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Solving Vaccine Pricing Models Considering Quantity Discounts and Equity Using Global Optimization Methods

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Abstract

This study employs global optimization techniques to examine optimal vaccine pricing strategies that consider quantity discounts and vaccine distribution equity, under centralized procurement by group purchasing organizations. Based on the economic characteristics of the vaccine market, a mathematical programming model incorporates the payment capacities and willingness to pay of different member countries, minimizing the maximum adjusted price disparities across pricing tiers and thereby enhancing the overall fairness of vaccine distribution. To further reduce computational complexity and enhance practical applicability, this study improves the model by reducing the number of binary variables. Experimental analysis is conducted using real-world data from the Vaccine Alliance (Gavi) and the Pan American Health Organization (PAHO). The results show that the improved model reduces computation time by over 30% on average and demonstrates effective control over price differentiation across various pricing tiers and parameter settings.

Keywords: vaccine pricing; discounts; equity; mixed integer programming

MSC: 90C11

1. Introduction

Vaccination is one of the most effective public health tools to prevent infectious diseases. Improving global access to vaccines to reduce infectious diseases equitably is critical to achieving UN Sustainable Development Goal 3: ensuring healthy lives and promoting well-being for all ages [1]. Since the outbreak of COVID-19 in 2019, global emphasis on vaccines has significantly increased. By the end of 2023, COVID-19 vaccines had become part of routine immunization programs. The widespread availability and importance of vaccines far exceed individual self-protection; their greater value lies in the public health benefits of herd immunity. Sulayman et al. [2] demonstrate that imperfect vaccines can still effectively reduce tuberculosis transmission when both efficacy and coverage are sufficiently high. Herd immunity can only be achieved if vaccination rates and vaccine performance together surpass a critical threshold. According to the Centers for Disease Control and Prevention (CDC) of the Ministry of Health and Welfare, herd immunity refers to the situation where a sufficient proportion of the population is vaccinated, thereby preventing the spread of disease in the community. Even those who are not vaccinated can receive indirect protection due to a reduced risk of infection. However, achieving herd immunity requires high vaccination rates to protect high-risk groups who cannot be vaccinated, including newborns, those with weakened immune systems, and those

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with chronic diseases. Therefore, governments and international organizations worldwide consider increasing vaccine coverage a top priority in public health to ensure overall social stability and health. According to the World Health Organization (WHO), as of 2023, more than 14.5 million children globally had missed all vaccination opportunities due to various reasons; the phenomenon of zero-dose children highlights the significant challenges that vaccination still faces globally [3].

However, the key to improving vaccine accessibility lies in setting reasonable and fair prices. Vaccine pricing involves multiple factors, including direct costs, national economic conditions, and income inequality, posing challenges to pricing decisions. Currently, vaccine procurement is often conducted through Group Purchasing Organizations (GPOs). While the previous literature has proposed various group procurement and pricing methods, this study employs mathematical programming models to explore different pricing strategies, aiming to achieve a faster and more equitable pricing approach, particularly in ensuring equitable access to vaccines in developing countries and promoting global health justice.

This study will provide an optimal pricing strategy for centralized vaccine procurement through group organizations, considering both order quantity discounts and the fairness of vaccine allocation, to ensure the fair distribution of vaccines to each member (country) within the organization. Considering the economic characteristics of the vaccine market, a mixed-integer programming model is employed to incorporate the affordability and willingness to pay of each member organization for tiered pricing, thereby minimizing the maximum difference between adjusted prices at each tier and improving the overall fairness of vaccine allocation. The mathematical model clearly defines the appropriate vaccine price for each member organization to meet the fairness requirements. Furthermore, to reduce the complexity of solving the mathematical model and enhance its practical application, this study improves the model by employing an efficient global optimization technique, reducing the number of constraints and binary variables, and shortening computation time. This study utilizes real data from two vaccine collective purchasing organizations, the Vaccine Alliance (Gavi) and the Pan American Health Organization (PAHO), to conduct experimental analysis and illustrate how optimal pricing strategies can effectively allocate vaccines to their members. The results show that the adopted mathematical model demonstrates a stable and practical ability to adjust price differences under different price levels and parameter settings. The improved model constructed in this study can not only be used for vaccine pricing and allocation decisions but also has good scalability and cross-situational application value, making a substantial contribution to promoting global vaccine equity and improving the efficiency of public resource allocation.

The rest of this research is structured as follows. A complete literature review on vaccine pricing is detailed in the next section. Section 3 explains the research methods. Section 4 presents the experimental analysis results and discusses the differences in different vaccine pricing strategies. A sensitivity analysis is also conducted to investigate the impact of the purchasing power parameter and the total philanthropic donation budget on adjusted vaccine prices. Finally, Section 5 contains the research conclusions and suggestions for future related research.

2. Literature Review

2.1. Overview of the Global Vaccine Market

The global vaccine market has experienced rapid growth in recent years. The World Health Organization (WHO) released the 2019 Global Vaccine Market Report, which analyzed the demand, supply, and pricing mechanisms of the vaccine market [4]. This initiative, launched by the WHO in 2018 as the MI4A (Vaccine Access to Market Information) policy,

aims to enhance global understanding of the current state of the vaccine market, thereby promoting equitable access to vaccines. Following the rapid outbreak and evolution of the COVID-19 pandemic, the WHO released the 2022 Global Vaccine Market Report [5], which reflected the health of the vaccine market and identified areas for improvement, particularly in achieving an equitable distribution of vaccine supply in response to emergencies such as pandemics.

The WHO recently released its 2023 Global Vaccine Market Report [6]. Analysis of data from WHO member states shows that middle-income countries purchased 60% of global vaccines, accounting for only 34% of the market value. In contrast, high-income countries, which account for only 29% of global vaccine sales, control 63% of the market value. One reason for this is that high-income countries tend to purchase more expensive vaccines, often for complex diseases or specific populations such as adults and the elderly. This makes vaccine research, clinical trials, and production more costly, with adult vaccines typically more expensive than pediatric vaccines, thus driving up market value. Another significant reason for the substantial price differences is the collective procurement mechanism employed by international organizations such as UNICEF and PAHO. These organizations, through large-scale bulk purchases, logistics allocation, and long-term supply contracts, have resulted in 80% of vaccines being priced lower than those purchased directly by individual countries. This group procurement model has played a crucial role in reducing vaccine prices and improving affordability and coverage.

In light of the aforementioned uneven distribution and pricing issues under group procurement mechanisms, this study delves into how international organizations can develop a reasonable and fair vaccine pricing mechanism through quantity discounts and pricing strategies when conducting group vaccine procurement. This mechanism aims to ensure that vaccines are distributed globally in an appropriate manner, thereby addressing the imbalance in the global vaccine supply chain.

2.2. Vaccine Pricing Methods

Pricing is the process of setting prices for products or services. In the pricing of medical products, the factors to be considered are far more complex than in other industries. The core issue is how to balance continuous innovation and production of medical products and services while ensuring that users can access the necessary medical resources at an affordable price. According to Seele et al. [7], the use of algorithms for pricing decisions can raise significant ethical concerns. This pricing strategy no longer focuses on traditional cost-based pricing but instead employs a dynamic and automated approach to generate or adjust real-time prices based on market conditions, consumer behavior, and competitor pricing, thereby maximizing profits. However, in the medical product market, the effects of pricing strategies on market fairness are especially critical, as they directly affect human well-being. Therefore, price fairness should take precedence over general economic considerations.

In recent years, the COVID-19 pandemic has led to a global focus on vaccine pricing. Vo et al. [8] used characteristics such as income, place of residence, and risk to differentiate groups and implemented a differentiated pricing strategy based on the group's willingness to pay. Their research showed that high-income groups and urban residents had significantly higher willingness to pay than low-income and rural residents, and individuals with higher risk perception had a stronger demand for vaccines. Furthermore, in a progressive pricing strategy, they suggested setting a lower price initially for a new vaccine to promote market acceptance, and then gradually increasing the price as demand grows and the market stabilizes. Simultaneously, market mechanisms combined with government subsidies can strike a balance between efficiency and fairness, effectively expanding vaccine coverage. By applying multiple pricing strategies and flexibly adjusting prices according

to individuals' willingness to pay for vaccines, vaccination coverage can be improved, ensuring that vaccines are distributed equitably among groups with different income levels and risk profiles.

During outbreaks of various infectious diseases, when vaccine supplies are insufficient, the issue of how to fairly and effectively distribute vaccines becomes a significant challenge faced by countries and organizations [9]. Fairness can generally be divided into two main types: horizontal equity and vertical equity. Horizontal equity emphasizes "equal treatment," ensuring that every group or individual in need has an equal opportunity to obtain resources to meet their needs [10]. Vertical equity, on the other hand, emphasizes "fair treatment of unequal individuals," providing resources in quantities commensurate with individual needs [11,12].

To ensure equitable access to vaccines, Yin et al. [13] emphasize that affordability is a crucial consideration in vaccine pricing decisions. Many countries and regions set price ceilings for vaccines based on their local economic circumstances. Procuring vaccines through international organizations must also consider the differences in affordability and willingness to pay among member states to ensure equitable access to vaccines for all member states, regardless of their capabilities. While uniform pricing simplifies the pricing process, it may still result in low-income countries being unable to afford vaccines at the same price. Tiered pricing, which sets different prices based on the economic capabilities of member states, can promote resource redistribution. For example, while Niger and India both meet the criteria for Gavi support, there are significant differences in their per capita gross national income (a measure of affordability) and government spending on routine immunization vaccines (a measure of willingness to pay). Using a uniform price may not necessarily achieve equitable vaccine access [1].

Furthermore, the supply and demand situation in the vaccine market directly affects its price elasticity. Therefore, vaccine prices are driven not only by costs but also by market demand. At the same time, governments can reduce the economic burden on the public through subsidies or health insurance. Yin et al. [13] argue that countries should make flexible pricing decisions based on a combination of factors, striking a balance between promoting public health and ensuring economic sustainability.

In summary, vaccine pricing is a highly complex and carefully considered decision-making process. When formulating pricing strategies, in addition to considering fundamental economic factors such as production costs, demand elasticity, and supply chain stability, ensuring equitable vaccine access requires incorporating broader influencing factors, including government policies and each country's affordability. These factors are intertwined and combine to form important metrics that influence the final price of vaccines.

2.3. Quantity Discounts

Besides discussing factors related to vaccine pricing, procurement strategies also play a crucial role, with quantity discounts being a common strategy. Specifically, quantity discounts refer to a unit discount applied when the buyer's purchase volume reaches a relative discount range set by the seller. The unit price gradually decreases as the order quantity increases, thereby reducing the buyer's total cost. For the buyer, this improves overall procurement value and efficiency, reducing the additional costs associated with frequent purchases. For the seller, it helps increase the size of individual orders, reduces inventory pressure, and optimizes production capacity, further promoting economies of scale.

According to [14], quantity discounts can be categorized into all-units discounts and incremental discounts. All-units discounts refer to a discount amount set by the seller based on large-volume orders. When the buyer's order quantity reaches a certain level, the

discount is applied evenly to each unit of the total purchase quantity, resulting in a lower price per unit. In contrast, incremental discounts involve the seller dividing the purchase volume into multiple tiers, each with a different unit price. The unit price decreases with each subsequent tier. When the buyer receives a discount, only orders exceeding a certain quantity qualify for the discount; the first few units are charged at the original price, while additional units exceeding the quantity threshold are discounted.

In the context of large-scale vaccine ordering, Group Purchasing Organizations (GPOs) play a crucial role in the healthcare product supply chain. Hu et al. [15] pointed out that GPOs, by aggregating the needs of multiple healthcare institutions and conducting collective bargaining, not only obtain more competitive prices but also reduce contract negotiation costs. For small- and medium-sized institutions or those in remote areas, the scale effect of GPOs can mitigate price inequalities caused by differences in purchasing power, enabling them to enjoy the same product prices and supply conditions as larger institutions. This plays a vital role in stabilizing the supply chain and mitigating the risk of shortages during pandemics. Furthermore, the research [16] on China's group drug procurement policy also confirms that this strategy can effectively lower drug prices, while also saving China's medical insurance fund considerable expenditure. However, the excessive compression of drug prices resulting from this policy has led to drug shortages, affecting patients' continued access to medication and even raising questions and concerns about drug quality.

In summary, collective procurement remains an important and efficient strategy in the healthcare market. This study examines vaccine pricing through group procurement, taking into account quantity discounts for large-scale orders. It has demonstrated significant advantages. However, the potential problems associated with this strategy cannot be ignored, including over-reliance on suppliers, insufficient price transparency, and product quality issues. These issues must be carefully assessed to ensure their long-term sustainability in terms of both public health and economic benefits.

2.4. Vaccine Pricing, Quantity Discounts, and Equity

While Sections 2.2 and 2.3 review vaccine pricing methods and quantity discount schemes separately, an emerging body of literature has examined their joint implications for equity in vaccine access. From a policy and health economics perspective, differential or tiered pricing has been widely discussed as a mechanism to improve affordability across countries with heterogeneous income levels, particularly in the context of essential medicines and vaccines. These studies emphasize distribution fairness and access outcomes, typically relying on conceptual frameworks, descriptive analyses, or cross-country comparisons rather than formal procurement models [17,18].

In parallel, empirical and institutional studies on group procurement mechanisms, such as those operated by Gavi and the PAHO, document how centralized purchasing and volume aggregation can lower prices and expand access, especially for smaller or lower-income buyers [19,20]. While these studies provide valuable evidence on affordability and availability, equity considerations are often discussed qualitatively and are not explicitly operationalized through quantitative indicators.

From an operations research perspective, vaccine procurement has been modeled using optimization and contract-based approaches, including quantity discount schemes designed to reduce procurement costs or coordinate vaccine supply and demand [21,22]. These models typically address vaccine-specific challenges such as demand uncertainty, supply constraints, and coordination across procurement stages. However, they predominantly prioritize efficiency and cost minimization objectives, with limited attention to distributional or equity-related outcomes across heterogeneous vaccine purchasers. Con-

sequently, the interaction between vaccine pricing mechanisms, quantity discounts, and equity considerations remains underexplored in procurement models calibrated to real-world group vaccine procurement data.

This study investigates optimal vaccine pricing in the context of group purchasing organizations, aiming to enhance equitable vaccine accessibility and improve resource allocation efficiency through optimal pricing decisions. Based on the work of Yu et al. [1], this research establishes an optimal pricing model for how social organizations (such as Gavi and PAHO) can set fair pricing strategies for their member countries. Although the existing method exhibits relatively short solution times in the current setting, the formulation remains a mixed-integer linear programming (MILP) problem. As the scope of the problem expands, for instance, the number of participating countries increases, or additional decision variables and constraints are incorporated, the resulting optimization model becomes increasingly complex. Prior studies in optimization theory have shown that the computational effort required to solve such problems may grow rapidly with problem size and can scale exponentially in the worst case, especially when integer decision variables are involved [23,24]. This issue is particularly pronounced in MILP formulations, where the presence of integer variables introduces combinatorial complexity and leads to an exponential growth of the search space under branch-and-bound solution algorithms. Consequently, developing an efficient solution approach is essential to maintain computational tractability and to facilitate future model extensions.

3. Methodology

This study investigates optimal vaccine pricing in the context of group purchasing organizations, aiming to enhance equitable vaccine accessibility and improve resource allocation efficiency through optimal pricing decisions. Based on the work of Yu et al. [1], this research establishes an optimal pricing model for how social organizations (such as Gavi and PAHO) can set fair pricing strategies for their member countries. To improve the model's solution efficiency and practical applicability, this study further simplifies the binary variables in the model, using a faster computational method to derive the optimal vaccine pricing strategy while considering specific factors in different regions, thereby improving vaccine accessibility and resource allocation efficiency.

3.1. Vaccine Pricing Model

This study enhances the efficiency of the mixed-integer programming model proposed by [1], while retaining the symbols and notations used in that model. This model comprehensively considers the payment ability and willingness of different groups, adopting a large-scale centralized procurement model by social organizations to achieve efficient allocation and equitable distribution of vaccine resources. In this study, practical data from international organizations such as Gavi, UNICEF, and WHO were cited as references for pricing decisions, making the model more practical and feasible.

3.1.1. Model Symbols

The model symbols and some subscripts used in this study refer to the notation in the model of Yu et al. [1]. The model's symbolic parameters comprise indices, input parameters, and decision variables. The explanations of each symbol are shown in Table 1 below.

Table 1. Symbols of the pricing model [1].

Class	Symbol	Description
Index	i	Member index, in descending order of ability to pay
	j	Tiered unit price index
Inputs	N	Number of members in the GPO
	ε_i	Price adjustment multiplier applied to member i
	q_i	Order quantity of member i
	Q	Total order quantity across all members
	$C(Q)$	GPO's procurement cost as a function of total order quantity
	f_a	Administrative fee rate charged by the GPO
	γ	GPO overhead rate on total procurement cost
	Π	Maximum number of different price tiers
	E	Total effective procurement costs of the GPO
	B	Total philanthropic donation budget
	G_i	Average government expenditures per newborn per year
	T_i	The total government expenditure on vaccines used in routine immunization
	M	A number that is much larger than any unit price, e.g., $C(Q)$
Decision variables	π_j	the price associated with tier j
	p_i	Price charged to member i, corresponding to only one tier π_j
	z_{ij}	Binary variable, 1 if jth tiered price is charged to member i; 0 otherwise
	r_i	The unit price subsidy for member i (in MIP-Subsidy)

The variables and parameters mentioned above include pricing factors, decision variables, and the costs considered in the procurement process. By combining quantity discounts and fairness factors, the model used in this study will be able to select appropriate pricing strategies based on member characteristics.

3.1.2. Vaccine Pricing Model Without Subsidy

The model proposed by Yu et al. [1] assumes that a group of N members purchase vaccines through a social organization composed of them, and that the members are arranged in descending order based on their ability to pay and indexed as $1, \ldots, N$. In addition to the ability to pay, the model considers differences in willingness to pay. To narrow the gap in perceived price and improve the fairness of perceived price, an adjustment multiplier ε_i is added to calculate the adjusted unit price $\varepsilon_i p_i$ in the objective function. Let δ be the adjusted price disparity, that is, $\delta = \max_i \varepsilon_i p_i - \min_i \varepsilon_i p_i$. The multipliers ε_i are based on each member's willingness to pay. Yu et al. [1] approximates a member's willingness to pay using the average annual government expenditure on vaccines for routine immunization per newborn, denoted as s_i. The price adjustment factor increases as s_i decreases. The multipliers are normalized by assigning the member with the largest government expenditure $\varepsilon = 1$, and the price adjustment multiplier ε_i can be calculated as follows [1]:

$$\varepsilon_i = 1 + \frac{\left(\max_i s_i\right) - s_i}{\max_i s_i - \min_i s_i}, \tag{1}$$

When the willingness to pay of member i decreases, the adjustment multiplier ε_i will increase, reflecting that member i has fewer resources for vaccine expenditures, indicating a lower capacity to pay. Furthermore, ε_i is a relative indicator and does not directly affect the final price; its range is limited to [1,2]. $\varepsilon_i = 1$ is set as the benchmark for the country with the highest willingness to pay, ensuring that price adjustments in other countries are based

on this benchmark. This setting ensures that even for members with the lowest willingness to pay, their adjusted prices will not exceed a particular range.

In the final pricing decision, assume Π is the maximum number of different price tiers that can be charged, and π_j represents the price of the j-th tier. Member i can only correspond to one tier π_j, where j ranges from $j = 1$ to $j = \Pi$. When the condition is met, $z_{ij} = 1$; otherwise, $z_{ij} = 0$. Furthermore, when $\Pi = 1$, a uniform pricing strategy is adopted, meaning all members are subject to the same price; when Π = N, a tiered pricing strategy is adopted, allocating members to different price tiers based on their ability to pay or other differential factors, thus applying different prices.

Furthermore, regarding vaccine procurement, this study assumes that q_i represents the number of vaccines purchased by member i through the GPO, and the total order quantity Q is the sum of all q_i. Since the model introduced by [1] is highly flexible and applicable to various pricing scenarios, this study uses the BCG (Bacillus Calmette-Guérin) vaccine as an experimental case, and the population of member i multiplied by the birth rate is used as the estimation basis for q_i. The cost function $C(Q)$ is a concave function, which can be expressed as $C(Q) = a\left(1 - e^{bQ}\right)$, where a represents the maximum possible cost, meaning that a approaches its maximum value when Q approaches zero while b determines the rate of cost reduction, and the rate of cost reduction gradually decreases as the order quantity increases. Additionally, considering that managing indirect costs is crucial for assessing the organization's actual expenditures and resource usage, the total expenditure of the GPO is expressed as $(1+\gamma)C(Q)$, where γ reflects the overhead rate on total procurement costs. Another factor affecting operating costs is the administrative fee rate f_a charged by the GPO to each member, which is directly applied to the member's additional expenses. Therefore, the total payment for member i is $(1 + f_a)p_iq_i$.

To ensure that the total payments received by a GPO are not less than its total procurement cost E, the following inequality can be constructed:

$$\sum_{i\in N}(1+f_a)p_iq_i \geq (1+\gamma)C(Q) \Longleftrightarrow \sum_{i\in N} p_iq_i \geq E = \frac{(1+\gamma)C(Q)}{(1+f_a)}, \tag{2}$$

The mixed-integer programming model proposed by [1] considers different price tiers and minimizes the maximum difference in adjusted prices between tiers. The concept of adjusted prices is based on willingness to pay, and the adjustment multiplier ε_i is shown in Equation (1). To minimize the maximum difference in adjusted prices between different tiers, the mathematical model of Model 1 is described as follows:

Model 1 [1]:

$$\text{Minimize}(\max_i \varepsilon_i p_i - \min_i \varepsilon_i p_i), \tag{3}$$

subject to:

$$\sum_{i\in N} p_iq_i \geq E, \tag{4}$$

$$p_i \geq p_{i+1},\ \forall i \in \{1,\ldots,N-1\}, \tag{5}$$

$$p_i \geq \pi_j - (1-z_{ij})M,\ \forall i \in \{1,\ldots,N\},\ \forall j \in \{1,2,\ldots,\Pi\}, \tag{6}$$

$$p_i \leq \pi_j + (1-z_{ij})M,\ \forall i \in \{1,\ldots,N\},\ \forall j \in \{1,2,\ldots,\Pi\}, \tag{7}$$

$$\sum_{j=1}^{\Pi} z_{ij} = 1, \forall i \in \{1,\ldots,N\}, \tag{8}$$

$$z_{ij} \in \{0,1\}, \forall i \in \{1,\ldots,N\},\ \forall j \in \{1,2,\ldots,\Pi\}. \tag{9}$$

Constraints (6)–(9) enforce that each price p_i must correspond to exactly one of the tiered prices π_j, by utilizing a binary variable z_{ij}. Member i will be charged π_j if $z_{ij} = 1$. M

is a big positive number. To more clearly illustrate the concept of Model 1, a real-world case study is analyzed using the following hypothetical scenario.

Example 1. *In a BCG vaccine procurement project, assume five countries purchase the vaccine though the GPO, each with different demands and willingness to pay. The total demand (Q) is set to Q = 650, the minimum cost threshold (E) is set to E = 1000, the adjustment multiplier* ε_i *to be between 1.2 and 1.9, and the number of price tiers to* $\Pi = 3$*. After calculation and analysis using the mathematical programming software Gurobi 12.0.1, the model in this study yields the optimal price tiers* $\pi_1 = 1.8196$*,* $\pi_2 = 1.4366$*, and* $\pi_3 = 1.5164$*, accurately assigning each country to the corresponding price tier. Then, after calculation according to the set adjustment multiplier, the adjusted price is obtained. The difference between the highest and lowest prices is 0.90986, significantly reducing the price differences between countries and achieving the goal of balancing price and fairness.*

3.1.3. Vaccine Pricing Model with Subsidy

The previous model, Model 1, does not consider that the GPO might receive the philanthropic donation and sponsorships. Yu et al. [1] also introduce a vaccine pricing model that involves the philanthropic donation. The model aims to improve the fairness of vaccine pricing by incorporating the total philanthropic donation budget. Assume p is the common unit price set by the GPO and r_i is the unit price subsidy for member i; Yu et al. [1] constructed an MIP-Subsidy Model as follows.

Model 2 [1]:

$$\text{Minimize (3)},$$

subject to:

$$p_i = p - r_i \; \forall i \in \{1, \ldots, N\}, \tag{10}$$

$$\textstyle\sum_i r_i q_i \leq B, \tag{11}$$

$$\text{(5)–(9)}.$$

Constraint (11) ensures that the total subsidy does not exceed the total philanthropic donation budget. Constraint (10) defines the unit price that each member pays. The objective function and constraints (5)–(9) remain the same as in Model 1. When $p = (B + E)/Q$, Models 1 and 2 lead to equivalent formulations [1].

In Model 2, to estimate the total philanthropic donation budget (B) for each group, Yu et al. [1] used information on the total effective procurement cost (E), the average government expenditures per newborn per year (G_i), and the average total expenditures on vaccines used in routine immunizations (T_i). Then the following formulation is derived.

$$B = E \times \left(1 - \frac{\sum_i G_i}{\sum_i T_i}\right) \Longleftrightarrow \frac{B}{E} = 1 - \frac{\sum_i G_i}{\sum_i T_i}. \tag{12}$$

To more clearly illustrate the concept of Model 2, a real-world case study is analyzed using the following hypothetical scenario.

Example 2. *In a BCG vaccine procurement project, assume five countries purchase the vaccine though the GPO, each with different demands and willingness to pay. The total demand (Q) is set to Q = 650, the minimum cost threshold (E) is set to E = 1000, and a total subsidy budget B = 500. The adjustment multiplier* ε_i *is between 1.2 and 1.9, and the number of price tiers* $\Pi = 3$*. After solving Model 2 using Gurobi 12.0.1, the optimal price tiers are the same as in Model 1:* $\pi_1 = 1.8196$*,* $\pi_2 = 1.5164$*, and* $\pi_3 = 1.4366$*. The results effectively allocate the five countries to the corresponding price tiers. Country 1 receives no subsidy, while the other four*

countries receive subsidies based on their willingness to pay and demand. Countries 2 to 4 receive 0.30327, and Country 5 receives 0.38308. The subsidy mechanism effectively reduces the payment burden, making the adjusted price more equitable.

3.2. Improved Vaccine Pricing Model

This study improves the Yu et al. [1] models by reducing the number of binary variables, thereby lowering computational complexity and enhancing solution efficiency. Constraint (8) is a special ordered set of type 1 (SOS1) constraint where only one variable can be nonzero. This study adopts the approach for handling SOS1 constraints, as introduced in [25–27], to reduce the number of binary variables in Models 1 and 2. For some j, $1 \leq j \leq \Pi$, j can be expressed as [25]:

$$j = 1 + \sum_{k=1}^{\theta} 2^{k-1} v_k,\ v \in \{0,1\},\ \theta = \lceil log_2 \Pi \rceil. \tag{13}$$

$S^+(k)$: the set composed of all j having $u_k = 1$ in $B(j)$, i.e., $S^+(k) = \{j | u_k = 1 \text{ in } B(j)\}$.
$S^-(k)$: the set composed of all j having $u_k = 0$ in $B(j)$, i.e., $S^-(k) = \{j | u_k = 0 \text{ in } B(j)\}$.
Then, $\sum_{i=1}^{n} v_i = 1,\ v_i \in \{0,1\}$ can be reformulated as [25]:

$$\sum_{j=1}^{n} \lambda_j = 1, \tag{14}$$

$$\sum_{j \in S^+(k)} \lambda_j = v_k,\ k = 1,2,\ldots,\lceil log_2 n \rceil, \tag{15}$$

$$v_{ij} \in \{0,1\}, \forall i \in \{1,\ldots,N\},\ \forall j \in \{1,2,\ldots,\Pi\}. \tag{16}$$

Additionally, this study incorporates $\pi_j \leq \pi_{j+1}$ into this model to restrict $\pi_1 \leq \ldots \leq \pi_{\Pi}$, then the prices of the first and last tiers in this model are not restricted by the upper and lower bounds of the stratified prices. Model 1 can be reformulated as follows.

Model 3:

Minimize (3),

subject to:

(4), (5),

$$\pi_j \leq \pi_{j+1},\ \forall j \in \{1,\ldots,\Pi - 1\}, \tag{17}$$

$$\pi_1 \leq p_i \leq \pi_1 + (1 - z_{i1})M,\ \forall i \in \{1,\ldots,N\}, \tag{18}$$

$$\pi_j - (1 - z_{ij})M \leq p_i \leq \pi_j + (1 - z_{ij})M, i \in \{1,\ldots,N\}, \forall j \in \{2,\ldots,\Pi - 1\}, \tag{19}$$

$$\pi_{\Pi} - (1 - z_{i\Pi})M \leq p_i \leq z_{i\Pi},\ \forall i \in \{1,\ldots,N\}, \tag{20}$$

$$\sum_{j \in S^+(k)} z_{ij} = v_{ik}, \forall i \in \{1,\ldots,N\}, \forall k \in \{1,\ldots,\lceil \log_2 \Pi \rceil\}, \tag{21}$$

$$\sum_{j=1}^{\Pi} z_{ij} = 1,\ \forall i \in \{1,\ldots,N\}, \tag{22}$$

$$v_{ik} \in \{0,1\}, \forall i \in \{1,\ldots,N\}, \forall k \in \{1,2,\ldots,\lceil \log_2 \Pi \rceil\}, \tag{23}$$

$$z_{ij} \geq 0,\ \forall i \in \{1,\ldots,N\}, \forall j \in \{1,\ldots,\Pi\}. \tag{24}$$

The SOS1 constraint (8) in Model 1 is replaced with Constraints (21)–(24) in Model 3, therefore reducing the number of binary variables from $O(\Pi)$ to $O(\log_2 \Pi)$. Constraint (17) in Model 3 is used to restrict $\pi_1 \leq \ldots \leq \pi_{\Pi}$, therefore constrains (6) and (7) in Model 1 can be replaced with constraints (17)–(20) in Model 3. Similarly, Model 2 can be reformulated as follows.

Model 4:

Minimize (3),

subject to:

(5), (10), (11), (17)–(24).

To further explore the solution efficiency of the improved model for larger problems, this study constructs a case of a group procurement of vaccines by 10 members as follows.

Example 3. *In a BCG vaccine procurement project, assume 10 countries purchase the vaccine through the GPO, each with different demands and willingness to pay. The total demand (Q) is set as 1190. The demand of country i (q_i) is set as $q_1 = 100$, $q_2 = 120$, $q_3 = 150$, $q_4 = 80$, $q_5 = 200$, $q_6 = 130$, $q_7 = 140$, $q_8 = 80$, $q_9 = 90$, $q_{10} = 100$.*

Table 2 lists the experimental results of solving Example 3 using Models 1 and 3. Both Models obtain the same objective value, and Model 3 spends about half of the time used by Model 1 to solve the problem.

Table 2. Experimental results of solving Example 3 by Models 1 and 3.

Methods	Model 1	Model 3
Solution time	0.0867 s	0.0439 s
Objective	0.51236	0.51236

4. Experimental Analysis Results and Discussions

This study utilizes the latest global health data for experimental analysis to develop optimal pricing strategies considering quantity discounts and fairness, aiming to improve vaccine accessibility and coverage in low- and lower-middle-income countries. The experimental analysis, based on real-world data from Gavi and PAHO, seeks to evaluate the impact of different pricing schemes on vaccine accessibility and verify the applicability and advantages of mixed-integer programming models in group purchasing scenarios.

4.1. Data Description

Gavi, a global public–private partnership, supports low-income countries in Africa, Asia, and parts of the Americas, dedicated to enhancing vaccine accessibility and improving the efficiency of public health resource allocation. PAHO, on the other hand, is a regional health organization focused on the Americas, using group purchasing mechanisms to reduce vaccine prices and promote the widespread and equitable distribution of vaccines in low- and middle-income countries. Based on global health data up to 2022, this study estimates model parameters for experimental analysis on the Gavi and PAHO groups, with 54 Gavi-eligible and 32 PAHO member countries. Due to the unavailability of data for some countries, the sample sizes for the Gavi group and the PAHO group are $N = 46$ and $N = 28$, respectively, in this study. The data used for the analysis covered economic and demographic indicators such as gross national income (GNI) per capita, PPP, total population, birth rate, and related government expenditure data on vaccines used in routine immunizations. This study utilizes data from the World Bank and WHO's Global Health Expenditure Database (GHED). The relevant data of Gavi and PAHO countries required for vaccine pricing through the GPO are listed in the Appendix A.

Furthermore, subsequent analyses consider an alternative method for calculating the price adjustment multiplier (the purchasing power parameter), as listed below.

$$\varepsilon_i' \doteq 1 + \frac{\left(\max_i s_i\right) - s_i}{\sum_i s_i / N}. \tag{25}$$

This alternative approach standardizes the adjustment mechanism by using the average willingness to pay of different countries, thus validating its robustness. Then, Python 3.12 is used to construct all models, and Gurobi 12.0.1 is applied to solve the models.

4.2. Experimental Results

This study reformulates the original model by reducing the number of constraints and binary variables to improve computational efficiency and enhance practical applicability. Tables 3 and 4 show that both the original model, Model 1, and the proposed model, Model 3, obtain the same solution for each problem; however, the proposed model, Model 3, requires less CPU time to obtain the globally optimal solution. The average percentage of CPU time reduction by the proposed Model 3 is over 30%.

Table 3. Comparisons of CPU time and objective of Models 1 and 3 for the Gavi group.

	Model 1		**Model 3**		
Number of Tiers	**CPU Time (s)**	**Objective**	**CPU Time (s)**	**Objective**	**Percentage Reduction in CPU Time**
$\Pi = 1$	0.0328	0.1457	0.0175	0.1457	47%
$\Pi = 2$	0.0534	0.1436	0.0306	0.1436	43%
$\Pi = 3$	0.0673	0.1436	0.0465	0.1436	31%
$\Pi = 4$	0.0585	0.1436	0.0417	0.1436	29%
$\Pi = 46$	0.1118	0.1436	0.0768	0.1436	31%

Table 4. Comparisons of CPU time and objective of Models 1 and 3 for the PAHO group.

	Model 2		**Model 4**		
Number of Tiers	**CPU Time (s)**	**Objective**	**CPU Time (s)**	**Objective**	**Percentage Reduction in CPU Time**
$\Pi = 1$	0.0825	0.2241	0.0486	0.2241	41%
$\Pi = 2$	0.0797	0.170	0.0421	0.170	47%
$\Pi = 3$	0.0425	0.170	0.0310	0.170	27%
$\Pi = 4$	0.0414	0.170	0.0300	0.170	28%
$\Pi = 28$	0.0977	0.170	0.0783	0.170	20%

Let $\delta_\Pi = \max\varepsilon_i p_i - \min\varepsilon_i p_i$ denote the adjusted price disparity and $\Delta_\Pi = \max p_i - \min p_i$ denote the absolute price disparity. Table 5 lists the optimal solutions under different pricing schemes to the vaccine pricing model for the Gavi group. For uniform pricing, p_i are identical for all countries; therefore, the absolute price disparity $\Delta_1 = 0$. δ_1 = 0.1457 is the greatest disparity under uniform pricing and decreases monotonically as Π increases, since the solution under Π pricing tiers remains feasible when an additional tier is introduced (i.e., the problem with Π+1 tiers). These findings are consistent with the results presented [1].

Table 5. Comparisons between different vaccine pricing schemes for the Gavi group.

Pricing Scheme	**max $\varepsilon_i p_i$**	**min $\varepsilon_i p_i$**	**δ_Π = max $\varepsilon_i p_i$ − min $\varepsilon_i p_i$**	**max p_i**	**min p_i**	**Δ_Π = max p_i − min p_i**
$\Pi = 1$	0.2913	0.1457	0.1457	0.1457	0.1457	0.0000
$\Pi = 2$	0.2871	0.1436	0.1435	0.1569	0.1436	0.0133
$\Pi = 46$	0.2871	0.1436	0.1435	0.1569	0.1436	0.0133

For the Gavi group, where N = 46, the uniform pricing scheme yields a unit price of 0.1457 and an adjusted price disparity of δ_1 = 0.1457. Introducing a second pricing tier (Π = 2) reduces the adjusted price disparity to δ_2 = 0.1435, although the absolute price

disparity increases to $\Delta_2 = 0.0133$. Notably, the optimal solutions to the vaccine pricing model remain invariant for all tiers ($2 \leq \Pi \leq 46$).

Table 6 lists the optimal solutions under different pricing schemes to the vaccine pricing model with subsidy for the Gavi group. Similarly to the results without subsidy, for uniform pricing, p_i are identical for all countries; therefore, the absolute price disparity $\Delta_1 = 0$. $\delta_1 = 0.1457$ is the greatest disparity under uniform pricing and decreases monotonically as Π increases. Introducing a second pricing tier ($\Pi = 2$) reduces the adjusted price disparity to $\delta_2 = 0.1444$, although the absolute price disparity increases to $\Delta_2 = 0.0135$. In the 3-tier pricing scheme, the adjusted price disparity decreases to $\delta_3 = 0.1435$ and the absolute price disparity increases to $\Delta_3 = 0.0133$. Then, the optimal solutions to the vaccine pricing model with subsidy remain invariant for all tiers ($3 \leq \Pi \leq 46$).

Table 6. Comparisons between different vaccine pricing schemes with subsidy for the Gavi group.

Pricing Scheme	$\max \varepsilon_i p_i$	$\min \varepsilon_i p_i$	$\delta_\Pi = \max \varepsilon_i p_i - \min \varepsilon_i p_i$	$\max p_i$	$\min p_i$	$\Delta_\Pi = \max p_i - \min p_i$
$\Pi = 1$	0.2913	0.1457	0.1457	0.1457	0.1457	0.0000
$\Pi = 2$	0.2889	0.1444	0.1444	0.1579	0.1444	0.0135
$\Pi = 3$	0.2871	0.1436	0.1435	0.1569	0.1436	0.0133
$\Pi = 46$	0.2871	0.1436	0.1435	0.1569	0.1436	0.0133

Table 7 lists the optimal solutions under different pricing schemes to the vaccine pricing model for the PAHO group. For uniform pricing, p_i are identical for all countries and $\Delta_1 = 0$. $\delta_1 = 0.2241$ is the highest price disparity under the uniform pricing scheme. For the PAHO group, where N = 28, the uniform pricing scheme yields a unit price 0.2241 and an adjusted price disparity $\delta_1 = 0.2241$. Introducing a second pricing tier ($\Pi = 2$) reduces δ_2 to 0.1700 and increases Δ_2 to 0.0495. The optimal solutions to the vaccine pricing model remain unchanged for all tiers ($2 \leq \Pi \leq 28$).

Table 7. Comparisons between different vaccine pricing schemes for the PAHO group.

Pricing Scheme	$\max \varepsilon_i p_i$	$\min \varepsilon_i p_i$	$\delta_\Pi = \max \varepsilon_i p_i - \min \varepsilon_i p_i$	$\max p_i$	$\min p_i$	$\Delta_\Pi = \max p_i - \min p_i$
$\Pi = 1$	0.4483	0.2241	0.2241	0.2241	0.2241	0.0000
$\Pi = 2$	0.4358	0.2658	0.1700	0.2674	0.2179	0.0495
$\Pi = 28$	0.4358	0.2658	0.1700	0.2674	0.2179	0.0495

Table 8 lists the optimal solutions under different pricing schemes to the vaccine pricing model with subsidy for the PAHO group. Similarly to the results without subsidy, for uniform pricing, p_i are identical for all countries; therefore, the absolute price disparity $\Delta_1 = 0$. $\delta_1 = 0.2242$ is the greatest disparity under uniform pricing and decreases monotonically as Π increases. In the 3-tier pricing scheme, the adjusted price disparity decreases to $\delta_3 = 0.1700$ and the absolute price disparity increases to $\Delta_3 = 0.0495$. Then, the optimal solutions to the vaccine pricing model with subsidy remain invariant for all tiers ($3 \leq \Pi \leq 28$).

Table 8. Comparisons between different vaccine pricing schemes with subsidy for the PAHO group.

Pricing Scheme	$\max \varepsilon_i p_i$	$\min \varepsilon_i p_i$	$\delta_\Pi = \max \varepsilon_i p_i - \min \varepsilon_i p_i$	$\max p_i$	$\min p_i$	$\Delta_\Pi = \max p_i - \min p_i$
$\Pi = 1$	0.4485	0.2242	0.2242	0.2242	0.2242	0.0000
$\Pi = 2$	0.4392	0.2660	0.1732	0.2694	0.2180	0.0514
$\Pi = 3$	0.4360	0.2660	0.1700	0.2675	0.2180	0.0495
$\Pi = 28$	0.4360	0.2659	0.1700	0.2675	0.2180	0.0495

Tiered pricing has been a critical mechanism for enhancing global vaccine accessibility, particularly in low- and middle-income countries. By providing differential prices to each country based on the income level, this model ensures that the vaccines remain affordable for resource-constrained countries. As [28] notes, tiered pricing for vaccines helps improve accessibility by making them more affordable for lower-income countries. Based on this concept, organizations such as Gavi and the United Nations Children's Fund (UNICEF) have institutionalized tiered pricing strategies to negotiate favorable rates with pharmaceutical companies, thereby leveraging pooled demand to secure equitable access. Recent initiatives by [29] highlight the continued importance of these models in maintaining affordability and ensuring that vaccines reach populations across diverse economic contexts.

4.3. Sensitivity Analysis

In the objective function, the price adjustment multiplier (purchasing power parameter) ε_i is one of the key elements that influence pricing strategies. It not only directly affects the price adjustment results but also serves as an important indicator reflecting the fairness and affordability of vaccine allocation strategies. To explore the impact of purchasing power parameter on adjusted prices, this section conducts a sensitivity analysis on the purchasing power parameter.

The previous alternative method ε_i' is used as the basis for comparing with the original purchasing power parameter ε_i to conduct a sensitivity analysis of the adjusted prices. The main difference between ε_i and ε_i' is the standardization method used for the denominator, which in turn affects the model's sensitivity to the willingness to pay of various countries. The original purchasing power parameter ε_i is standardized based on the gap between the maximum and minimum willingness to pay, mapping each country's value to a range of 1 to 2. The alternative purchasing power parameter ε_i' is standardized based on the average willingness to pay of each country, by comparing the willingness to pay of individual countries with the average value.

Figures 1 and 2 below illustrate the ε_i and ε_i' calculated based on the data from the Gavi group and the PAHO group, respectively. As can be observed from the figure, the original purchasing power parameter ε_i and the alternative purchasing power parameter ε_i' exhibit significant distributional differences across different countries. ε_i has a relatively smooth distribution with limited differences between countries, while ε_i' shows a larger fluctuation range, with more pronounced differences between countries. This indicates that if the model objective is to control the impact of extreme values, using ε_i helps maintain the model's robustness under differences in purchasing power; conversely, if the goal is to strengthen the reflection of purchasing power disparities by the price allocation strategy, then ε_i' can be considered to achieve more differentiated price adjustments between countries with high and low willingness to pay. Given that the primary objective of this study is to enhance fairness in vaccine allocation across countries with heterogeneous economic capacities, ε_i' is therefore more closely aligned with the fairness objective emphasized in this study.

An experimental analysis is conducted to explore the impact of adjusting ε_i on the changes in the optimal price of the pricing model at different price levels (Π) in the Gavi and PAHO groups. It can be observed that after adjusting ε_i, the optimal solution results of the Gavi group change significantly at each price level. First, under the uniform pricing strategy, the adjusted $\max \varepsilon_i p_i$ increases significantly, from 0.2913 to 0.6176; while δ_1 increases from 0.1457 to 0.4720, indicating that the standardization of the parameter ε_i' amplifies the gap in willingness to pay between countries, thus significantly increasing the price adjustment range of the model when facing countries with extreme payment capacity. Extending this to a multi-tiered scenario, we find that the adjusted $\delta_\Pi = 0.4612$ for two-tiered pricing

($\Pi = 2$) to differentiated-tiered pricing ($\Pi = 46$), significantly higher than the unadjusted 0.1436. This indicates that even with the parameter ε_i', the model still exhibits a substantial price difference under a multi-tiered pricing strategy. Furthermore, Δ_Π also increases from 0.0133 to 0.0208, reflecting a more significant degree of price differentiation under the tiered pricing strategy.

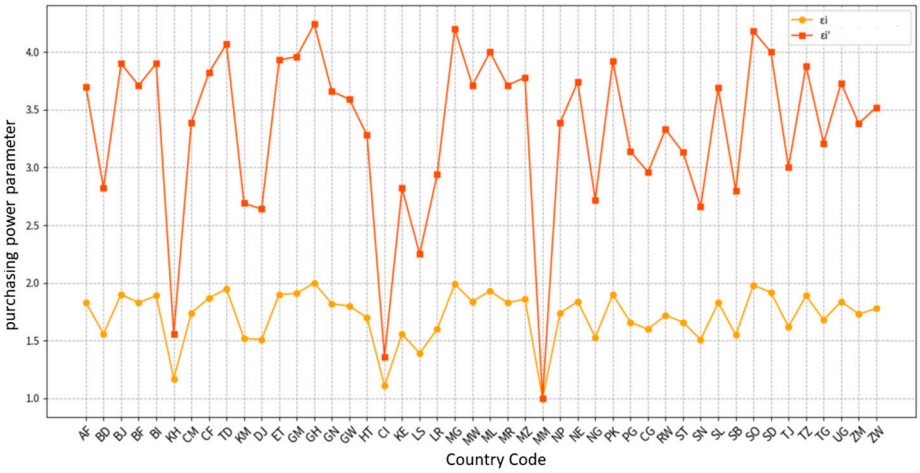


Figure 1. Comparisons of purchasing power parameters for the Gavi countries.

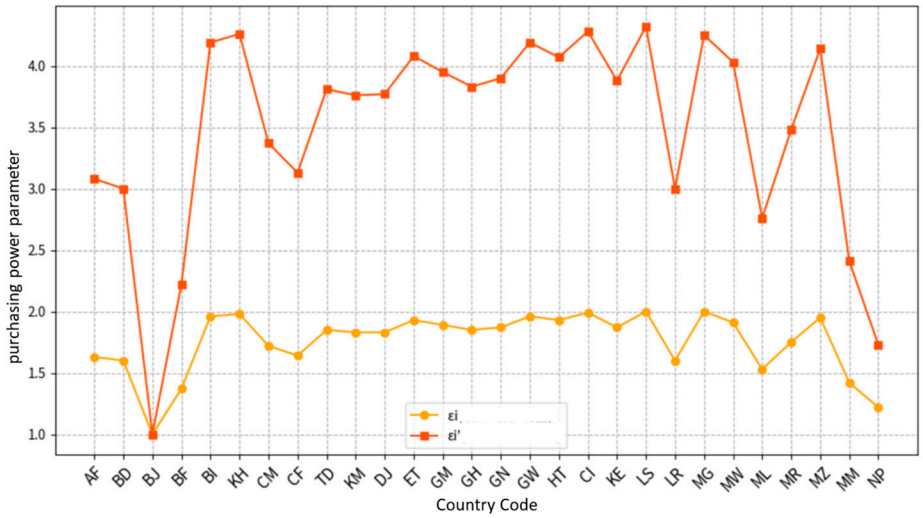


Figure 2. Comparisons of purchasing power parameters for the PAHO countries.

Compared to the Gavi group, the PAHO group exhibits the same phenomenon. Under the $\Pi = 1$ strategy, the $\max\varepsilon_i p_i$ value rises sharply from 0.4483 to 0.9504, and δ_1 increases dramatically from 0.2241 to 0.7262, indicating a significant amplification of the willingness-to-pay gap. Even with price tiers subdivided to $\Pi = 2$ to $\Pi = 28$, δ_Π remains high at 0.6839, compared to only 0.1700 before the adjustment. This indicates a significant increase in price distribution under both two-tiered pricing ($\Pi = 2$) and differentiated-tiered pricing ($\Pi = 46$) strategies. However, while the decrease of Δ_Π from 0.0495 to 0.0308 mitigates extreme price differences, it preserves some degree of price disparity between countries.

Further analysis of the differences between the PAHO and Gavi groups after parameter adjustment reveals that the price distribution in the PAHO group changed significantly more dramatically. This is primarily because the distribution of willingness to pay among countries within the PAHO group is more dispersed than in the Gavi group. Firstly, the PAHO group comprises some middle- and high-income countries, as well as low-income countries, resulting in significant disparities in payment capacity among countries within

the group, which leads to higher variability in its willingness-to-pay parameters, s_i. When the model uses the alternative purchasing power parameter ε_i' derived by standardization based on the overall average, it will further amplify the willingness-to-pay characteristics of countries that significantly deviate from the average level, thereby enhancing the price differentiation between countries with high and low willingness-to-pay. In contrast, the Gavi group members are primarily from low-income countries, and the overall gap in payment capacity is relatively concentrated. Even with the same parameter adjustment, the price distribution changes tend to be stable, demonstrating the robustness of the model when dealing with a relatively uniform willingness-to-pay structure. This difference highlights the importance of the willingness-to-pay distribution structure for sensitivity and fairness analysis of the model.

4.4. Discussions

The experimental analysis systematically evaluates the performance of alternative pricing methods under different procurement settings using real-world data from Gavi and PAHO. The results indicate that pricing design plays a central role in determining both allocation outcomes and adjusted price dispersion. In particular, tiered pricing mechanisms outperform uniform pricing in terms of facilitating broader distribution and reducing cross-country price disparities, especially in regions characterized by higher income heterogeneity.

In current experimental conditions with relatively small sample sizes, such as in Gavi and PAHO, the solution times for both the original and proposed models are negligible. However, the primary objective of the proposed method is not to achieve immediate acceleration in small-scale instances, but to enhance computational scalability as the model is extended. In practical or hypothetical large-scale applications, the number of participating countries, additional decision variables, and constraints may increase substantially. Under such extensions, the underlying MILP formulation may experience a rapid increase in computational complexity [23,24]. This issue is particularly significant in MILP formulations, where the presence of integer variables introduces combinatorial complexity and leads to an exponential growth of the search space under branch-and-bound solution algorithms. By reducing the dimension of the formulation structure, the proposed method is designed to mitigate this growth and efficiently solve larger or more complex instances.

The finding that PAHO exhibits a greater price dispersion, mainly due to higher income inequality among member countries, has important implications for the design of the GPO policy. In regions characterized by substantial economic heterogeneity, a uniform group procurement mechanism may not fully accommodate the diverse affordability constraints faced by the participating countries. To address this challenge, GPOs operating in high-inequality regions may consider adopting differentiated pricing levels, income-adjusted contribution schemes, or hybrid procurement structures that combine centralized negotiations with flexible allocation rules. Such policy instruments can help preserve the efficiency gains of group procurement while mitigating the distribution imbalances caused by heterogeneous income levels. These considerations suggest that the effectiveness of GPO arrangements is closely related not only to the scale economy but also to the degree of income distribution within the participating region.

5. Conclusions

5.1. Conclusions and Key Implications

Vaccine equity is fundamentally concerned with ensuring that all populations worldwide have equal access to immunization, regardless of economic status. A central mechanism for achieving this goal lies in establishing appropriate vaccine pricing structures

that reflect buyers' ability and willingness to pay, thereby improving both accessibility and affordability. Building on prior research, this study reformulates two existing models, one incorporating subsidies and one without, originally proposed in [1], to enhance computational efficiency through the reduction in binary variables. Using real-world data from Gavi and PAHO, the experimental analysis highlights the tangible effects of different pricing mechanisms on vaccine accessibility. The findings demonstrate that tiered pricing not only facilitates broader distribution but also strengthens perceptions of fairness by minimizing adjusted price disparities, thereby reinforcing its role as a critical instrument in advancing global health equity.

This study provides empirical evidence that pricing mechanisms play a decisive role in determining the outcomes of the vaccine distribution and the price differences across countries within the group procurement system. Using real-world data from Gavi and PAHO, the results reveal significant discrepancies in adjusted prices and distribution patterns, particularly in regions characterized by high income heterogeneity. These discrepancies emphasize that uniform pricing mechanisms can lead to distribution imbalances, whereas tiered pricing structures systematically reduce adjusted price dispersion and facilitate broader access. In addition to identifying these discrepancies, the study demonstrates that such outcomes are structurally related to the interaction between income distribution, subsidy design, and price rules. The comparative analysis of Gavi and PAHO indicates that regions characterized by greater economic inequality face fundamentally distinct procurement challenges, and that pricing design constitutes a key instrument for addressing these challenges. The contribution of this study is application-driven, combining model reformulation with real-world data to generate empirical insights into pricing and equity outcomes. The analytical results contribute to the procurement literature by quantitatively demonstrating how alternative pricing mechanisms translate into measurable differences in equity-related outcomes.

The proposed model can be practically integrated into the GPO negotiation process as a decision support tool, rather than replacing existing procurement practices. Before a price is finalized, GPO administrators can use the model to simulate alternative pricing structures, such as uniform pricing and tiered pricing in different subsidies and budget scenarios. The resulting adjusted price distribution indicators provide a quantitative reference to support negotiations with manufacturers, especially for differentiated pricing arrangements in regions with different income levels. In this way, the model facilitates more structured, evidence-based negotiations while preserving managerial discretion.

5.2. Limitations and Future Research Directions

While this study provides quantitative insights into how pricing mechanisms and procurement design influence vaccine allocation and price dispersion within group purchasing organizations, several aspects of real-world vaccine procurement remain beyond the scope of the current framework. In particular, vaccine heterogeneity, cold-chain logistics costs, and within-country distribution inequalities are not explicitly modeled.

In addition, the experimental analysis relies on aggregated procurement data from Gavi and PAHO. This aggregation enables the examination of system-level pricing and allocation patterns within group procurement organizations, facilitating comparative analysis by reducing data noise. However, it does not capture regional heterogeneity, temporal dynamics, or differences across vaccine types. Accordingly, the results should be interpreted as reflecting structural relationships at an aggregated level.

Future research may extend the proposed framework by incorporating practical considerations such as differentiated vaccine types, cold-chain logistics costs, and within-country distribution inequalities, thereby strengthening the model's real-world applicability. More-

over, cross-regional, cross-temporal, and cross-vaccine-type validation would further enhance the robustness and external validity of the findings as more disaggregated data become available. In addition to vaccines, the modeling framework may also be adapted to the pricing and allocation of other public health resources, such as medicines, medical equipment, and emergency response supplies. As noted by Moye-Holz and Vogler [30], pricing policies can lead to substantial disparities in drug prices and affordability across countries, underscoring the importance of effective pricing and procurement strategies in promoting equitable access. In this regard, future research that integrates real-world procurement contexts and cross-domain applications may further enhance the practical value of the proposed model for global public health resource management and the design of equity-oriented policies.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Appendix A.1. Data Sources for Relevant Data for the Gavi and the PAHO Countries

- Gross national income per capita: https://data.worldbank.org/indicator/NY.GNP.PCAP.PP.CD (accessed on 15 April 2025)
- Total population: https://data.worldbank.org/indicator/SP.POP.TOTL (accessed on 15 April 2025)
- Birth rate: https://data.worldbank.org/indicator/SP.DYN.CBRT.IN (accessed on 15 April 2025)
- Government expenditure on vaccines: https://apps.who.int/nha/database/select/indicators/en (accessed on 15 April 2025)

Appendix A.2. Summary of Relevant Data for the Gavi and the PAHO Countries

Table A1. Relevant data required in vaccine pricing for the Gavi countries.

CC	GNI Per Capita	TP	BR	q_i	G_i	T_i	s_i	ε_i	$\varepsilon_i^{'}$
AF	2130	40.58	35.14	1426.06	4025.53	8050.94	2.82	1.83	3.7
BD	8790	169.39	17.48	2960.85	20,080.48	20,080.48	6.78	1.56	2.82
BJ	3800	13.76	36.07	496.32	941.73	941.73	1.9	1.9	3.9
BF	2530	22.51	34.95	786.74	2192.72	3405.52	2.79	1.83	3.71
BI	890	13.32	34.11	454.37	869.47	2001.83	1.91	1.89	3.9
KH	6650	17.2	18.97	326.3	4051.27	5471.69	12.42	1.17	1.56
CM	5060	27.63	34.35	949.24	3980.11	5726.54	4.19	1.74	3.39
CF	1280	5.1	42.34	215.87	486.11	486.11	2.25	1.87	3.82
TD	1780	18.46	43.18	796.97	919.44	1399.31	1.15	1.95	4.07
KM	3730	0.83	28.89	24.1	177.5	343.52	7.37	1.52	2.69
DJ	6640	1.14	21.91	24.92	188.6	188.6	7.57	1.51	2.64
ET	2830	125.38	31.84	3991.61	7130.46	13,687.41	1.79	1.9	3.93
GM	3020	2.64	33	87	143.86	222.32	1.65	1.91	3.96
GH	7090	33.15	27.08	897.68	338.87	677.74	0.38	2	4.24
GN	3990	14.06	33.86	475.84	1421.82	2597.52	2.99	1.82	3.66
GW	2700	2.11	30.61	64.45	213.91	376.37	3.32	1.8	3.59
HT	3270	11.5	23.15	266.26	1253.88	2561.05	4.71	1.7	3.28
CI	6490	30.4	33	1003.04	13,379.34	15,321.36	13.34	1.11	1.36
KE	5790	54.25	27.54	1494.11	10,133.05	15,909.68	6.78	1.56	2.82
LS	3320	2.29	25.78	58.93	550.02	550.02	9.33	1.39	2.25
LR	1590	5.37	31	166.55	1036.49	1815.85	6.22	1.6	2.94
MG	1700	30.44	30.6	931.23	534.11	1503.88	0.57	1.99	4.2
MW	1720	20.57	32.61	670.77	1852.46	5330.9	2.76	1.84	3.71
ML	2420	23.07	41.22	950.99	1391.99	1739.33	1.46	1.93	4
MR	6450	4.88	32.95	160.67	448.06	732.88	2.79	1.83	3.71
MZ	1460	32.66	36.12	1179.58	2906.02	8002.6	2.46	1.86	3.78
MM	5630	53.76	16.83	904.89	13,530.69	15,722.75	14.95	1	1
NP	5130	29.72	20.17	599.21	2533.83	3864.28	4.23	1.74	3.39
NE	1680	25.31	45.03	1139.77	3023.77	5264.56	2.65	1.84	3.74
NG	5790	223.15	36.61	8169.78	58,968.66	66,441.12	7.22	1.53	2.72
PK	5840	243.7	27.23	6636.7	12,109.2	16,236.11	1.82	1.9	3.92
PG	4160	10.2	25.11	256.22	1367.26	2816.03	5.34	1.66	3.14
CG	5930	6.04	30	181.05	1115.7	1410.35	6.16	1.6	2.96
RW	3030	13.65	29.47	402.35	1800.14	1800.14	4.47	1.72	3.33
ST	6150	0.23	27.97	6.33	34.1	70.52	5.39	1.66	3.13
SN	4380	17.65	32.07	566.02	4240.37	6236.47	7.49	1.51	2.66
SL	3110	8.28	30.79	254.83	723.45	1405.87	2.84	1.83	3.69
SB	2710	0.78	29.32	22.9	157.25	284.86	6.87	1.55	2.8
SO	1480	17.8	43.09	767.01	514.85	514.85	0.67	1.98	4.18
SD	3290	49.38	33.03	1630.98	2415.42	2415.42	1.48	1.92	4
TJ	5990	10.18	26.03	264.99	1578.41	2107.6	5.96	1.62	3
TZ	3730	64.71	35.81	2317.4	4667.73	4667.73	2.01	1.89	3.88
TG	2870	9.09	31.48	286.15	1435.27	2322.14	5.02	1.68	3.21
UG	2860	47.31	36.22	1713.43	4553.86	11,215.06	2.66	1.84	3.73
ZM	3610	20.15	34.13	687.76	2927.75	6979.92	4.26	1.73	3.38
ZW	3480	16.07	30.09	483.45	1751.96	4301.06	3.62	1.78	3.52

CC: country code. GNI per capita: gross national income per capita ($USD). TP: total population (millions). BR: birth rate (per thousand people). q_i: order quantity of member i (thousands). G_i: average government expenditures per newborn per year ($USD). T_i: total government expenditure on vaccines used in routine immunization ($USD). s_i: average annual government expenditure on vaccines for routine immunization per newborn ($USD). ε_i: price adjustment multiplier applied to member i in constraint (1). ε_i': alternative price adjustment multiplier applied to member i in constraint (25).

Table A2. Relevant data required in vaccine pricing for the PAHO countries.

CC	GNI Per Capita	TP	BR	q_i	G_i	T_i	s_i	ε_i	$\varepsilon_i^{'}$
AG	28,580	0.09	11.98	1.11	177.45	178.21	159.49	1.63	3.08
AR	29,050	45.4	13.79	626.36	105,270.1	108,844.3	168.07	1.6	3
BS	32,730	0.4	11	4.37	1720.84	1745.68	393.52	1	1
BB	19,260	0.28	10.78	3.04	780.91	797.73	256.52	1.37	2.22
BZ	12,830	0.4	17.76	7.15	247.34	274.05	34.58	1.96	4.19
BO	10,070	12.08	21.6	260.85	6927.89	7565.92	26.56	1.98	4.26
BR	19,330	210.31	12.65	2660.17	335,969.1	337,230.2	126.3	1.72	3.37
CL	29,470	19.55	11.76	229.85	35,377.61	35,377.61	153.92	1.64	3.13
CO	20,200	51.74	13.92	720.24	55,698.01	55,698.01	77.33	1.85	3.81
CR	24,080	5.08	11.69	59.39	4940.54	4960.13	83.19	1.83	3.76
DM	17,800	0.07	13.28	0.89	72.87	88.73	82.12	1.83	3.77
DO	23,450	11.23	18.11	203.4	9600.22	10,428.35	47.2	1.93	4.08
EC	15,030	17.82	16.58	295.57	18,103.35	18,295.84	61.25	1.89	3.95
SV	11,120	6.28	15.8	99.25	7439.3	7528.33	74.96	1.85	3.83
GD	16,400	0.12	15.62	1.83	123.38	132.69	67.58	1.87	3.9
GT	12,750	17.85	20.86	372.33	12,670.51	13,464.26	34.03	1.96	4.19
GY	24,050	0.82	19.9	16.35	778.7	828.06	23.89	1.93	4.07
HN	6270	10.46	20.85	218.17	5213.06	5972.85	47.63	1.99	4.28
JM	10,570	2.84	11.53	32.74	2284.19	2383.17	67.77	1.87	3.88
NI	7220	6.73	20.02	134.73	2715.96	3109.75	20.16	2	4.32
PA	34,600	4.4	17.4	76.57	12,861.33	13,139.11	167.96	1.6	3
PY	15,820	6.76	20.33	137.43	3838.92	3866.55	27.93	2	4.25
PE	15,530	33.48	17.38	581.67	30,365.68	30,571.62	52.2	1.91	4.03
KN	30,970	0.05	12	0.56	109.77	109.77	195.83	1.53	2.76
LC	22,530	0.18	11	1.97	223.98	324.68	113.89	1.75	3.48
SR	18,450	0.62	17.98	11.21	448.97	448.97	40.06	1.95	4.14
TT	31,630	1.37	11.38	15.55	3650.95	3656.31	234.85	1.42	2.41
UY	29,790	3.39	10.42	35.33	11,008.79	11,008.82	311.6	1.22	1.73

CC: country code. GNI per capita: gross national income per capita ($USD). TP: total population (millions). BR: birth rate (per thousand people). q_i: order quantity of member i (thousands). G_i: average government expenditures per newborn per year ($USD). T_i: total government expenditure on vaccines used in routine immunization ($USD). s_i: average annual government expenditure on vaccines for routine immunization per newborn ($USD). ε_i: price adjustment multiplier applied to member i in constraint (1). ε_i': alternative price adjustment multiplier applied to member i in constraint (25).

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