Proceedings of the 2021 Winter Simulation Conference
S. Kim, B. Feng, K. Smith, S. Masoud, Z. Zheng, C. Szabo, and M. Loper, eds.

EXPLORING MARKET SEGMENT ASSIGNMENT STRATEGIES TO MONOPSONISTIC ENTITIES IN A HYPOTHETICALLY COORDINATED VACCINE MARKET

Bruno Alves-Maciel
Ruben A. Proano

Department of Industrial and Systems Engineering
Rochester Institute of Technology
One Lomb Memorial Drive
Rochester, NY, 14623, UNITED STATES

ABSTRACT

This study presents a simulation-optimization approach for implementing the first stage of a four-stage optimization framework used to simulate a hypothetically coordinated vaccine market. The study's overall goal is to optimally make procurement decisions that result in more affordable vaccines for the buyers and profitable for their producers. In the initial stage, groups of market segments are assigned to coordinating entities that will make optimal procurement decisions under tiered pricing and pool procurement mechanisms. We explore nine different market-to-entity assignment policies through variants of a min-max optimization problem that mimics assignment policies with varying levels of cooperation among market segments. Our results show that market segments with low purchasing power can maximize their savings if they procure together with market segments with higher purchasing power. Additionally, market assignments that result in coordinating entities serving similar size populations mitigate the profit reduction of transferring savings to low-income market segments.

1 INTRODUCTION

This study presents a simulation-optimization process to enhance global pediatric vaccine affordability via a market-agent design. International organizations recognize vaccines as a cost-effective healthcare intervention with savings that can be 16 times higher than the costs of treating preventable illnesses (Gavi 2018; Ozawa et al. 2016). However, 19.5 million children worldwide still do not have access to routine immunizations (World Health Organization 2019). We hypothesize that pediatric vaccine access is partially affected by the lack of coordination in the global vaccine market among buyers and the asymmetric power relationship between buyers and large vaccine producers (Proano et al. 2012; Mosquera 2016; Alves-Maciel and Proano 2021). Currently, countries can procure vaccines on their own or through pooled procurement mechanisms. Examples of such pooling include the Pan American Health Organization (PAHO) Revolving Fund, or low-income countries that buy vaccines at UNICEF's prices with Gavi's financial support (The World Bank and the GAVI Alliance 2010a). In this study, pooled procurement agents are referred to as "coordinating entities" who make procurement decisions to benefit the buyers and the vaccine producers.

This paper complements a preliminary study where we determined that cooperation among coordinating entities increases both affordability and profits for the global vaccine market (Alves-Maciel and Proano 2021). However, fewer coordinating entities in the global market increase aggregate affordability of target low-income countries at the expense of profits for vaccine producers. The previous study simulates the global vaccine market as a system in which multiple coordinating entities sequentially make optimal procurement decisions for groups of countries without cooperating with other entities. The countries of each entity are also divided into different market segments based on their GNI per capita. Optimal decisions are determined

978-1-6654-3311-2/21/$31.00 ©2021 IEEE

via a three-stage optimization process iteratively applied to each entity. ”Stage 1” maximizes total social surplus (total welfare) by determining which vaccines each of the defined coordinating entities buys and in which quantities. ”Stage 2” and ”Stage 3” use the resulting procuring quantities to determine a range of prices per vaccine that maintains the optimal total social surplus of ”Stage 1” (Proano et al. 2012). Countries in the vaccine market were organized into market segments for pricing purposes in a tiered pricing scheme (The World Bank and the GAVI Alliance 2010b). Alves-Maciel and Proano (2021) studied the effect of procurement cooperation in the vaccine market (i.e., the number of independent coordinating entities) on savings and profits. For assigning market segments to each coordinating entity, market segments were ranked based on the average GNI per capita of their countries, then greedily assigned to coordinating entities so that each entity has the same number of market segments.

In this study, we evaluate the effect on affordability and profits of using nine proposed policies on assigning market segments to coordinating entities on the same simulated global vaccine market. We use streams of randomized data as inputs for our optimization-simulation process to determine the optimal assignment of market segments into coordinating entities and then feed those entities into the same three-stage approach of Alves-Maciel and Proano (2021) to determine savings and profits at the market segment level. The proposed strategy is equivalent to adding a preliminary optimization stage, ”Stage 0”, for assigning market segments to coordinating entities, to the three-stage approached tested in our previous study. A general max-min optimization approach is used to generate eight different optimization problem representations for ”Stage 0”, depending on the market assignment policy being simulated. Table 1 describes the policy selected for comparison. It should be stressed that during the simulation, each coordinating entity goes through all four stages before the next coordinating entity starts its negotiation. We assume that coordinating entities representing market segments with higher GNI per capita negotiate first (i.e., the sum of the GNI per capita of the market segments assigned to each coordinating entity determines the negotiation order).

Section 2 briefly explores the existing literature of assignment problems for group buying both in the context of simulation or pure optimization. Section 3 explains the simulation process, including mathematical modeling used in the distribution of market segments to coordinating entities and the metrics of interest collected at each iteration of the simulation. Section 4 summarizes experimental results and their implications. Section 5 offers concluding remarks.

2 LITERATURE REVIEW

The literature on assignment problems is extensive (Lau et al. 2016; DeSarbo and Grisaffe 1998; Milne et al. 2018). However, the literature that links assignment problems with group-buying in a simulated market is still limited. Bertsimas et al. (2011) explores how fairness in the coordinated allocation of resources among multiple stakeholders, with their own utility functions, compares to an allocation with an optimal social surplus. The paper maximizes the minimum utility of resource allocation for each stakeholder while still guaranteeing a certain level of overall utility. The study proposes that the solution with the highest overall utility might not be the fairest. For our case, this implies that allocating market segments to coordinating entities should consider the overall system performance and the impact on the different market segments and the producers. Salles and Barria (2008) upholds this assertion. However, contrast is offered by Şen and Çınar (2010), who offers a way to explore a range of performances, rather than considering optimizing fairness as maximizing the minimum utility among stakeholders. However, Şen and Çınar (2010) also incorporates allocation criteria into the process by incorporating weights in a prior stage to the max-min solution, which then determines the actual allocation. This approach shows a single objective function formulation generating a value that can be used regardless of the chosen criteria, which only affect the value of parameters.

Specific to simulation, there is a rich coalition-forming literature that can focus both on buyers or sellers. A common assumption is that there exists a leader forming the coalition, for whom utility is maximized (Yu et al. 2015; Boongasame et al. 2012; Ray and Vohra 1997; Chen and Sun 2011). This assumption

Table 1: Simulated sorting criteria for determining which market segments are assigned to each coordinating entity.

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

does not apply when the leader forming the coalition is an independent organization outside of buyers or sellers and tries to maximize total social surplus (i.e., a coordinating entity). This gap in the literature widens when the independent entity explores different criteria in forming such coalitions in a group-buying procedure. Simulation studies on coalition forming in the global vaccine market are currently non-existent. This creates both methodological and application opportunities for this study.

3 METHODOLOGY

3.1 Simulation Overview

At the start of the simulation process, we decide on a sorting policy from Table 1 so that ”Stage 0” can assign market segments to coordinating entities. This means that there are nine scenarios to be simulated. For each scenario, we generate 50 instances of data randomizing the reservation prices between 90% and 110% of their base values (i.e., the maximum prices each market segment is willing to pay for a dose of each available vaccine is different for each instance). Thus, the total amount spent in each instance of the simulated negotiation (i.e., the market value) is different.

Our fixed experimental setup consists of: (1) 194 countries grouped into 12 market segments based on their income per capita; (2) 4 non-cooperating coordinating entities procuring vaccines sequentially; (3) 14 vaccine producers offering; and (4) 52 vaccine products. By calculating the average GNI per capita of the countries in the 12 market segments and applying the classification used by The World Bank (2017), markets 1 to 3 are considered high-income, 4-6 are considered upper-middle-income, 7-9 are considered lower-middle-income, and 10-12 are considered low-income. The baseline reservation prices for each vaccine in a market were estimated based on the procedure proposed by Mosquera (2016). The sequence in which coordinating entities negotiate depends on the sum of the GNI per capita of its assigned market segments. The one with the highest sum of GNI per capita negotiates first, whereas the one with the lowest GNI per capita negotiates last (DeSarbo and Grisaffe 1998; Alves-Maciel and Proano 2021).

The simulation process flows as shown in Algorithm 1. The formulation of ”Stages 1, 2, and 3” are omitted from this manuscript but can be found in Alves-Maciel and Proano (2021).

The simulation process flows thusly: (1) 50 instances of data are generated; (2) One of the scenarios shown in Table 1 is chosen for comparison; (3) ”Stage 0” is solved for one of the randomized instances; (4) the first coordinating entity resulting from solving ”Stage 0” is then used as input to solve ”Stage 1”, determining which vaccines should be produced, and how much of each should be bought by each market segment represented by that coordinating entity; (5) We solve ”Stages 2 and 3” for the same coordinating entity to determine the range of prices that maximize surplus for the procurement quantities resulting from ”Stage 1”; (6) For coordinating entities 2 to 4, repeat steps 4 and 5; (7) Calculate performance metrics for the data instance being used; (8) For randomized data instances 2 to 49, repeat steps 3 to 7; (9) Repeat steps 2 to 8 for the remaining scenarios; (10) compare overall results in each scenario. The formulation of ”Stages 1, 2, and 3” are omitted from this manuscript due to space constraints but can be found in Alves-Maciel and Proano (2021).

Algorithm 1 Simulation Flow

```
Generate instances of data randomizing $R_{bm}$ between 90%-110% of base value $\forall b \in B,\ m \in M$.
for $s \in$ Scenario list do
    for $n \in$ Set of instances do
        Solve ”Stage 0” to define the assignment of market segments to coordinating entities.
        for $e \in$ Coordinated entities, ordered by sum of the market GNIs do
            Solve Stage 1 for coordinating entity $e$, defining $X_{bm}$ and $g_b\ \forall b \in B,\ m \in M$.
            Using $X_{bm}$ and $g_b\ \forall b \in B,\ m \in M$, solve Stage 2 for coordinating entity $e$.
            Using $X_{bm}$ and $g_b\ \forall b \in B,\ m \in M$, solve Stage 3 for coordinating entity $e$.
        Calculate performance metrics for instance $n$.
    Compute descriptive statistics for scenario $s$.
Compare results across all scenarios.
```

The performance of the simulated instances for each of the problem representations for ”Stage 0” is summarized via the metrics described in Table 2 using the notation introduced in Section 3.2. These metrics are expressed relative to the total dollar value of the vaccine market.

3.2 Notation

The formulation for ”Stage 0” is represented as a family of max-min problems whose constraints change depending on the problem criteria listed in Table 1, except for the benchmark O1. To describe these problem formulations, we rely on the following notation:

Sets:

Table 2: Metrics used to compare the proposed scenarios.

Metric	Description	Expression
Customer Surplus (CS)	Difference between reservation prices for a dose of vaccine and the lower bound of prices defined in ”Stage 2”.	$(R_{bm} - Y_{bm}) X_{bm}$
Revenue (P)	Upper bound of prices defined in ”Stage 3” times the number of doses bought.	$X_{bm} Y_{bm}$
Market Value (MV)	Total monetary value in the vaccine market. Sum of all customer savings and all profit across all market segments and coordinating entities, for all vaccines. Costs of vaccines being produced are subtracted from the revenue to represent profits.	$\sum_{e \in E} \sum_{b \in B} \sum_{m \in M} CS + (P - C_b g_b)$
Total Social Surplus (TSS)	An aggregate indicator of the savings obtained by all countries relative to the prices they were willing to pay and the profits obtained by all vaccine producers.	$\left(\sum_{m \in M} \sum_{b \in B} R_{bm} X_{bm} - C_b g_b \right)$

B: set of vaccines
M: set of market segments
E: set of coordinating entities, ordered based on descending average GNI per capita of the represented market segments

Parameters:

R_{bm}: Reservation price of vaccine $b \in B$ for countries in market segment $m \in M$ (i.e., maximum price per dose that market $m \in M$ is willing to pay for vaccine $b \in B$)
l_m: Average birth cohort per year of countries in market $m \in M$
C_b: Annualized R&D and production fixed cost necessary to produce vaccine $b \in B$, considering a desired rate of return
gni_m: Average gross national income (GNI) per capita among countries in market $m \in M$
G_L: Income threshold per capita under which countries in a market segment are considered low-income countries
G_H: Income threshold per per capita above which countries are considered high-income countries
F: Large constant

Variables:

K: lower bound used in the characterization of the max-min criteria described in Table 1. The values and units taken by this variable are a function of integrating the constraints (5) to (10) to characterize the different ”Stage 0” assignment problems.
Z_{em}: Binary variable taking a value of 1 if market $m \in M$ is assigned to entity $e \in E$, or 0 otherwise
X_{bm}: Number of vaccine doses of vaccine $b \in B$ to be purchased by country $m \in M$. Decision variable for ”Stage 1”
g_b: Binary variable indicating whether $b \in B$ is being produced or not. Decision variable for ”Stage 1”
Y_{bm}: Price paid for vaccine $b \in B$ in country $m \in M$. Decision variable for ”Stage 2” and ”Stage 3”
s_e: Auxiliary binary variable indicating whether entity $e \in E$ serves at least one low-income market segment for problems O4, O5, O6 and O7, or high-income for problems O8 and O9.

3.3 Stage 0

The objective (1) and constraints (2), (3), and (4) are common to all ”Stage 0” problem representations.The remaining constraints will be added to the model depending on the assignment policy. The objective function (1) maximizes the lower bound K. Restriction (2) guarantees that at least a country is assigned to each entity. Restriction (3) enforces that each market segment is assigned to exactly one entity. Restriction (4) ensures that coordinating entities maintain a negotiation order based on a decreasing GNI per capita.

To represent problem O2, inequality (5) is added to the core model (expressions (1) to (4)). The added constraint makes K the lower bound on the highest total prices per dose that market segments assigned to any entity are willing to pay. Similarly, problem O3 is characterized by adding restriction (6) to the core model ((1) to (4)). The added constraint makes K the lower bond of the population served by any entity.

To represent problem O4, (7), (11) and (12) are added to the core model making K represents the lower bound on the highest total reservation prices of entities that coordinate at least one low-income market.

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

For characterizing problem O6, we integrate constraints (9), (11) and (12) to the core model to make K the lower bound on the total reservation prices of the entities with at least one market with low-income countries, excluding entities with high-income markets. Problem O7 is similar but considering the population, and requires (10), (11) and (12) to be used in conjunction with the core model.

Problems O8 and O9 require, respectively, (7), (13) and (14), and (8), (13) and (14) to be used together with the core model. They function as O4 and O5, but for high-income countries.

Restrictions (11) and (12) force the binary variable s_e to be 0 if no low-income countries are assigned to a coordinating entity e. Restrictions (13) and (14) force the binary variable s_e to be 0 if no high-income markets are assigned to the coordinating entity e.

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

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

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

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

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

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

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

$$K \leq s_e \left(\sum_{m\in M} Z_{em} l_m \right) + (1-s_e)F \qquad \forall \;\; e \in E \tag{8}$$

$$K \leq s_e \left(\sum_{m\in M: gni_m \leq G_H} \sum_{b\in B} Z_{em} R_{bm} \right) + (1-s_e)F \forall \; e \in E \tag{9}$$

$$K \leq s_e \left(\sum_{m\in M: gni_m \leq G_H} Z_{em} l_m \right) + (1-s_e)F \qquad \forall \; e \in E \tag{10}$$

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

$$0 \geq \sum_{m\in M: gni_m \leq G_L} Z_{em} - ||M|| s_e \qquad \forall \; e \in E \tag{12}$$

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

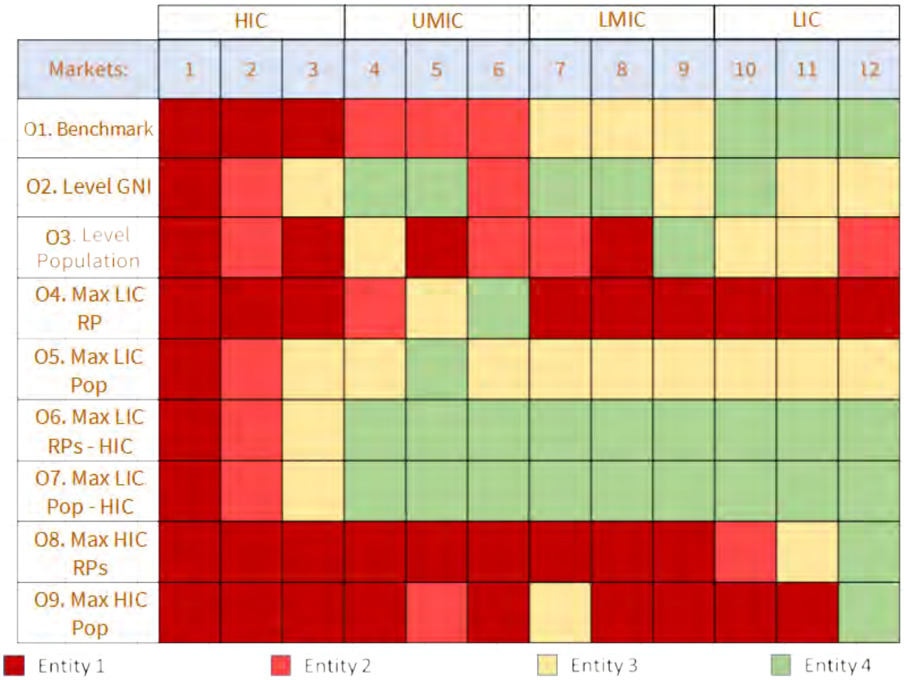
$$0 \geq \sum_{m\in M: gni_m \geq G_H} Z_{em} - ||M|| s_e \qquad \forall \; e \in E \tag{14}$$

4 RESULTS

4.1 Outputs

The simulation generates visible patterns in the resulting assignments for specific criteria, as shown in Figure 1. O3 groups all low-income markets with the high-income markets in Entity 1 (the one that negotiates first). When high-income markets are excluded in O5 and O6, all market segments except high-income ones are joined together in a coordinating entity. However, the sum of the prices that those market segments are willing to pay is still smaller than that of individual high-income market segments, justifying why they negotiate first. As the same distribution is observed in O5 and O6, the results of O5 have been omitted from subsequent figures.

Figure 2 shows $\frac{TSS}{MV}$, $\frac{TCS}{MV}$ and $\frac{TPF}{MV}$ (i.e., $\sum_{m\in M}\sum_{b\in B} TP - C_b g_b$) with an overall view of the system. Figure 3 shows the same for low-income market segments (i.e., markets 10, 11, 12), as the focus of our research is on this group. Figure 4 shows the aggregate customer surplus and revenue for market segments 4, 5, 6 (those classified as upper-middle-income in the World Bank classification), since the results are the most relevant for our analysis. Results specific for high-income and lower-middle-income market segments were

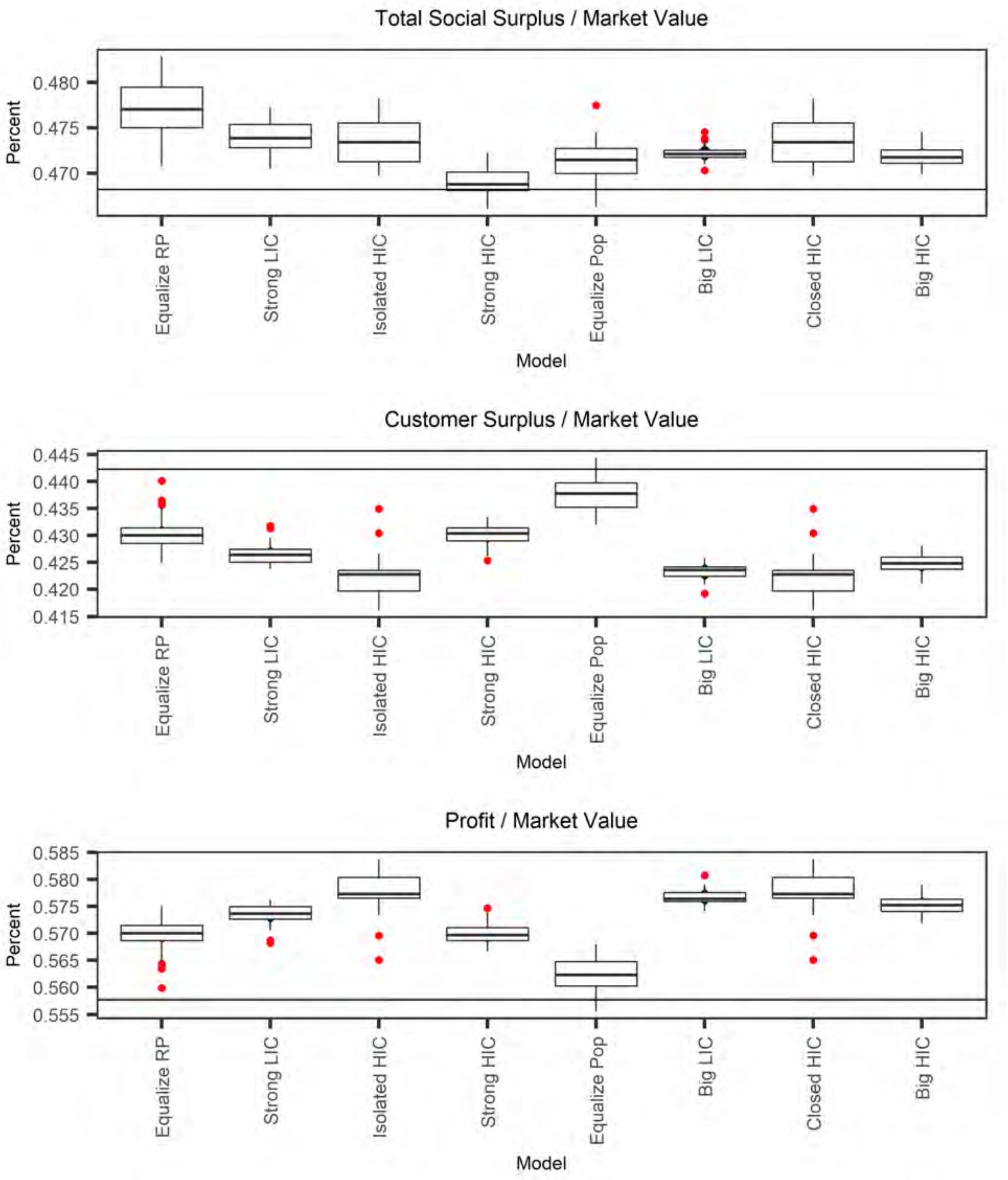


	HIC			UMIC			LMIC			LIC		
Markets:	1	2	3	4	5	6	7	8	9	10	11	12
O1. Benchmark	🟥	🟥	🟥	🟧	🟧	🟧	🟨	🟨	🟨	🟩	🟩	🟩
O2. Level GNI	🟥	🟧	🟨	🟩	🟩	🟧	🟩	🟩	🟨	🟩	🟨	🟨
O3. Level Population	🟥	🟧	🟥	🟨	🟥	🟧	🟧	🟥	🟩	🟨	🟨	🟧
O4. Max LIC RP	🟥	🟥	🟥	🟧	🟨	🟩	🟥	🟥	🟥	🟥	🟥	🟥
O5. Max LIC Pop	🟥	🟧	🟨	🟨	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨
O6. Max LIC RPs - HIC	🟥	🟧	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
O7. Max LIC Pop - HIC	🟥	🟧	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
O8. Max HIC RPs	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟧	🟨	🟩
O9. Max HIC Pop	🟥	🟥	🟥	🟥	🟧	🟥	🟨	🟥	🟥	🟥	🟥	🟩

🟥 Entity 1 🟧 Entity 2 🟨 Entity 3 🟩 Entity 4

Figure 1: Assignment of market segments (columns) into coordinating entities (colors) depending on the criteria used (lines).

omitted, but are provided in the repository referenced in Appendix A. The solid lines in Figures 2 to 3 show the performance for benchmark market-to-entity assignment.


Total Social Surplus / Market Value

Customer Surplus / Market Value

Profit / Market Value

Figure 2: Comparison between $\frac{TSS}{MV}$, $\frac{TCS}{MV}$, and $\frac{TPF}{MV}$ across different criteria.

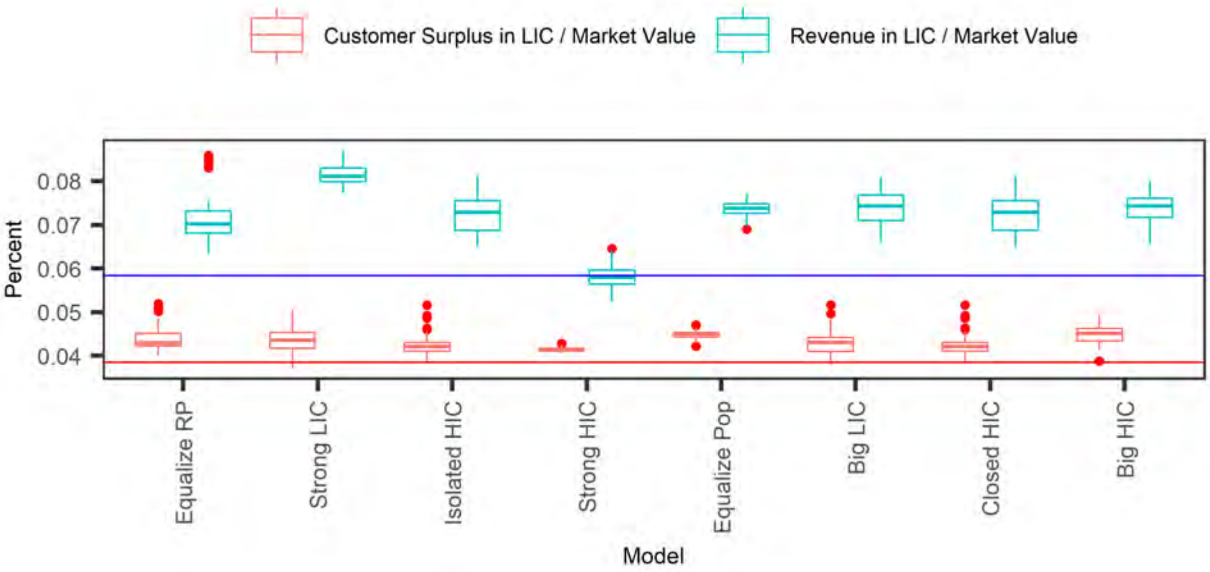


Figure 3: Comparison of customer surplus and revenue across different criteria for low-income market segments (LIC).

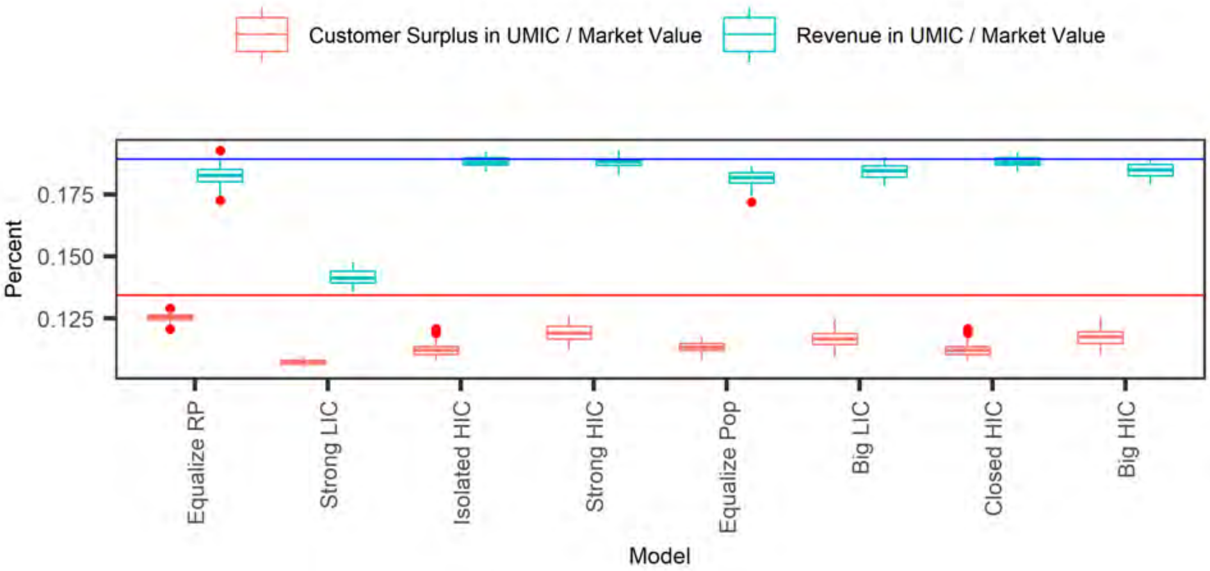


Figure 4: Comparison of customer surplus and revenue across different criteria for upper-middle-income market segments (UMIC).

4.2 Discussion

As shown in Figure 2, all proposed criteria perform better than the benchmark scenario in terms of overall total social surplus but worse in customer surplus. However, Figure 3 shows that the overall savings specific to low-income countries also improve in all considered scenarios. However, when looking at the overall customer surplus in Figure 2, we see a decrease in performance instead. The decrease in overall customer surplus derives mainly from upper-middle-income countries, as seen in Figure 4. The same figures also show that sales to low-income countries are also responsible for the increase in profitability. As the improvement in profit for vaccine producers is greater than the decrease in savings, the resulting surplus is positive, as shown in Figure 2.

5 CONCLUSION

The trends seen in section 4 suggest that low-income countries benefit from negotiating in conjunction with higher-income countries. Savings for low-income countries are improved, while upper-middle-income countries worsen. This arrangement is also beneficial to vaccine producers. This means that any of the proposed criteria can be used to mitigate the diminished profits seen in previous experiments when not all entities in the vaccine market cooperate. Those results also suggest that coordinating entities such as Gavi limiting their services to low-income countries might induce further savings to target low-income markets if some higher-income countries were included in their pool procurement efforts. The increase in profits might be an incentive for producers to join the coordinated market. The additional access of supply can result in lower-price per dose for UMIC and HIC than if these markets procure on their own. Even if high-income countries cannot be convinced to participate, scenarios O6 and O7 show that affordability and profits can still improve as long as upper-middle-income countries cooperate. To minimize the impact on upper-middle-income countries, criteria O3 (equalizing the population across different coordinating entities) can be implemented to offer improvements to low-income countries and vaccine producers.

ACKNOWLEDGMENTS

This study was funded by The Bill & Melinda Gates Foundation, grant OP1152241.

A APPENDICES

Additional figures and the generated data can be found in the repository https://github.com/ba8641/WinterSimulation2021.git. The manuscript for the unpublished Alves-Maciel and Proano (2021) can be found there as well.

REFERENCES

Alves-Maciel, B., and R. A. Proano. 2021. “Enhancing affordability and profit in a non-cooperative coordinated pediatric vaccine market”. Manuscript under review.

Bertsimas, D., V. F. Farias, and N. Trichakis. 2011. “The price of fairness”. *Operations Research* 59(1):17–31.

Boongasame, L., P. Temdee, and F. Daneshgar. 2012. “Forming buyer coalition scheme with connection of a coalition leader”. *Journal of Theoretical and Applied Electronic Commerce Research* 7(1):111–122.

Chen, J., and D. Sun. 2011. “Resource constrained multirobot task allocation based on leader–follower coalition methodology”. *The International Journal of Robotics Research* 30(12):1423–1434.

DeSarbo, W. S., and D. Grisaffe. 1998. “Combinatorial optimization approaches to constrained market segmentation: an application to industrial market segmentation”. *Marketing Letters* 9(2):115–134.

Gavi, the Vaccine Alliance 2018. “Cost-effective”. https://www.gavi.org/about/value/cost-effective/, accessed 3rd April.

Lau, H., D. Nakandala, P. Samaranayake, and P. Shum. 2016. “A hybrid multi-criteria decision model for supporting customer-focused profitability analysis”. *Industrial Management & Data Systems*.

Milne, R. J., M. Salari, and L. Kattan. 2018. “Robust optimization of airplane passenger seating assignments”. *Aerospace* 5(3):80.

Mosquera, G. 2016. *Vaccine access and affordability in a coordinated market under stochastic reservation prices*. Master thesis, Department of Industrial and Systems Engineering, Rochester Institute of Technology, Rochester, New York. https://scholarworks.rit.edu/theses/8957/, accessed 2nd August 2020.

Ozawa, S., S. Clark, A. Portnoy, S. Grewal, L. Brenzel, and D. G. Walker. 2016. "Return on investment from childhood immunization in low-and middle-income countries, 2011–20". *Health Affairs* 35(2):199–207.

Proano, R. A., S. H. Jacobson, and W. Zhang. 2012. "Making combination vaccines more accessible to low-income countries: The antigen bundle pricing problem". *Omega* 40(1):53–64.

Ray, D., and R. Vohra. 1997. "Equilibrium binding agreements". *Journal of Economic Theory* 73(1):30–78.

Salles, R. M., and J. A. Barria. 2008. "Lexicographic maximin optimisation for fair bandwidth allocation in computer networks". *European Journal of Operational Research* 185(2):778–794.

Şen, C. G., and G. Çınar. 2010. "Evaluation and pre-allocation of operators with multiple skills: A combined fuzzy AHP and max–min approach". *Expert Systems with Applications* 37(3):2043–2053.

The World Bank 2017. "How are the income group thresholds determined?". https://datahelpdesk.worldbank.org/knowledgebase/articles/378833-how-are-the-income-group-thresholds-determined, accessed 18th October 2020.

The World Bank and the GAVI Alliance 2010a. "Brief 12: The Vaccine Market - Pooled Procurement". https://www.who.int/immunization/programmes_systems/financing/analyses/Brief_12_Pooled_Procurement.pdf, accessed 4th April 2020.

The World Bank and the GAVI Alliance 2010b. "Immunization Financing Toolkit: A Resource for Policy Makers and Program Managers". https://www.who.int/immunization/programmes_systems/financing/tools/final_toolkit_2011.pdf?ua=1, accessed 4th April 2020.

World Health Organization 2019. "Immunization Coverage". https://www.who.int/en/news-room/fact-sheets/detail/immunization-coverage, accessed 27th May 2020.

Yu, F., T. Kaihara, N. Fujii, C. Sun, and W. Yang. 2015. "A multi-attribute multi-item negotiation mechanism of supply chain networks between buyers and sellers". *International Journal of Production Research* 53(20):6143–6160.

AUTHOR BIOGRAPHIES

BRUNO ALVES-MACIEL is a Ph.D. candidate in the Kate Gleason College of Engineering of the Rochester Institute of Technology, where he has studied since graduating in Industrial Engineering at the University of Sao Paulo. He has focused his research on global healthcare, developing optimization and simulation techniques to address global welfare for routine vaccine immunizations. Other interests include machine learning-supported optimization, logistics, and data analytics. He is expected to finish his thesis by Summer 2021. His e-mail address is ba8641@rit.edu.

Dr. RUBEN A. PROANO is an associate professor at the Industrial & Systems Engineering department at the Rochester Institute of Technology. He earned his Ph.D. in Industrial Engineering at the University of Illinois at Urbana-Champaign. His research focuses on the application of Operations Research to the solution of health problems. His e-mail address is rpmeie@rit.edu