profit

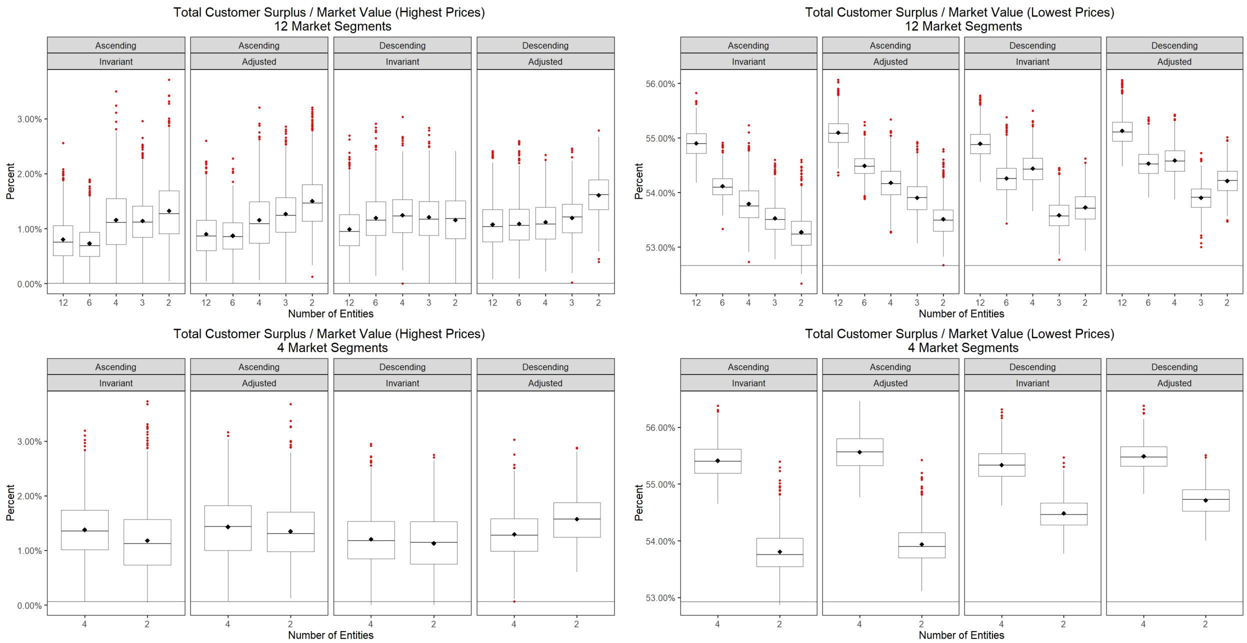

Figure 2 Aggregated $\frac{TCS}{MV}$ in the global vaccine market for experimental scenarios with 12 and 4 market segments, resulting from grouping countries in a varying number of coordinating entities, different procurement priorities, and choice of fixed cost recovery policy. $\frac{TCS}{MV}$ increases as the number of entities increase. Other factors have a smaller impact.

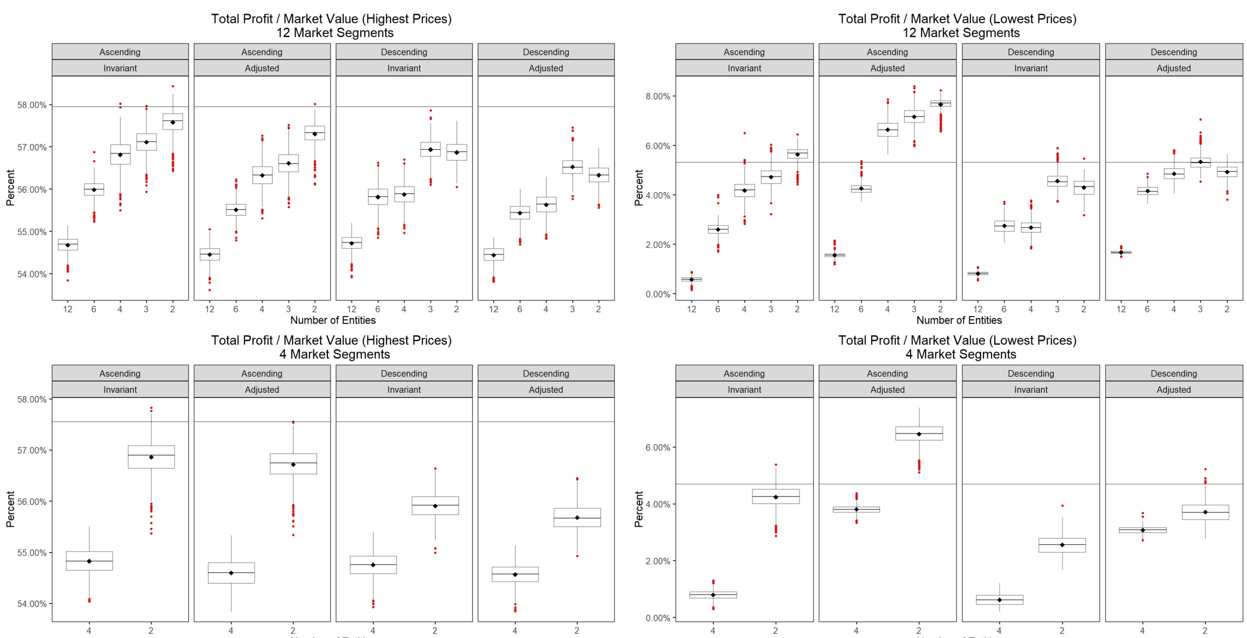

Figure 3 Aggregated $\frac{TPF}{MV}$ in the global vaccine market for experimental scenarios with 12 and 4 market segments resulting from grouping countries in a varying number of coordinating entities, different procurement priorities, and choice of fixed cost recovery policy. $\frac{TPF}{MV}$ decreases as the number of entities increase. Other factors have a smaller impact.

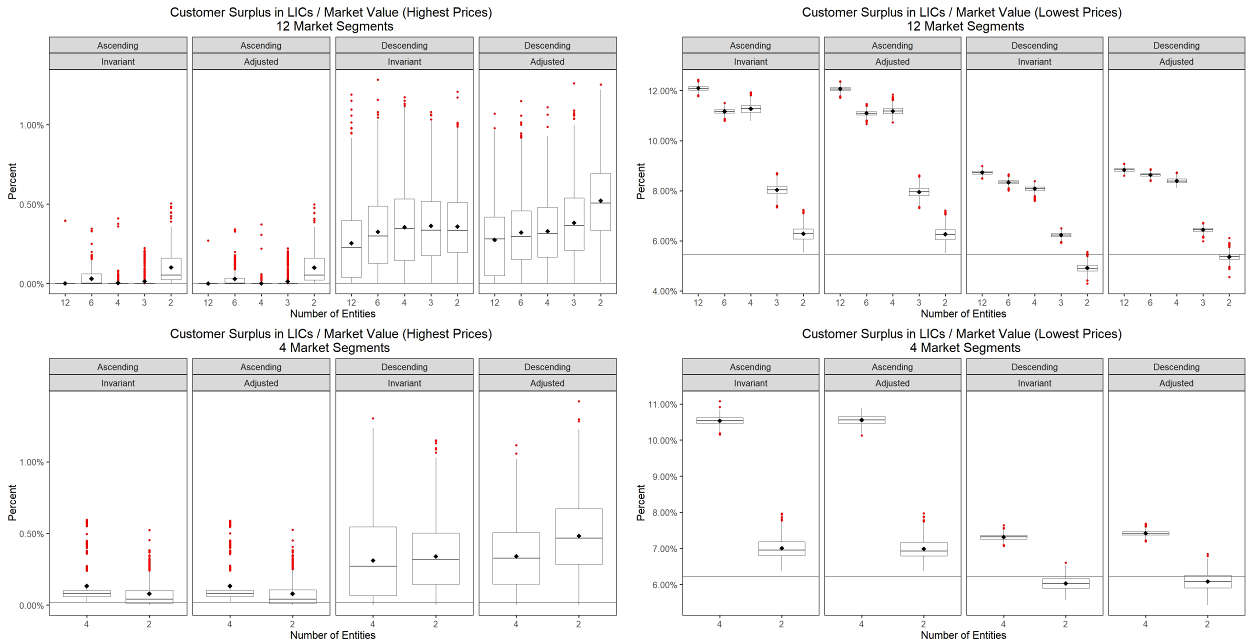

Figure 4 $\frac{TCS}{MV}$ **for low-income countries (LIC) at low and high prices for scenarios with 12 and 4 market segments. At least affordable prices (high prices),** $\frac{TCS}{MV}$ **for LIC improves as the number of entities decreases. Descending priority provides overall better results at the highest price levels than at low prices levels, suggesting interaction between the two. The adjusted cost recovery policy also seems to generate better results in most scenarios.**

expand when the market is more cooperative (i.e., fewer coordinating entities), while entities leverage on tier pricing opportunities by coordinating multiple market segments.

Figure 2 shows that the most significant total customer surplus ($\frac{TCS}{MV}$) occurs for the lowest prices, increasing affordability when there are more entities, or equivalently when the number of market segments per entity decreases. Additionally, there is little difference in total customer surplus resulting from adopting an 'adjusted' or 'invariant' policy to recover the fixed cost annuities, or from ordering the coordinating entities in an 'ascending' or 'descending' manner. At the highest prices, the total customer surplus captures less than 2% of the market value and shows a mild improvement trend when the number of coordinating entities decreases, especially with 12 market segments.

Figure 3 shows that under high prices and a market configuration of 12 markets segments, the profitability ($\frac{TPF}{MV}$) increases as the number of coordinating entities decreases or as the number of markets per entity increases. Scenarios following 'ascending' procuring policy dominate those following a 'descending' policy. Similar trends exist for changes in $\frac{TPF}{MV}$ for scenarios under most affordable prices for 12 and 4 markets. However, in these cases, the profit as a fraction of the global market value (MV) is lower than 10%.

Under high prices, low-income countries (LIC) can ensure a small customer surplus, between 0 and 2% of the MV, as the prices paid per dose are the closest to their stated reservation prices. However, at low prices, their customer surplus can be as high as 12% of the MV. Figure **??** shows that at

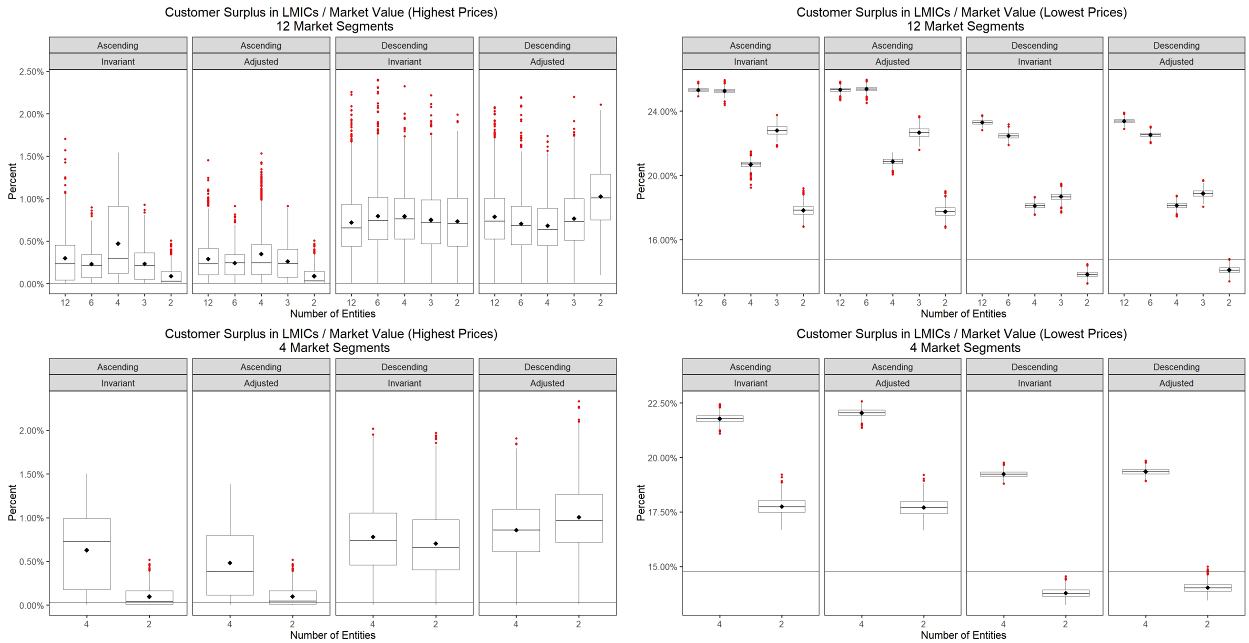

Figure 5 $\frac{TCS}{MV}$ **for lower-middle-income countries (LMIC) for scenarios with 12 and 4 market segments. At the least affordable prices (high prices),** $\frac{TCS}{MV}$ **for LMIC is higher following an adjusted cost recovering policy. At the most affordable prices (low prices),** $\frac{TCS}{MV}$ **for LMIC improves as the number of coordinating entities increases.**

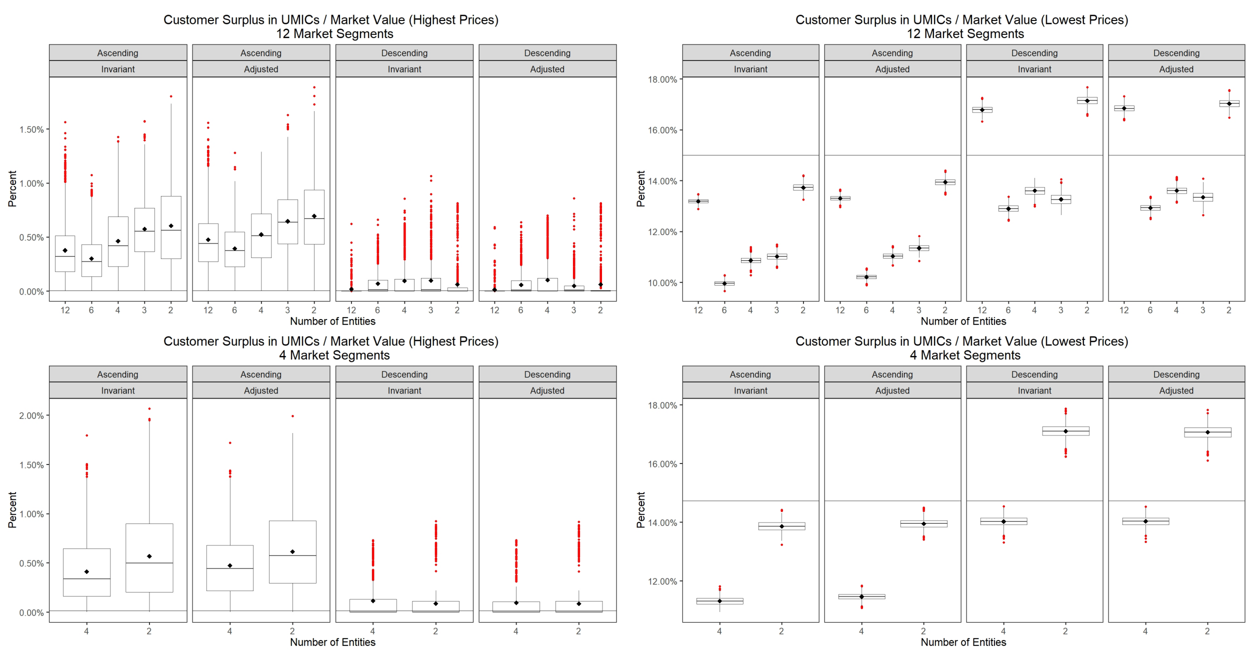

Figure 6 $\frac{TCS}{MV}$ **for upper-middle-income countries (UMIC) at high and low prices for scenarios with 12 and 4 market segments.** $\frac{TCS}{MV}$ **for UMIC at high prices improves with a lower number of coordinating entities. The ascending procuring order tends to generate higher affordability for UMIC. At low prices there is higher variability.**

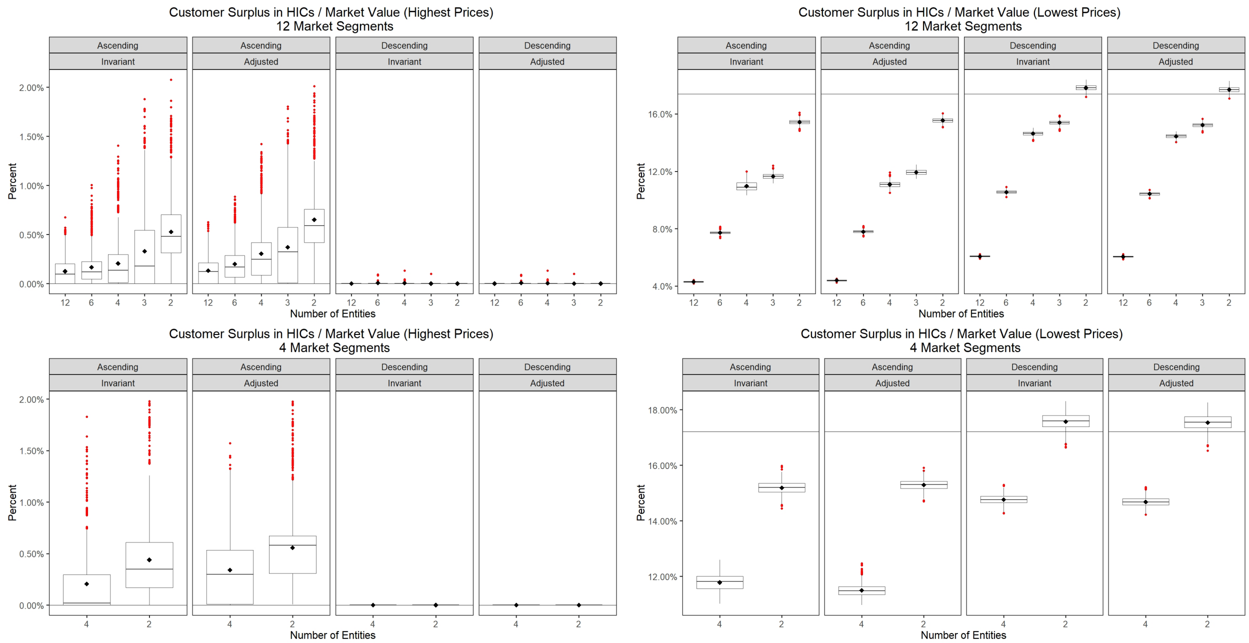

Figure 7 $\frac{TCS}{MV}$ **for high-income countries (HIC) for scenarios with 12 and 4 market segments at high and low prices. At the most affordable prices affordability decreases as the number of coordinating entities increases.**

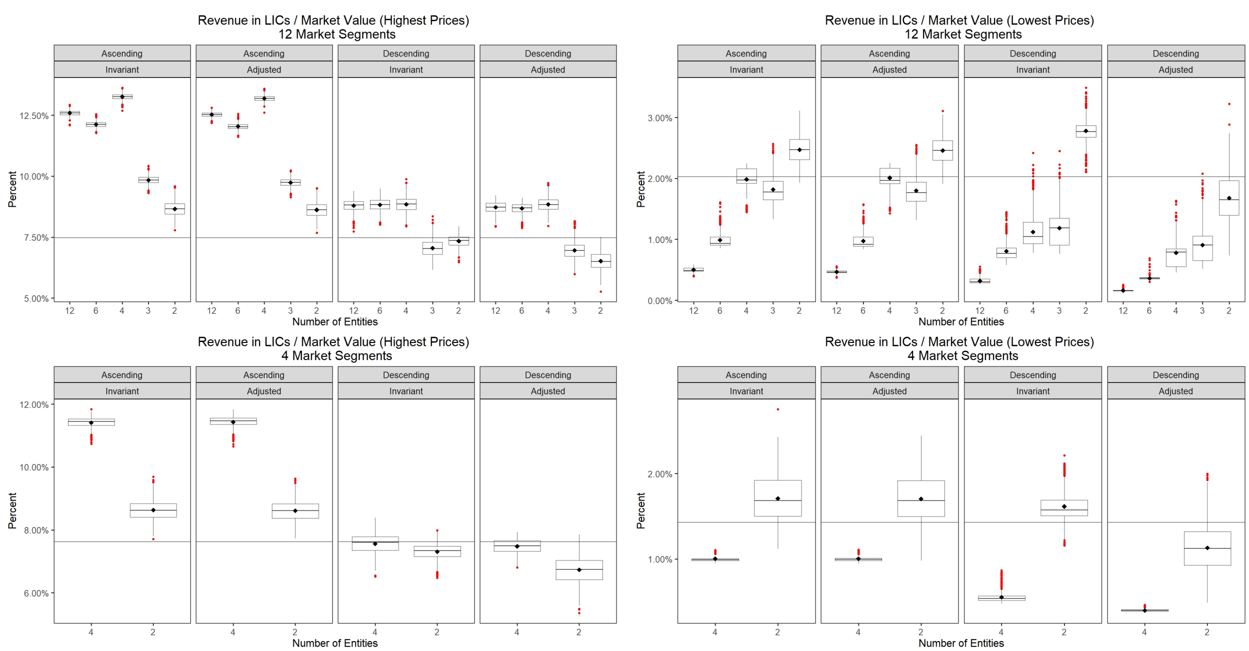

Figure 8 **Revenue obtained from sales to low-income countries (LIC) across all experimental scenarios for 12 and 4 market segments. At the most profitable prices (high prices) revenue increases as the number of coordinating entities increases. This situation is reversed when using the least profitable prices (low prices). The ascending priority order dominates the descending order for LIC.**

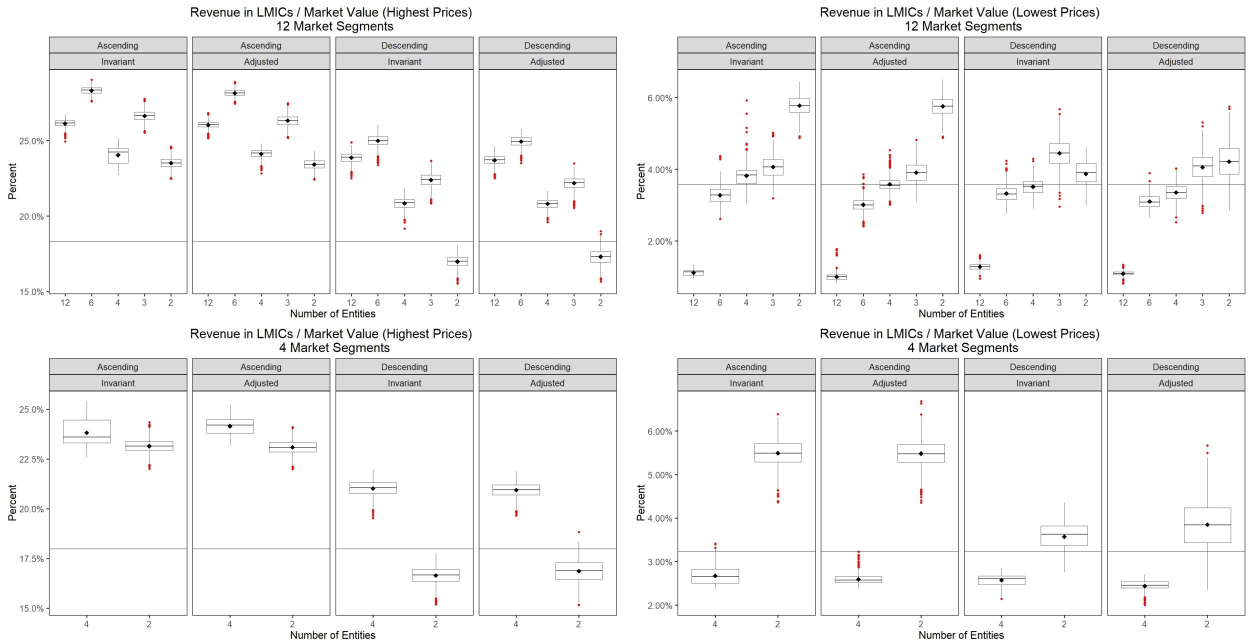

Figure 9 Comparison between the revenue obtained from lower-middle-income countries across experimental scenarios with 12 and 4 market segments. At high prices and ascending order, revenue generally dominates descending order scenarios. Revenue at high prices from sales to LMIC increases with the number of coordinating entities.

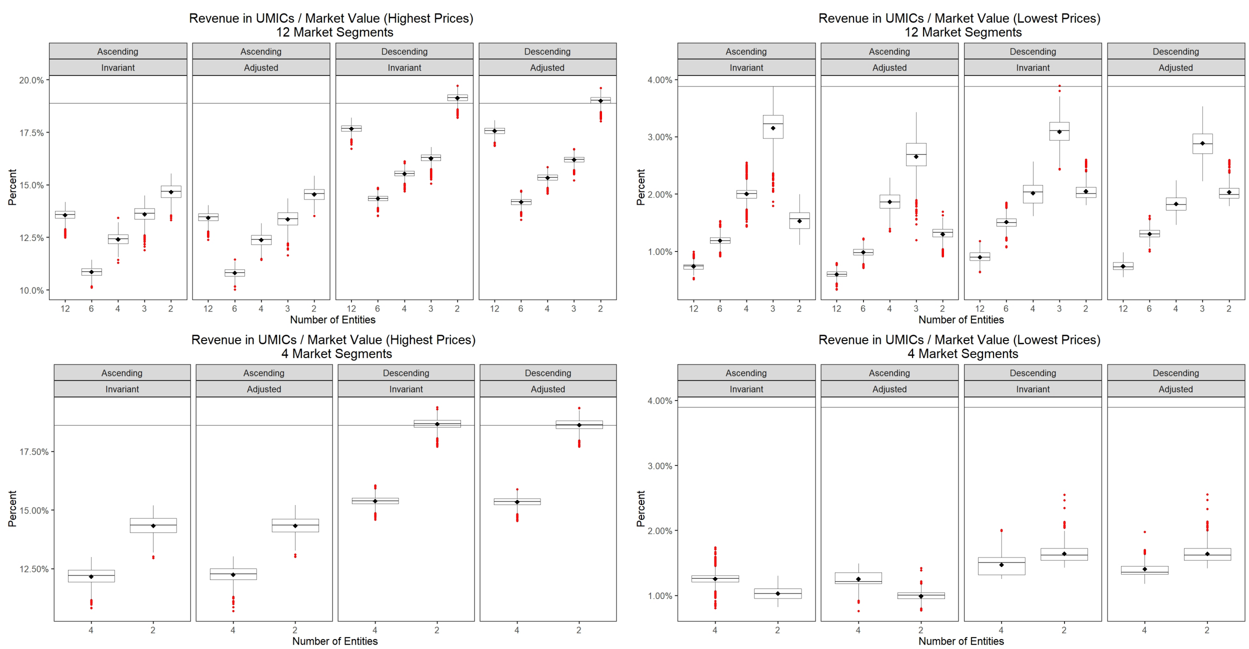

Figure 10 Revenue from sales to upper-middle-income countries (UMIC) across experimental scenarios with 12 and 4 market segments. At high price levels, revenue decreases as the number of entities increases. A descending priority procuring order offers higher revenue from sales to UMIC than an ascending order.

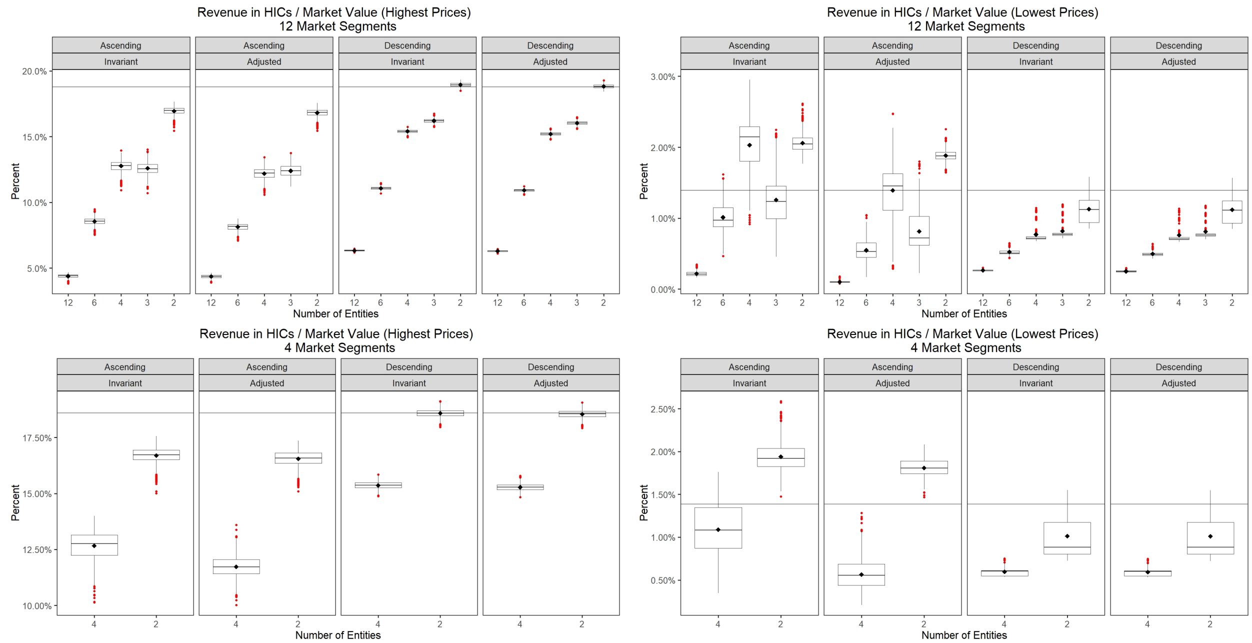

Figure 11 **Revenue from sales to high-income countries (HIC) across scenarios with 12 and 4 market segments. Revenue declines for an increasing number of coordinating entities.**

low prices, customer surplus for countries in low-income market segments decreases as the number of entities decrease, or equivalently, as the number of market segments per coordinating entity increases, especially when entities follow an 'ascending' procuring order. This behavior is the same as the one observed when considering the customer surplus across all markets. A complimentary trend is observed in Figure 8, which shows that at high prices, higher revenue can be extracted from LICs as the number of coordinating entities decreases. However, the growth in revenue at most profitable prices can be as high as 13% of the MV, while the revenue at low prices for LIC is lower than 2% on average. When the number of coordinating entities is low (the number of markets each entity supports increases). Entities favor generating affordability for markets with higher saving opportunities, which are markets segments with higher reservation price values (i.e., HIC and UMIC).

The trends for the customer surplus and revenue generated for lower-middle-income countries (LMIC) are the same as for LIC (See Figure 5 and 9.) However, the customer surplus that can be extracted at low prices for LMIC can be more than double of those extracted for LIC. LMIC can also maximize their affordability at low prices by increasing the number of coordinating entities and by following an ascending procurement priority.

Figures 6, 7, 10, an 11 show that for upper-middle- and high-income countries (UMIC and HIC, respectively) affordability at high prices is null, as the optimal procurement plans requires vaccines to be sold at reservation prices for those markets, especially under a descending procuring order. On

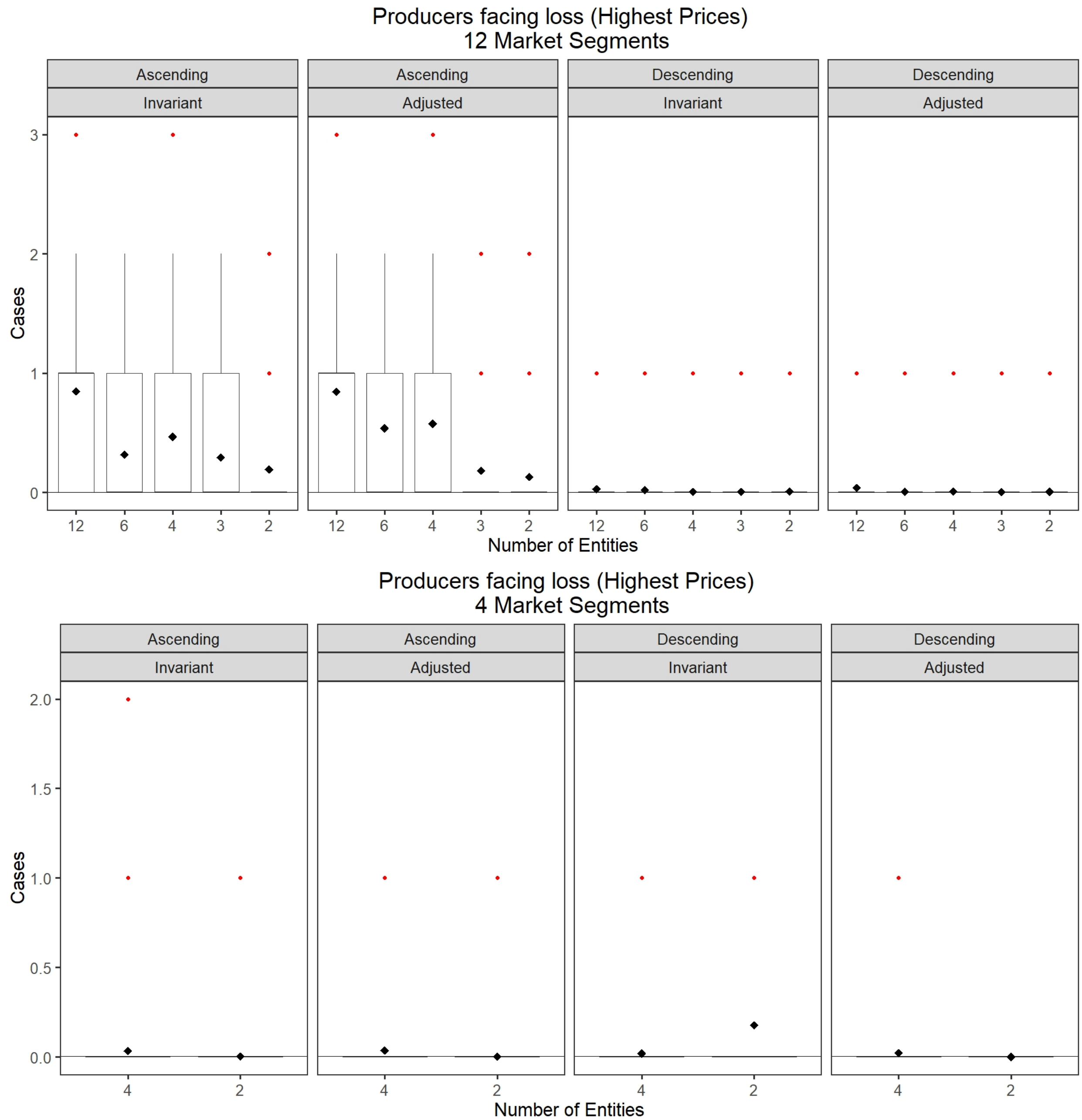

Figure 12 **Number of producers facing losses across all experimental scenarios.**

the contrary, at low price levels, customer surplus increases by having fewer coordinating entities. The gains in affordability are on average below 1% of the MV at high prices, yet at low prices, they can be significant.

The revenue in UMIC and HIC increases at high prices by having less coordinating entities, or by assigning a larger number of markets to each entity and by following a descending procurement policy.

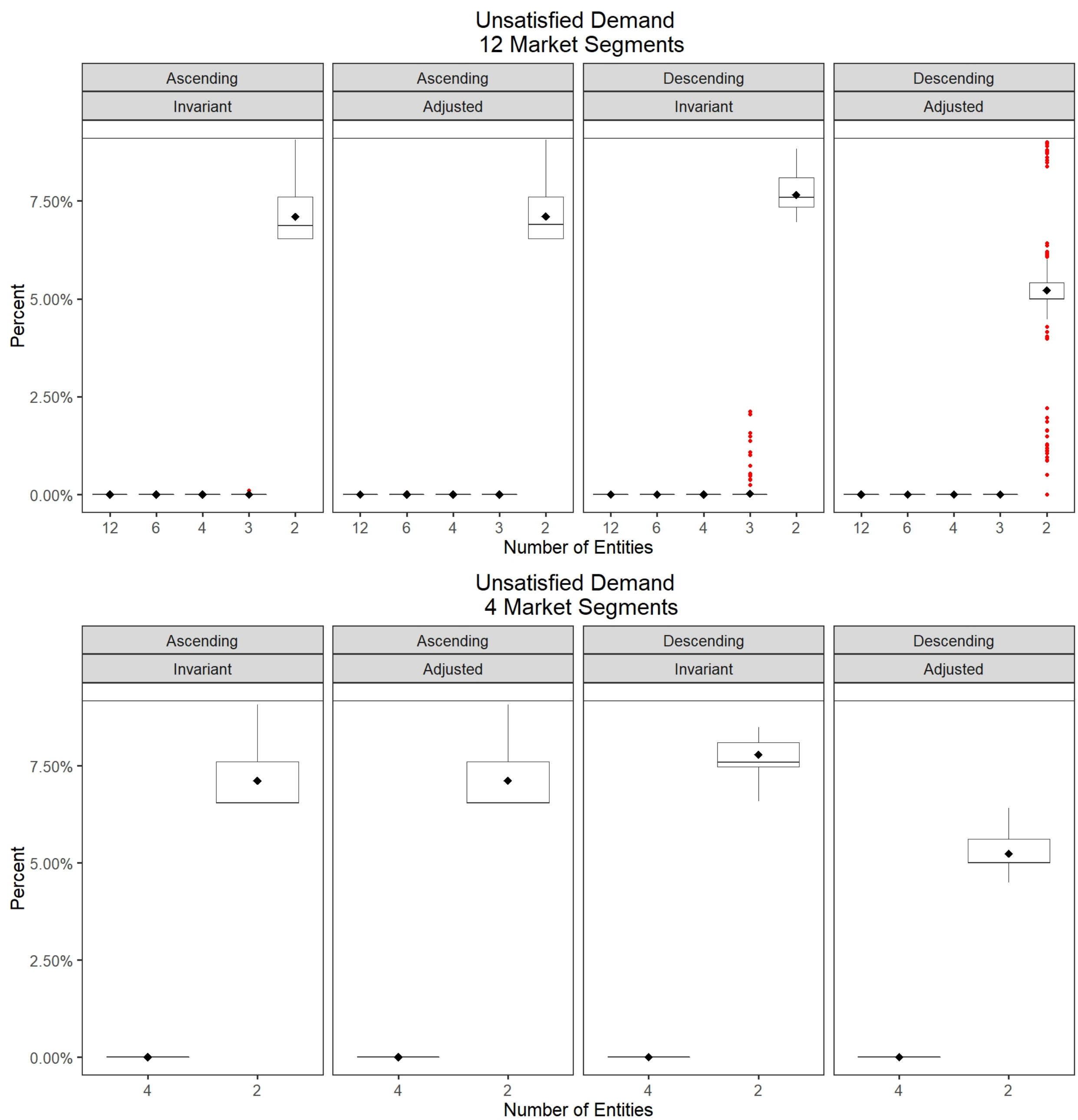

Figure 13 **Unsatisfied antigen demand across experimental scenarios with 12 and 4 market segments.**

Figure 12 shows that it is easier to ensure ROI for producers if a descending procuring order is followed. Figure 13 shows that it is easier to meet antigen demands when the number of market segments per coordinating entity is low.

5. Conclusions

Results suggest that under a non-cooperative vaccine market, there are opportunities to concentrate affordability on LIC and LMIC and generate profit from sales to UMIC and HIC to enhance global market sustainability, while maintaining affordable prices for all countries regardless of their income level. When considering multiple coordinating entities, results at the lowest profitable prices suggest that affordability for low-income countries can be more easily improved when there are more coordinating entities. This arrangement also allows for more of the demand to be covered, and hence potentially increasing coverage. However, producers see lower profit levels when negotiating with multiple coordinating entities, mostly due to a revenue decrease from upper-middle-income countries (profit from sales to LIC increase). This suggests that the value generated by higher-income countries falls at a faster rate than the revenue increase from low-income countries. The results using the highest profitable prices suggest that while some fragmentation in the market is always beneficial, the optimal amount of cooperation may change depending on the final negotiated price.

Additionally, comparing the fixed costs recovering policies, if producers decide to adjust their annuity based on the volume of vaccines that have already been sold, affordability and profits are not significantly improved. However, maintaining an 'invariant' policy better distributes the profits so that fewer producers face losses, suggesting the 'adjusted' policy is not effective in recovering the annuity of unsold vaccine supply. Furthermore, ordering the entities by descending GNI helps prevent losses.

The trends in figures 4 to 11 suggest that to increase customer surplus while guaranteeing a desired profit level for the producers, the vaccine market should organize low- and lower-middle-income countries into more non-cooperating entities, and high- and upper-middle-income countries in fewer coordinating entities. This is a different organization to what is currently seen in the market, in which lower-income countries are the ones organized into fewer coordinating entities while higher-income countries negotiate independently.

This study opens several avenues for extensions. It is unknown whether the results hold when grouping market segments into coordinating entities through criteria other than income per capita. Other criteria might also be applied when prioritizing coordinating entities in the negotiation order, foremost among them the population numbers.

This study solely shares insights from an academic experiment that assumes that all procuring entities aim to buy vaccines affordably, and yet trying to ensure that producers obtained the desired return on their sales. Under this hypothetically altruistic buying, there are opportunities to enhance affordability. The effort to implement the proposed vaccine procurement mechanism will require that all decision-makers act as coordinating entities have access to a system that allows them to determine optimal procurement plans, but most importantly of establishing a consensus that allows coordinating entities to buy following the recommended order. The challenge to determine the incentives to induce such consensus is not trivial and are beyond the scope of this study.

6. Appendix A: Other Figures

All figures generating during the study have been uploaded to the GitHub repository at https://github.com/ba8641/ME_General.git.

Total Markets	Market segment	Countries
12	1	1 to 5
	2	6 to 26
	3	27 to 57
	4	58 to 65
	5	66 to 75
	6	76 to 109
	7	110 to 113
	8	114 to 134
	9	135 to 158
	10	159 to 172
	11	173 to 191
	12	192 to 194
8	1	1 and 2
	2	3 to 57
	3	58 to 65
	4	66 to 109
	5	110 to 123
	6	124 to 158
	7	159 to 180
	8	181 to 194
4	1	1 to 57
	2	58 to 109
	3	110 to 158
	4	159 to 194
2	1	1 to 131
	2	132 to 194
1	1	1 to 194

Table 7 Countries grouped into each market segment considered in the experiments discussed in this paper

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