The Equity-Efficiency Tradeoff: Informing Resource Allocation Policies Through Equity-Aware Epidemic Modelling

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1. INTRODUCTION

Equitable allocation of resources such as vaccines are a central challenge in epidemic response, particularly when disease burden is unequally distributed across population subgroups. While most existing research on epidemic resource allocation focuses on maximizing efficiency, typically by minimizing infections or deaths, relatively little attention has been given to the equity implications of these strategies. Real-world populations often exhibit stark disparities in transmission risk and disease vulnerability, raising questions about how to allocate limited resources fairly. Furthermore, there is no standard definition of equity or consensus on how to incorporate it into optimization frameworks for resource allocation.

To address these gaps, our work systematically characterizes the equity-efficiency tradeoff by **comparing equity-aware optimization strategies** and identifying disparity contexts, such as differences in **transmission and mortality rates**, where equity goals become more or less costly.

2. OBJECTIVES

We will develop a deterministic SIRVQD model to simulate disease outbreaks under unequal disease burden across multiple subpopulations. The model incorporates heterogeneous transmission (β) and mortality (μ) rates, enabling us to evaluate how different vaccine allocation strategies affect health outcomes. Our analysis compares across two dimensions: disparity contexts (transmission vs. mortality differences) and equity-aware optimization strategies. We quantify the **cost of fairness (CoF)**, the efficiency loss when shifting from equity-blind to equity-focused approaches, across varying levels of equity priority.

Our proposed research addresses the key allocation questions: How do population disparities influence the optimal distribution of resources? **How do optimization strategies inform equity in the resource distribution and impact the resulting health outcomes?**

3. METHODOLOGY

Figure 1 shows the disease progression for a single subpopulation. Individuals transition between compartments: susceptible (S), vaccinated (V), infected not in quarantine (I), infected in quarantine (Q), recovered (R), and deceased (D). Susceptible and vaccinated individuals may become infected through contact with infected individuals; vaccination reduces susceptibility, while quarantine reduces infectivity. Infected individuals may enter quarantine and subsequently recover or die. Although the model is set up to include the testing dimension that allows test-seeking individuals to transition to the quarantined compartment upon a positive test result, testing as a resource is outside the scope of this study.

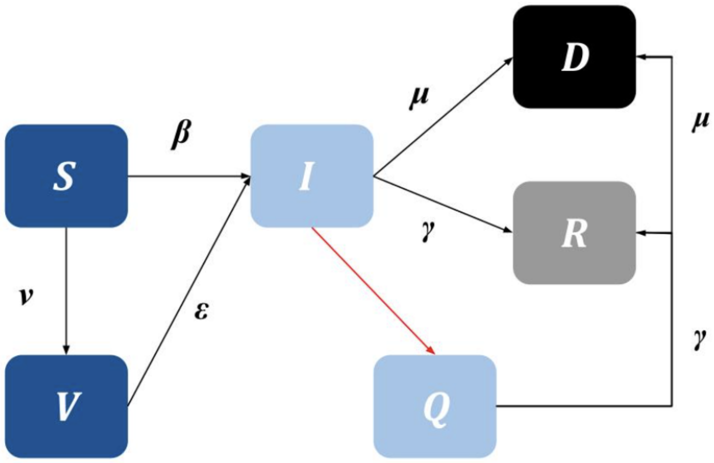

Fig. 1: Model Schematic

We developed a simulation pipeline that supports tuning parameter values for n subgroups, capturing heterogeneity in disease dynamics. By adjusting transmission rates (β) and mortality rates (μ), we model disparities in transmission risk and disease vulnerability. Disease progression is simulated over 100 time steps by repeatedly solving the system of differential equations. For each disparity type, mortality and transmission, we consider two subgroups: Group A with fixed parameters calibrated to measles and Group B with parameters varied across four values, creating A-to-B ratios of 1, 1.25, 1.5, 1.75, and 2. Given an initial supply of vaccines to distribute between Groups A and B, the model determines the optimal allocation percentages that minimize total deaths.

In parallel with simulating varying disparity levels for each disparity type, we computed the optimal vaccine allocation using four equity-aware optimization strategies from the literature:

1. **Objective-function penalization** – a weighted sum balancing total deaths and group-level disparity[1]
2. **Equity-constrained optimization** – efficiency maximization subject to a cap on allowable disparity[2,3]
3. **Min-max optimization** – minimizing deaths in the worst-off group[4]
4. **Nash bargaining optimization** – minimizing the product of differences in deaths between the equity-aware and equity-blind allocations[5]

For each disparity-strategy combination, we run the deterministic simulation and evaluate the **CoF** in terms of deaths and infections, the **Gini coefficient** (ranging from 0 for perfect equity to 1 for maximum inequity), and the resulting **allocation patterns**.

4. RESULTS

Our findings, summarized in Fig. 2, demonstrate that the equity–efficiency tradeoff is highly context-dependent, varying with the type of disparity present. When mortality is the source of disparity, optimal vaccine allocations shift abruptly as equity weight increases, reflecting the higher marginal benefit of preventing deaths directly compared to reducing transmission. This indicates that small changes in equity prioritization can lead to large redistributions of resources in mortality-driven contexts, making allocation decisions more sensitive and potentially more contentious.

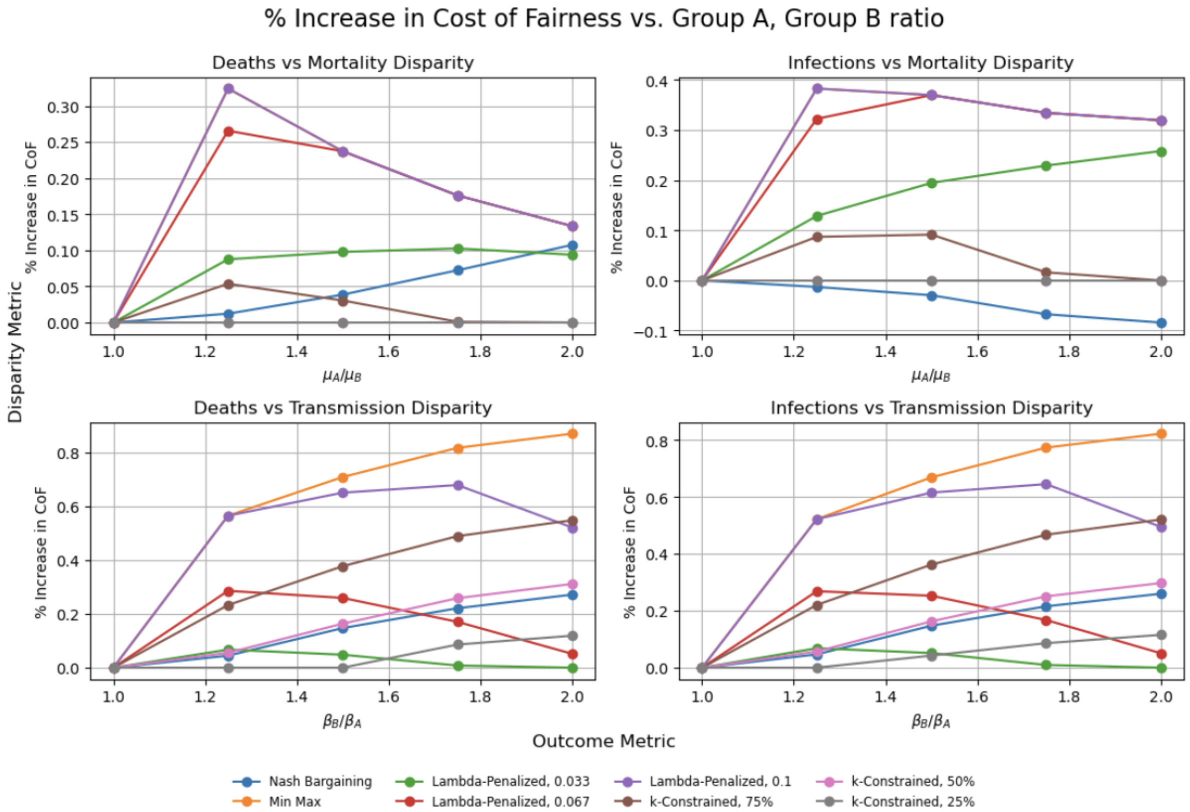

Fig. 2: Summary of CoF

Among the optimization strategies, **Nash bargaining** tends to produce allocations that are evenly distributed between groups. However, under mortality-driven disparities, this approach introduces a notable spillover effect: while total infections are reduced, the number of deaths increases relative to the equity-blind solution, highlighting a tradeoff between outcomes when optimizing for fairness using this strategy. In contrast, **min-max optimization** consistently prioritizes the worst-off group, ensuring strong equity but often at the cost of overall efficiency, which could have significant implications for policy decisions under resource scarcity. Among the optimization strategies, Nash bargaining tends to produce allocations that are evenly distributed between groups. However, under mortality-driven disparities, this approach introduces a notable spillover effect: while total infections are reduced, the number of deaths increases relative to the equity-blind solution, highlighting a tradeoff between outcomes when optimizing for fairness using this strategy. In contrast, min-max optimization consistently prioritizes the worst-off group, ensuring strong equity but often at the cost of overall efficiency, which could have significant implications for policy decisions under resource scarcity. This behavior can be attributed to the allocation patterns inherent in each strategy. As shown in Fig. 3, the Nash bargaining method distributes vaccines relatively evenly across groups, regardless of the level of disparity. In contrast, the min-max strategy consistently allocates all available vaccines to the most disadvantaged group. This difference is further illustrated in Fig. 4, where Nash bargaining exhibits higher normalized Gini values, indicating lower fairness, while the min-max approach consistently achieves a Gini value of 0, representing perfect fairness.

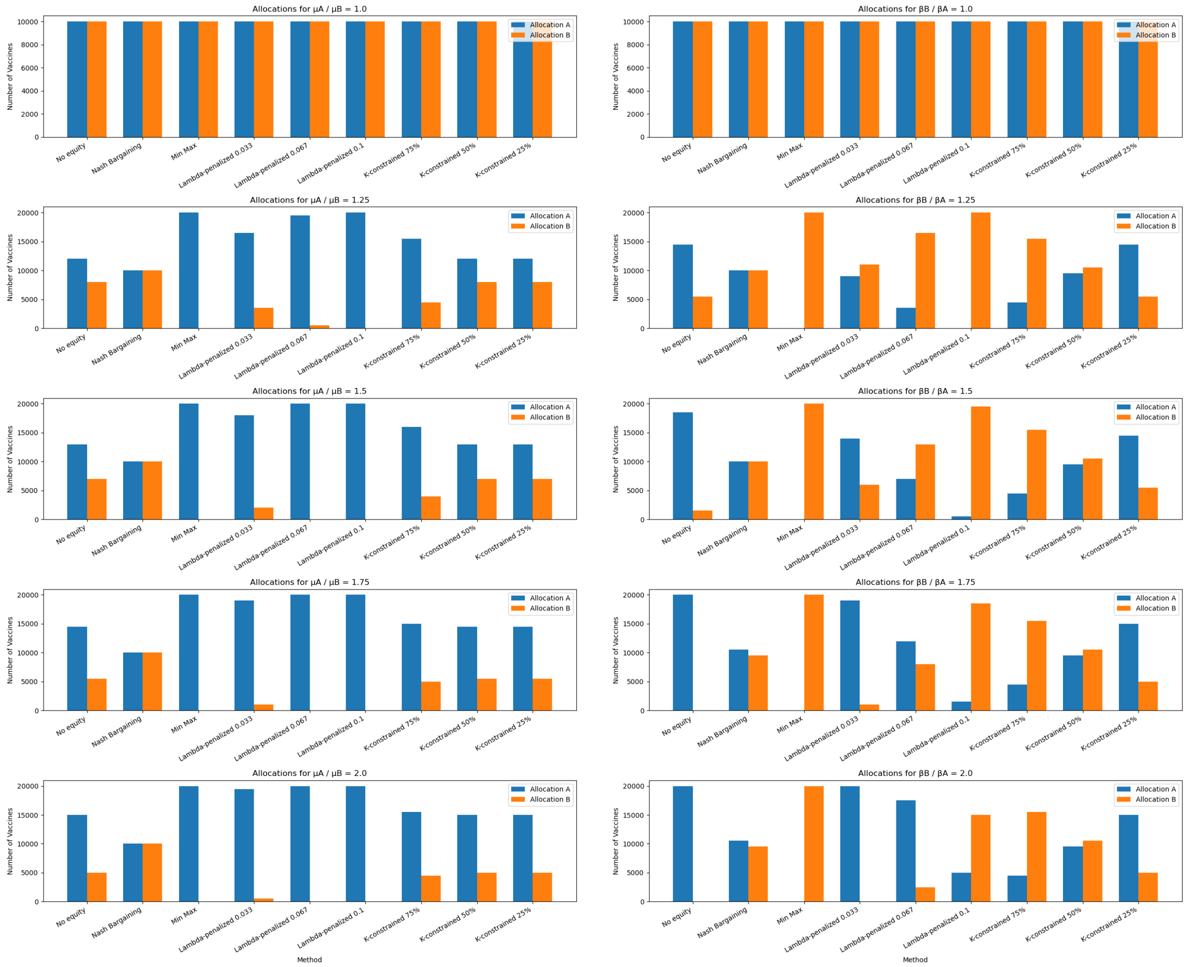

Fig. 3: Allocation Patterns Across Methods and Disparity Levels

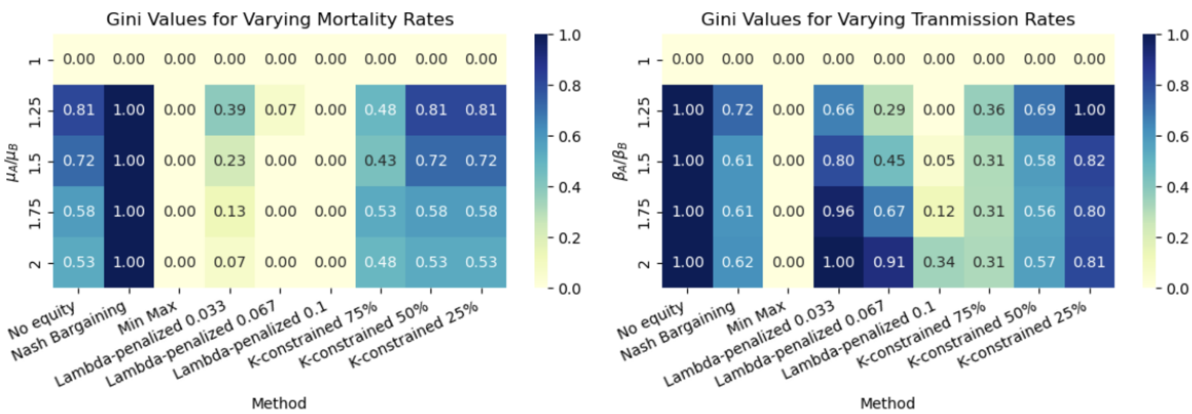

Fig. 4: Summary of Gini Coefficients Normalized Across Rows

Additionally, strategies such as the **equity-constrained approach** exhibit greater robustness across disparity types, maintaining a narrower and more stable range of Gini values. This stability suggests that constraint-based methods may offer a more predictable and controllable mechanism for balancing equity and efficiency, making them potentially more suitable for real-world implementation where variability in population characteristics is expected.

5. BROADER IMPACT

With a 2% annual probability of an outbreak comparable to COVID-19[6] and potential global economic losses reaching up to USD 16 trillion,[7] there is an urgent need for innovative models that can guide resource allocation. Our research will advance epidemic modeling and provide critically needed evidence-informed recommendations for controlling future outbreaks. By explicitly considering equity in resource allocation, our work also aims to reduce disparities in health outcomes across different populations, ensuring that vulnerable groups are not disproportionately affected.

References

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