An Integrated Economic Epidemiology Model Minimizing COVID-19 Burden of Disease and Economic Growth Trade-off

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Introduction

COVID-19 (Coronavirus Disease 2019) is considered the greatest outbreak of the 21st century, causing great loss of human lives and well-being, as well as global economic disruption. Stay-at-home (SAH) orders, while partially responsible for the economic disruption, have been proven to be an effective measure to control the pandemic spread [4]. Furthermore, evidence suggests that SAH might facilitate a quicker economic recovery by alleviating the pandemic, which is the underlying cause of the economic downturn [1]. Therefore, despite the immediate economic challenges posed by SAH orders, their implementation is crucial for long-term public health and economic stability.

Consequently, it is essential to consider models that incorporate both epidemiological and economic factors to minimize the trade-off between the COVID-19 burden of disease and economic growth. While agent-based models have been used to understand and mitigate the disease, they often overlook economic factors crucial for effective disease management [11]. Alternatively, there are SIR (Susceptible-Infected-Recovered) economic epidemiological models that aim to optimize health expenditures [7], but they do not account for the impact of lockdown policies, which is more suited to an SEIR (Susceptible-Exposed-Infectious-Recovered) framework, especially in the context of COVID-19. Hence, integrating economic considerations into SEIR models could provide a more comprehensive approach to managing the pandemic and its economic impacts.

To address these gaps, we propose an integrated economic-epidemiological model that optimizes lockdown policies by balancing disease control and economic growth. Our model, calibrated using both epidemiological data and economic indicators, offers a more comprehensive approach to pandemic management for policymakers. Our study highlights the importance of interdisciplinary research in addressing complex global challenges like COVID-19 and sets the stage for future work in economic epidemiology.

Methods

Data source. We obtained epidemiology data on US COVID-19 cases from The Google Health COVID-19 Open Data Repository [13], vaccination data from [10], and testing data from [8]. We extracted economic data from the Federal Reserve Board up to Quarter 4 of 2023 (Q4 2023) [2].

Covasim implementation. We calibrated our model using Covasim [9] based on cases and deaths in the US from January 2020 to March 2020, allowing us to establish the transmission rate and relative death probability as priors for our simulations. We then employed Covasim to model different scenarios in the US from January 2020 to December 2023, measuring cumulative infections and deaths in response to changes in lockdown policies. Specifically, we simulated different scenarios only varying the lockdown policies but keeping consistent testing, vaccination, and contact tracing interventions to examine their impact.

FRB/US implementation. We used the FRB/US model [2] to investigate how a specific SAH policy could affect the US economy. Firstly, we ran a simulation reversing the effect of the SAH orders implemented during Q2 2020 across the US to determine the economic impact of COVID-19 if no SAH orders had been implemented, serving as our base case. Then, we forecasted the US economic trajectory under the effect of different potential lockdown policies and calculated the loss in Gross Domestic Product (GDP) from Q1 2020 to Q4 2023 compared to the base case. The economic simulation is set up so that all the variables are consistent with historical economic data, except for the "Labor Market" and "Aggregate Output Identities" sector variables. Specifically, the Civilian Employment variable will undergo shocks as an SAH is implemented, resulting in a decrease in GDP.

Integration of economic epidemiological model. We quantitatively assessed the negative effects of COVID-19 on lives, health, and well-being using Disability-Adjusted Life Years (DALY). We calculated the DALY metric according to the step-by-step guide and disability weights (DW) for COVID-19 provided by the European Burden of Disease Network protocol [14]. In calculating Years Lived with Disability (YLD), we categorized COVID-19 patients into four health states: Mild/Moderate, Severe, Critical, and Post-acute with DWs of 0.05, 0.133, 0.655, and 0.219 for these conditions respectively [14]. The average duration an infected individual spends in each compartment before transitioning to another was based on the Covasim model framework [9]. We obtained the number of cases in each compartment from the corresponding outputs of the Covasim model. For compatibility with the Covasim output, we did not differentiate Years of Life Lost (YLL) by age groups but used an average remaining life expectancy of 11.7 years for individuals who died from COVID-19 [6] (Fig. 1). Then, we calculated the monetary value of the human health cost caused by the COVID-19 pandemic at $95,075 USD per DALY, which is 1.46 times the average GDP per capita of the US in 2019 [3]. Finally, we implemented a gradient descent algorithm to evaluate the economic and public health trade-off and minimize the total monetary loss of GDP and DALY.

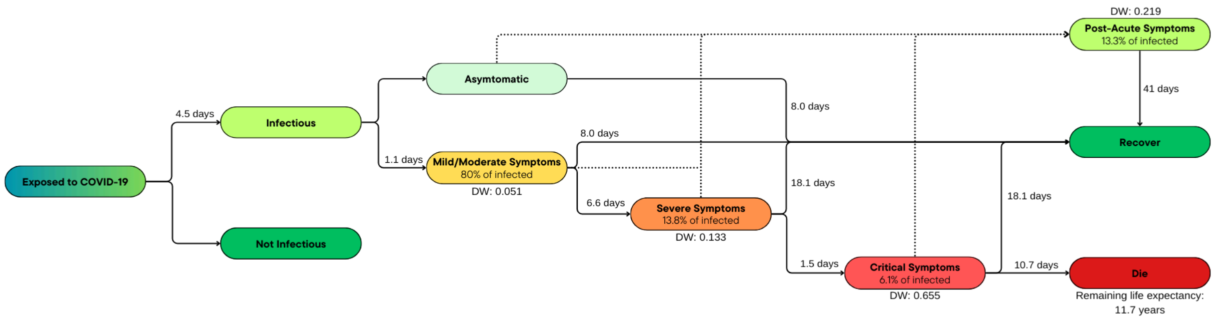

Figure 1. COVID-19 Compartments Flowchart with corresponding Disability Weights

Results

To minimize the trade-off between the COVID-19 burden of disease and economic growth, we designed an integrated economic-epidemiological model architecture using a gradient descent algorithm (Fig. 2). The process begins with defining an SAH order scenario and parameters, including the starting week (week 1 is the first week of 2020) and duration of the SAH order, consistent testing, vaccination, and contact tracing interventions. This scenario is then fed into Covasim and FRB/US, which simulate the impact of the SAH order on disease spread and economic outcomes, as measured by losses in GDP and DALY. Specifically, we modeled our simulation to decrease the number of employed individuals by 1.9% for every additional week of SAH order and to reduce the transmission rate (β) by 50% during the SAH period ([1]; [4]). The result is evaluated using gradient descent to optimize the SAH order, aiming to find the best starting week and duration by minimizing total loss. The process iterates with adjustments based on gradient descent results until the total loss can't be further improved, representing the optimal balance between public health and economic impacts.

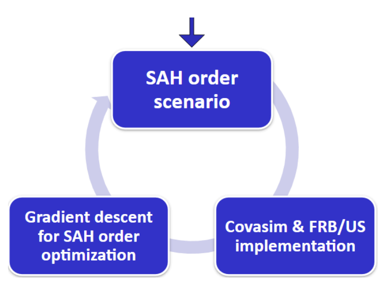

Figure 2. Integrated economic-epidemiological model architecture with gradient descent optimizer

To find the SAH policy with the least total monetary loss to the economy and health, we calculated GDP and DALY losses from January 2020 to December 2023 of different SAH order scenarios using our integrated economic-epidemiological model. Our results showed that the optimal SAH policy is implemented starting the 5th week of 2020, lasting a duration of 15 weeks. This policy resulted in a total combined loss of $11.98 trillion USD (Tab. 1), consisting of a GDP reduction of $2.13 trillion USD (Tab. 1) and a DALY loss of $9.85 trillion USD (Tab. 1).

Table 1. Calculation of Minimal Economic and Health-Related Losses Due to COVID-19.

GDP Loss	**DALY Loss**	**Total Loss**
$2,126,433,593,343.008	$9,850,798,603,090.773	$11,977,232,196,433.781

To evaluate the economic trade-off of our custom SAH policy generated by our integrated economic-epidemiological model, we employed FRB/US to compare the economic effects of a no SAH policy versus our custom SAH policy by measuring GDP loss and civilian employment loss. The simulation period spanned from Q3 2019 to Q4 2023. The no SAH policy was set to have zero loss throughout the simulation period. Overall, there was an immediate negative impact on the economy when our policy took effect in Q1 2020, reaching its worst shortly after in Q2 2020. However, the economy gradually recovered thereafter and reached the same state as before the policy by Q4 2023 (Fig. 3).

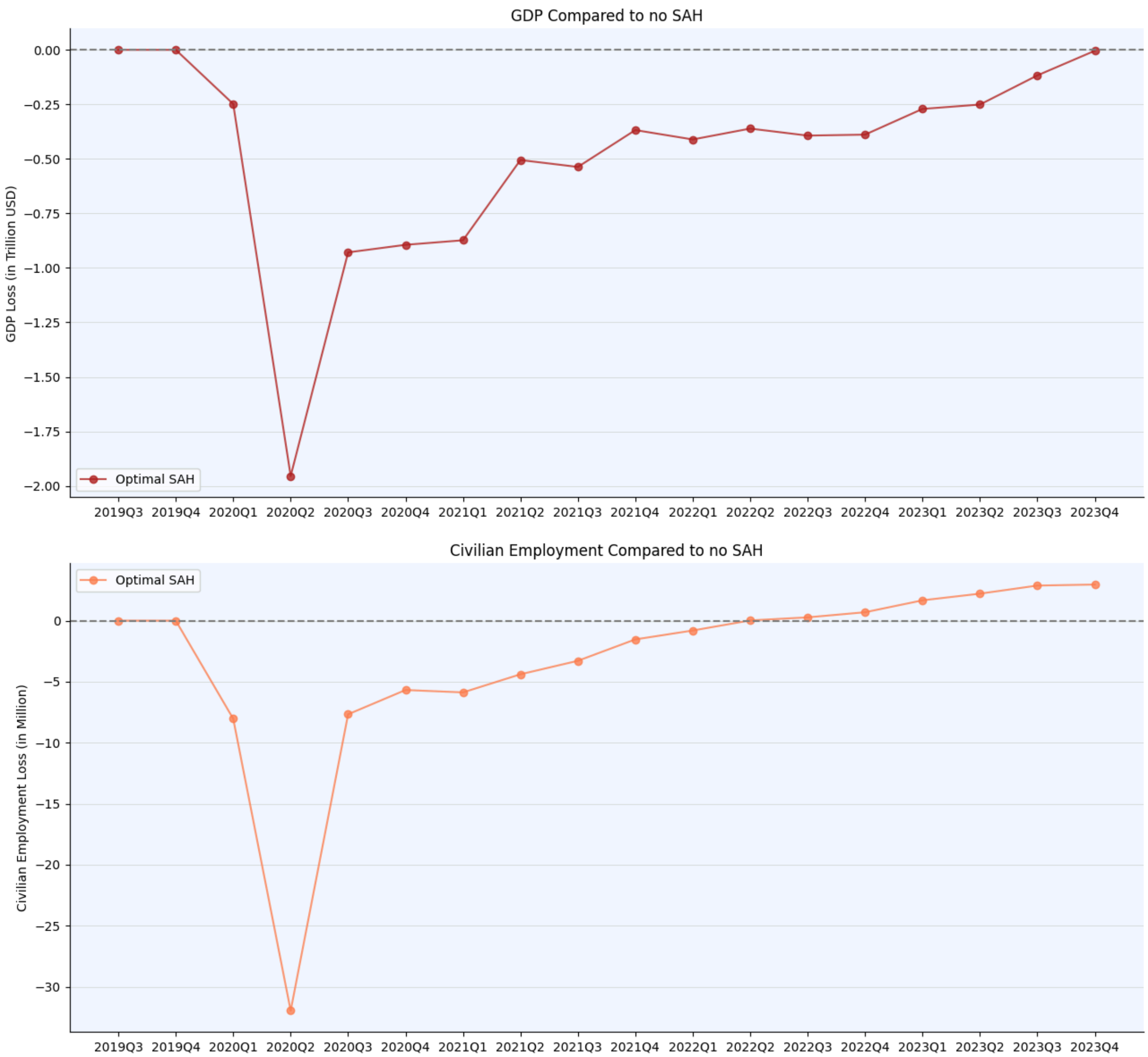

Figure 3. Economic impact of custom SAH policy versus no SAH policy

To assess the COVID-19 burden of disease for our custom SAH policy with minimal economic and health-related losses according to our integrated economic-epidemiological model, we employed Covasim to model different scenarios from 2020 to 2023 and measure cumulative infections and deaths in response to policy changes. The onset of the SAH policy was indicated by the period in which a change in the transmission rate occurred. Consistent testing, vaccination, and contact tracing interventions were also included in all simulations. Overall, our custom SAH policy resulted in a decrease in both cumulative infections and deaths compared to a scenario with no SAH policy (Fig. 4).

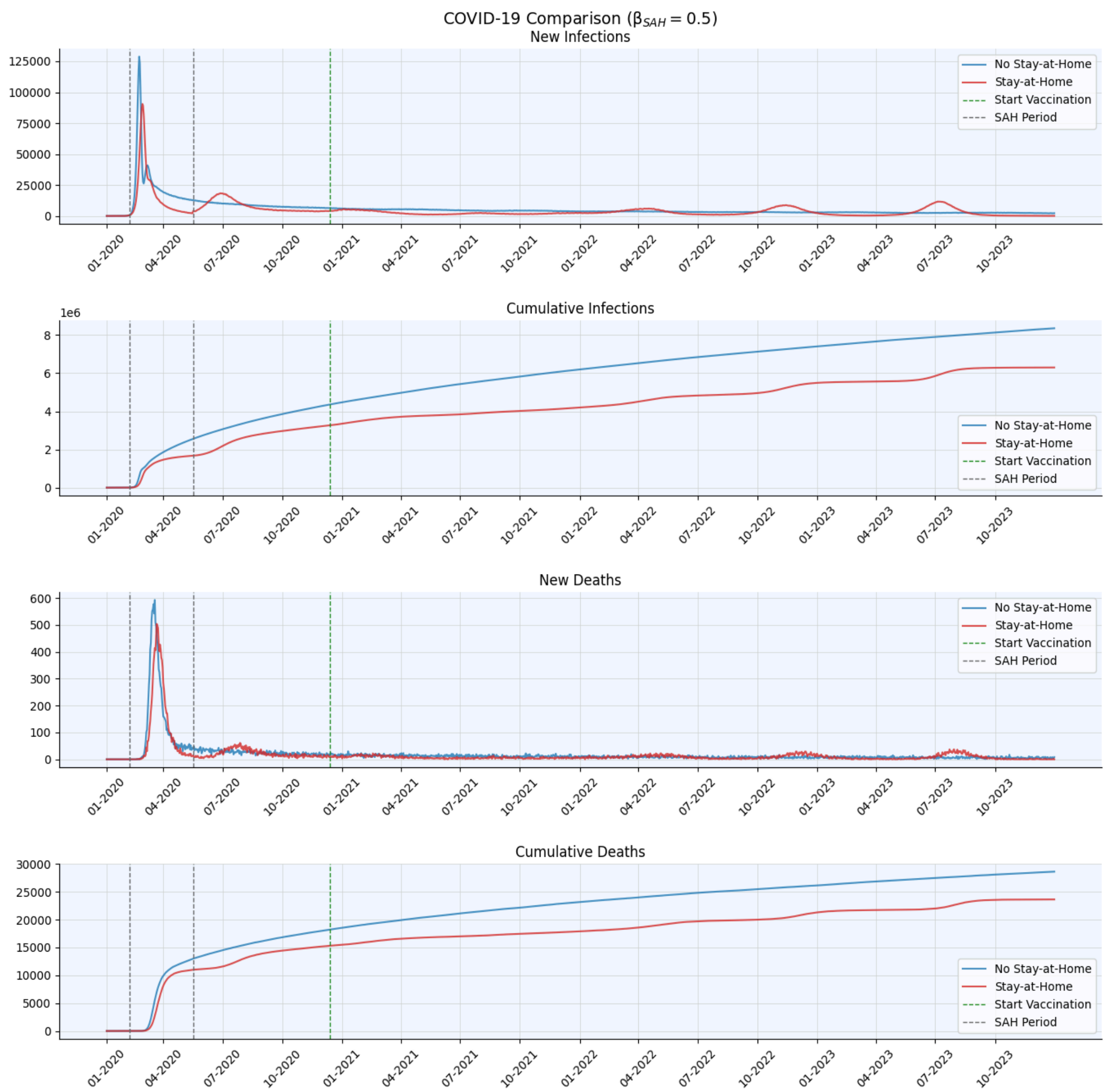

Figure 4. Comparison of COVID-19 outcome per population of 1 million people between the optimal custom SAH policy and no SAH policy

Discussion

This study represents an integrated economic-epidemiological model to optimize lockdown policies by balancing disease control and economic growth. The result shows that the DALY loss outweighs the economic loss. This suggests that policymakers should prioritize controlling the pandemic over maintaining the economy. Specifically, policymakers should prioritize implementing effective, rigid SAH orders. Further experiments showed that if the transmission rate during the SAH period is lowered to 30%, rather than 50%, of the normal rate, the SAH duration would only be 12 weeks instead of 15 weeks. The more cooperative people are with SAH orders, the lower the transmission rate will be.

Our experiment was designed to find the one optimal continuous SAH period that is universally applied to the entire population, balancing out the pandemic and economic impact. The general optimal solution to the pandemic likely involves multiple disjoint SAH periods, localized to the areas with bad epidemiological progression, so the SAH orders are more effective in slowing the pandemic progression to wait for vaccination, as well as minimizing the recessive effects on the economy. However, due to the limited computing resources and the inherent structure of the underlying frameworks, we leave this for future research. Overall, our study sets the stage for incorporating an economic-epidemiological framework to tackle complex interdisciplinary global challenges like COVID-19, warranting further investigations.

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