Public policy and economic dynamics of COVID-19 spread: a mathematical modeling study

Uri Goldsztejn*[1], David Schwartzman*[2], and Arye Nehorai[3]

[1]Washington University in St. Louis, Department of Biomedical Engineering, St. Louis, 63130, USA
[2]Washington University in St. Louis, Olin School of Business, St. Louis, 63130, USA
[3]Washington University in St. Louis, Department of Electrical and Systems Engineering, St. Louis, 63130, USA

* These authors contributed equally to this work.

Corresponding author: Dr. Arye Nehorai.
Email: nehorai@wustl.edu

Abstract

With the COVID-19 pandemic infecting millions of people, large-scale quarantine policies have been enacted across the globe. To assess the impact of quarantine measures on deaths, hospitalizations, and economic output, we expand the classical SEIR model to simulate the spread of COVID-19, incorporating effects of restrictive measures and segmenting the population based on health risk and economic vulnerability. For 76 weeks in a population of 330 million, we simulate a baseline scenario leaving current quarantine restrictions in place, rapidly reducing quarantine restrictions for non-seniors shortly after outbreak containment, and gradually relaxing quarantine restrictions for non-seniors. In the baseline scenario, there are 207,906 deaths and the economy shrinks by 34.0%. With a rapid relaxation, a second outbreak takes place, with 788,815 deaths, and the economy shrinks by 28.2%. With a gradual relaxation, there are 221,743 deaths, and the economy shrinks by 29.4%. Additionally, hospitalizations, deaths, and economic output are quite sensitive to disease spread by asymptomatic people. Strict restrictions on seniors with very gradual lifting of quarantine for non-seniors results in a limited number of deaths and lesser economic damage. Therefore, we recommend this strategy and measures that reduce non-quarantined disease spread to control the pandemic while making quarantine economically viable.

Keywords: coronavirus, economy, quarantine measures.

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Introduction

As of April 10th, 2020, the number of confirmed cases of coronavirus disease 2019 (COVID-19) worldwide stands at over 1,690,000, and at least 102,500 individuals have died from this disease since the first reports of a pneumonia of unknown etiology in December, 2019. (1; 2; 3) As COVID-19 expands to new territories, after a latent phase with few new reported infections daily, the virus spreads rapidly and local outbreaks begin. The virus's containment is complicated by its high transmissibility, relatively low case fatality rate, and lengthy asymptomatic infectious period. (4) Currently, the most successful measure to prevent the rapid expansion of COVID-19 has been to implement quarantine policies to restrain travel and physical interactions between individuals. (5; 6)

Extreme quarantine policies have devastating consequences for the global economy. Quarantine policies may be an effective short-term measure, but indefinite quarantine until a vaccine becomes available would prevent billions of individuals worldwide from receiving an income, and could particularly devastate countries with weaker economies. This economic harm could increase mortality given the correlation between mortality and income, (7) especially for children. (8)

Computational models that simulate the expansion of the disease can guide public policy makers in mitigating the detrimental outcomes of the outbreak (9). Existing epidemiological models estimate the number of unknown infected individuals, forecast the number of patients requiring intensive care treatment, predict the death toll, and evaluate the outcomes of different policies.

In compartmental modeling, different disease stages are modeled as compartments, and transitions between compartments are modeled by a system of differential equations. (10) Compartmental models provide useful insight into the mechanisms governing the spread of the disease and help evaluate public policies. (11; 12; 13) Some papers focus on how quarantine restrictions affect disease spread. (6; 13; 14; 15; 16) Time series approaches use available data to statistically forecast the evolution of the disease. (17; 18; 19) While times series models have precise results, they do not illuminate the dynamics of the disease spread. To accurately predict the spread of disease and evaluate consequences beyond the infectious disease itself, models must take into account how mitigation measures might impact the economy. (20; 21; 22) Existing epidemiological models usually do not integrate the economic aspects of public policy aimed at controlling the spread of the disease. To the best of our knowledge, no models incorporating public policy responses take into account both the distinctions in risk types within the population and the differential economic impacts of quarantine policies.

We propose an ad hoc compartmental model for the spread of COVID-19 and the economic effects of quarantine restrictions. Our model includes, among other compartments, a large group of asymptomatic infected individuals and compartments that represent quarantined individuals. We separate the population into four groups in our simulations, according to age and the economic impact of remaining in quarantine for an extended period of time. Upon infection, senior individuals present much larger co-morbidity and mortality rates than younger individuals. Also, generalized country-wide lockdowns completely suppress the productivity of some workers while having minimal implications for others. By modeling our population as having different risk groups, economic risks from quarantine, and productivity levels, we can make more specific predictions, and are able to provide more targeted policy recommendations than existing methods. Since the state of the economy has important health effects and that public policy needs to incorporate economic effects and how citizens perceive lockdown restrictions, we model public policies that balance the number of deaths and damage to economic productivity. In addition, we model improvements in medical knowledge about a recently discovered disease as decreasing the case fatality rate over time.

Our simulations yield three main findings: 1) maintaining a non-strictly enforced quarantine policy and releasing the population after disease levels begin diminishing would lead to a second outbreak. 2) an extremely strict quarantine policy for the senior population, combined with an extremely gradual removal of mandatory quarantine for younger citizens after the outbreak is largely controlled, can lessen economic damage without catastrophic increases in the number of hospitalized and dead individuals. However, if the quarantine policy for the senior population is not strictly enforced, there can be disastrous consequences. No quarantine restriction approach resolves the pandemic, and lockdown policies can only be used as a bridge to a global vaccination program. 3) Strict isolation policies and a strong reduction of contagiousness from the asymptomatic infected individuals can reduce the total number of hospitalizations and the number of deaths as compared to loosely enforced measures. Therefore, stark measures must be enforced to prevent a prolonged pandemic.

Results

Model overview

We use an expanded SEIR model, incorporating different levels of disease risk and economic damage from quarantine, as well as improved disease knowledge over time. We present the health and economic dynamics of our model.

Epidemiological model and dynamics

To model the spread of COVID-19, we design a compartmental model with ten interconnected compartments. Each compartment is subdivided into two parts, one containing the senior population and the other containing the rest of the population.

The connectivity of the compartments is illustrated in Fig. 1, and the abbreviations used are listed in Table 1. Susceptible individuals get exposed to COVID-19 at a rate proportional to the number of asymptomatic and hospitalized infected individuals. Exposed individuals then become infected and asymptomatic. These individuals can either recover from their current state or develop serious symptoms and become hospitalized. The fraction of infected

asymptomatic individuals that become hospitalized follows a Bernoulli distribution, with a low probability for the general population and a higher probability for the senior population.
The hospitalized individuals either die or recover at appropriate rates, which depend on whether the hospitalized population is above certain saturation points. The case fatality rate decreases over time to account for better knowledge by the healthcare system.
Individuals who are not hospitalized enter or leave quarantine compartments according to public policy, expressed by κ and $\theta' \cdot v$, where v is a vector containing the number of reported infections, deaths, and the current state of the economy, and θ is a weight vector that reflects the relative importance the public policy gives to the economy and the number of cases. The Greek letters represent the transition delays between the compartments and were derived from published data about the progression rate of COVID-19.

Economic Model and Dynamics

In our model, there are occupations more affected by lockdown and occupations less affected by lockdown. In our simulation, we have two types of workers: those whose productivity is highly damaged by a quarantine and those whose productivity is less damaged. The total economic output is the sum of the outputs of the individuals in each group minus the costs of treating the infected. For the long-term economic output beyond the pandemic period, deaths impose a penalty on future economic output, dependent on the discount rate r.
The productivity of each labor group is the sum of the productivity of all the individuals in that labor group. The cost of treating the infected is the number of individuals of each risk type times the cost of treating each risk type. Different workers of the same labor type might be under different lockdown restrictions based on their age or risk type. In our simulation, there are four levels of productivity for four types of workers: older workers whose jobs are highly damaged by a lockdown (y_{HRH}), older workers whose jobs are less damaged by a lockdown (y_{HRL}), younger workers whose jobs are highly damaged by a lockdown (y_{LRH}), and younger workers whose jobs are less damaged by a lockdown (y_{LRL}). The workers whose jobs are highly damaged by a lockdown lose a higher percentage of their productivity (represented by ψ) than workers who jobs are less damaged by a lockdown (represented by ϕ).
The dynamics of output in this model depend on the rate at which workers in different productivity and health groups move in and out of quarantine and the rates with which their health states change. A complete mathematical description of the model, and the values used for transfer rates, appear in the Appendix. Additionally, a full simulation, showing the evolution of the number of individuals in every compartment is shown in Supplementary Fig. 1.

Using a population of 330 million, we simulate the evolution of public policy given the preferences of the policymakers over 76 weeks. In each scenario, to imitate current strict lockdown policies, we start with 85.6 % of non-seniors and

Abbreviation	Description
S	Susceptible population
Q^S	Quarantined susceptible population
E	Exposed population
Q^E	Quarantined exposed population
I^H	Infected hospitalized population
I^A	Infected asymptomatic population
Q^{I^A}	Quarantined infected asymptomatic population
D	Dead population
R	Recovered population
Q^R	Quarantined recovered population

Table 1: Abbreviations used in the compartmental model.

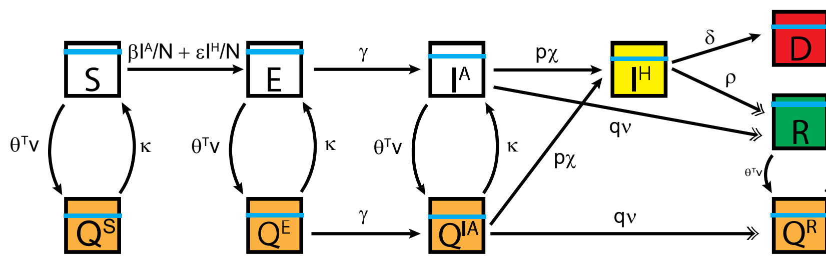

Figure 1: **Compartmental model.** Each box represents an individual compartment and the arrows represent transitions between the compartments. The individuals in every compartment are divided by age, as represented by the cyan bars, and by their productivity, as represented by the background color of the boxes. White boxes represent normal productivity, dead individuals (in red) have no productivity, quarantined individuals have a decreased productivity, and hospitalized individuals have no productivity and incur into treatment costs. As individuals recover, they receive a small boost in productivity due to their acquired immunity.

95.6 % of seniors in quarantine. Public policy and media information shifts the population in and out of quarantine. We keep the non-quarantined population above zero because some jobs that could potentially spread disease continue to operate because they are deemed essential in a pandemic economy. For this reason, there is not much room for further strengthening the quarantine for non-seniors.

Baseline scenario

In the baseline scenario, we keep the current quarantine status ($\theta = 0$, $\kappa = 0$). Leaving the quarantine in place results in 207,906 total deaths. The peak number of hospitalized is 189,136, which strains hospital capacity but does not saturate it, as shown in Fig. 2a and Fig. 2c. Deaths first accelerate as more non-quarantined people get infected, but then level off. There are 32,131 deaths among non-seniors and 175,775 among seniors, as shown in Fig. 2b and Fig. 2d, respectively. Since both young people and seniors have strict quarantine restrictions imposed on them, most of the deaths occur in the senior population, which is more vulnerable to the disease.

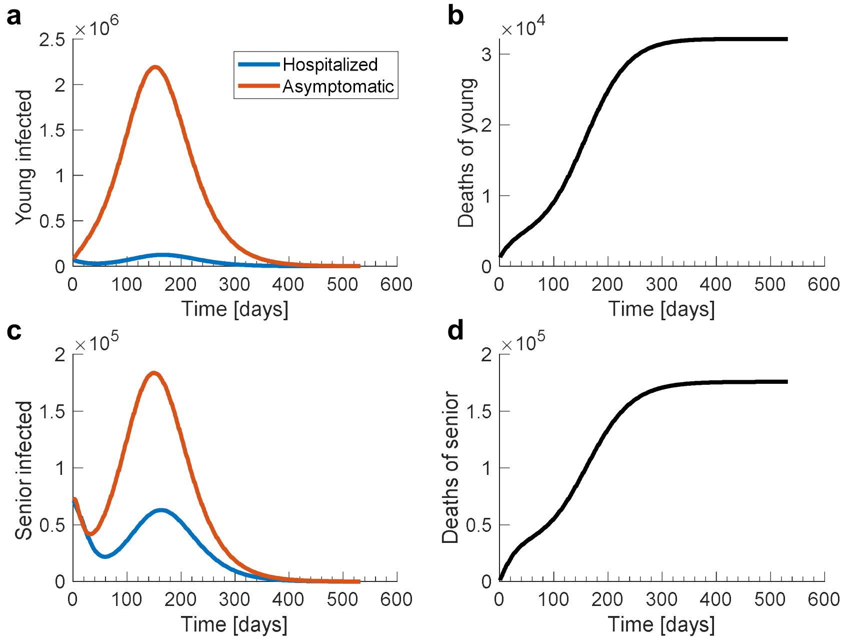

Figure 2: **Compartments in the baseline scenario.** **a**. Number of infected asymptomatic and hospitalized young individuals. **b**. Number of deaths for the younger population. **c**. Number of infected asymptomatic and hospitalized senior individuals **d**. Number of deaths in the senior population.

The economy in the baseline scenario, shown in Fig. 3, shrinks slightly from its initial restricted levels, as some people are hospitalized and die. This is costly for the economy, and there is no increase in productivity from others, as they are all still in quarantine. Given that the initial restrictions on economic output are high, the economic productivity in this scenario is quite low for a prolonged period of time.

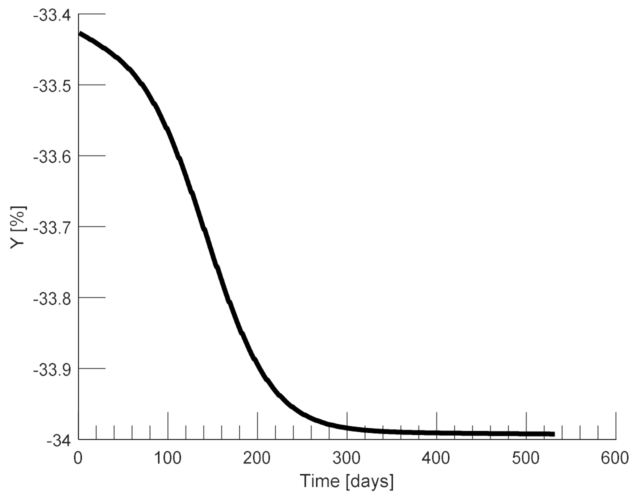

Figure 3: **Economic output in the baseline scenario.** The economic output is measured as the total productivity of all the individuals in the population minus the costs of treating the hospitalized. The economy is shown as a percent change from pre-virus productivity.

Sudden release of the population after control of outbreak, but before complete eradication

In this scenario, we maintain the quarantine policy detailed in the baseline simulation, and then release the non-senior isolated population at a rate of 10 % daily and the senior population at a rate of 0.1 % daily. As can be seen in Fig. 4a, when the isolated population is released in week 40, a large second outbreak soon takes place after the release of the population. With a sudden release, the peak number of hospitalized is 4,363,654, which exceeds hospital capacity enough to increase the fatality rate. There are 788,815 total deaths, as shown in Fig. 4b, with 242,869 deaths among non-seniors and 545,946 among seniors, necessitating a re-imposition of restrictions.
Fig. 4a shows a decreasing number of infections before the second outbreak. During this period, the very low number of newly infected and deaths may suggest that COVID-19 has been successfully mitigated, and the pressure to resume normal activities may grow. The economy is strongly boosted shortly after strict restrictions are removed. However, due to the large initial fraction of asymptomatic infected individuals, a sudden relaxation of quarantine restrictions after the disease is largely controlled leads to a second outbreak, with increased deaths and infections. The economic dynamics of this scenario are shown in Fig. 4c. After a short-term economic boost, the second outbreak damages economic productivity again, although the productivity boost for quarantined recovered individuals leads to a smaller jump.

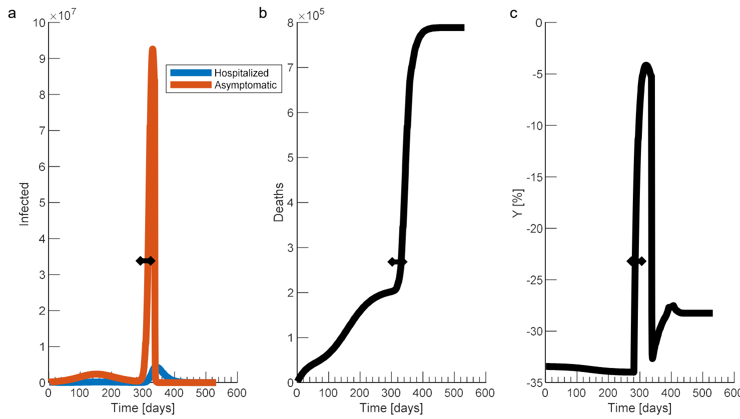

Figure 4: **Sudden release of quarantine measures after outbreak containment.** Completely relaxing the quarantine measures after the outbreak is controlled but before completely eradicating the virus leads to a second outbreak. **a**. Number of infected asymptomatic and hospitalized individuals in the total population. **b**. Number of deaths in the total population. **c**. Economic productivity. The black bars indicate the period while the quarantine measures are removed. The quarantine measures are re-enforced after the second outbreak takes place.

Progressive restart of the economy before the pandemic is over

In this scenario, we investigate a gradual relaxation of the quarantine restrictions. Various studies have shown that the case fatality rate for the senior population is larger than that of the younger population.(23; 24) The marked difference in mortality according to age suggests that enforcing an extremely strict isolation policy for the senior population while allowing the general population to slowly resume normal activities could potentially balance disease spread and economic damage. As in the sudden release scenario, policymakers loosen quarantine restrictions in week 40, releasing the non-senior isolated population at a rate of 0.1 % daily. This gradual relaxation does not lead to a second outbreak, as can be seen from the number of infected individuals in Fig. 5a and Fig. 5c. In this state, the peak number of hospitalized is 189,136, which does not saturate the health care system. There are 33,750 non-senior deaths and 187,993 senior deaths, as shown in Fig. 5b and Fig. 5d, respectively. In this scenario, there are 13,837 more deaths than in the baseline scenario and a 29.4 % decrease in economic productivity, with output trending upwards as more individuals are released from quarantine.

We see in Fig. 5 and Fig. 6 that relaxing restrictions on seniors as well does not improve economic productivity and results in substantially more deaths. Additionally, if the rate at which the general population abandons isolation measures increases rapidly, a second outbreak could take place. Strict enforce-

ment of quarantine restrictions for seniors is vital, as without strict enforcement for senior individuals, the number of deaths is almost one million.
Economic output is higher in the gradual quarantine relaxation scenario with strict enforcement of quarantine for seniors. However, since in this scenario COVID-19 becomes endemic and does not disappear, relaxing isolation policies for the senior population at any time leads to an extremely large number of hospitalized and dead individuals. Therefore, although this scenario can lead to an acceptable economic situation with a controlled number of hospitalizations and deaths, it is not a viable long-term solution. Any quarantine policy that does not eliminate the disease can serve only as bridge to a global vaccination campaign.

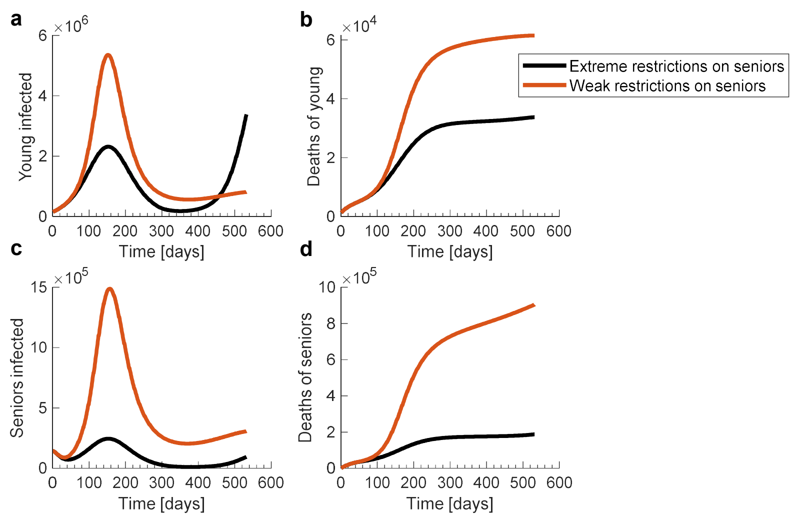

Figure 5: **Progressive release of the young population with extremely strict quarantine measures for the seniors.** **a**. Total number of infected young individuals, including the hospitalized individuals. **b**. Deaths in the young population. **c**. Total number of infected senior individuals including the hospitalized individuals. **d**. Deaths in the senior population. **a-d**. The black curve represents the scenario where the quarantine policies for the seniors are extreme. The red curve represents the scenario where the policy is weakly implemented and the quarantine measures for the senior population are not extreme.

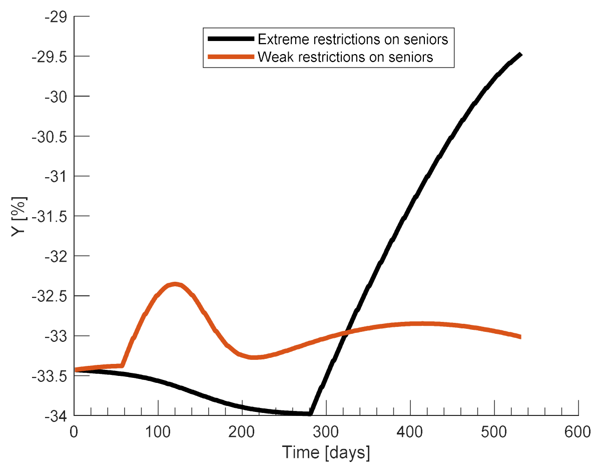

Figure 6: **Economic effect of extreme quarantine policies for seniors and relaxed policies for the young.** The productivity of the society over time with respect to the pre-virus state. The black curve represents the scenario where the quarantine policies for the seniors are extreme. The red curve represents the scenario where the policy is weakly implemented and the quarantine measures for the senior population are not extreme.

Effect of public policy on controlling the spread of COVID-19

First, from Fig. 7a-c, we observe that the total number of hospitalizations and deaths decrease with the strictness of isolation of hospitalized patients (ϵ), while economic productivity grows slightly. We see a much larger decrease in hospitalizations and deaths, and a larger increase in economic productivity, as disease spread of asymptomatic patients (β) is reduced. This observation suggests the importance of public health measures that slow disease spread among non-quarantined individuals that do not know their disease status.
Secondly, from Fig. 7d-f, we observe that as the strictness of isolation measures increase, the number of deaths and hospitalizations decrease, while economic output is first flat, and then at certain level of quarantine measures, begins to sharply decrease. Meanwhile, at higher levels of quarantine restrictions, the change in hospitalizations accelerates, but the change in deaths decelerates.
Finally, we see in Fig. 7g-i that as policymakers put more emphasis on economic productivity, at lower levels of emphasis, there are increases in hospitalizations, deaths, and economic productivity, but as the policymaker prioritizes the economy more, hospitalizations and deaths continue to increase, while economic output shrinks. We see that if policymakers value short-term economic productivity highly relative to disease spread, there is a danger of quarantine policies leading to larger death tolls.

Scenario	Baseline	Sudden release	Gradual Release
Peak number of hospitalizations	189,136	4,363,654	189,136
Non-senior deaths	32,131	242,869	33,750
Senior deaths	175,775	545,946	187,993
Net change in productivity	-34.0%	-28.2%	-29.4%

Table 2: **Summary of predicted results from the different scenarios.** Maximum number of simultaneous hospitalizations during the pandemic, deaths from the non-senior and senior populations, and net change in productivity from current situation to a year and a half from the time of submission. In the baseline scenario, the restrictions do not change. In the sudden release scenario, after the disease is mostly brought under control, restrictions for non-seniors are suddenly relaxed. In the gradual release scenario, after the disease is mostly brought under control, restrictions for non-seniors are gradually relaxed.

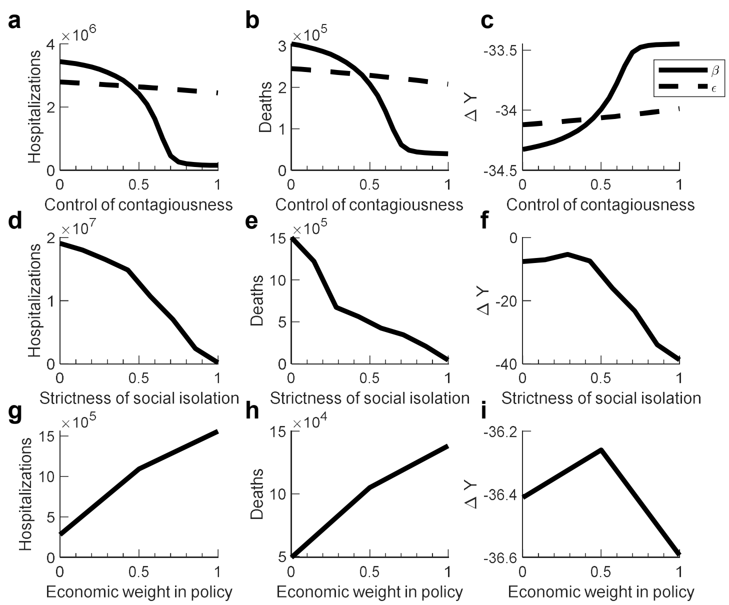

Figure 7: **Sensitivity analysis. a-c**. Total hospitalizations, deaths, and net change in economic productivity for one and a half years depending on the control of contagiousness of asymptomatic (β) and hospitalized (ϵ) individuals. **d-f**. Total hospitalizations, deaths, and net change in economic productivity for one and a half years depending on the strictness of enforcement of quarantine measures. **g-i**. Total hospitalizations, deaths, and net change in economic productivity for one and a half years depending on the relative importance of the economic situation in the public policies.

Discussion

We present a model of COVID-19 in a population with different risk groups and different levels of economic vulnerability to public policy aimed at preventing disease spread. We focus our model on a situation where disease is ongoing and quarantine measures are already in place. By modeling our population with different risk groups and economic groups, we are able to produce specific policy suggestions that allow for a finer targeting of the spread of COVID-19. The individuals most vulnerable to COVID-19 are primarily those who can be protected from the disease without crippling the economy. We suggest stringent lockdowns for higher-risk groups. Our simulations show that in order to protect the most vulnerable, any lockdown relaxation must be gradual, even for the less vulnerable.

Beyond the short-term, lockdown policy does not need to be as severe for lower-risk groups. Quarantine restrictions can lessen over time for lower-risk people while still minimizing deaths. Lessening quarantine restrictions allows the economy to recover to -30 % of pre-restriction productivity, as opposed to -34 % when quarantine restrictions are left in place. It is important that policy relaxation be gradual, as this limits the spread of disease, and can allow for less restrictive measures in the future. In real-world terms, the gradual relaxation suggested by our model can correspond to the lifting of restrictions on in-person work operations several industries at a time, or to gradually increasing the number of low-risk people allowed to gather in one place. However, unless measures are relaxed slowly, a second outbreak occurs, so recovery of economic output is slow.

These results also suggest that optimal policies may differ in various countries independent of the level of disease spread and healthcare capacity. For instance, in countries with more vulnerable economies that have a younger population, the consequences from disease may be less than in other countries, while consequences from lockdown policies may be higher than in other countries.

We also see that contagiousness of asymptomatic infected individuals (β) has an important effect on disease spread and mortality, and this suggests that strictly enforcing quarantines is especially important for policymakers to prioritize. Measures that decrease spread out of quarantine, such as universal mask-wearing, and increased testing to inform asymptomatic infected individuals of their status could reduce contagiousness. Lower β could allow for quarantine measures to be relaxed more quickly. However, if policymakers prioritize short-term economic productivity more, their quarantine policies may lead to many times more deaths and hospitalizations with minimal short-term economic gain. Our results demonstrate that keeping a stringent quarantine on at least a substantial portion of the population is necessary to avert large numbers of deaths. More investigation is required as to how to keep such a quarantine sustainable over time, both through targeted relaxation, as we suggest, but also through safe provision of services to the quarantined and increased infrastructure for at-home economic productivity. (25) More workers may be required for maintaining a quarantined population over time. Additionally, continued compliance with quarantine may require a variety of measures, including enforcement, education from public health officials, and infrastructure for alternatives to traditional social and entertainment options.

Furthermore, policymakers should use other tools to supplement quarantine policy, including contact tracing and other containment measures. Successful quarantine policy can more quickly bring disease levels down to a level where more targeted tools can control future outbreaks. Our simulations suggest that quarantine policy alone cannot end a pandemic without a level of enforcement that may not be realistic, and one that necessitates extreme economic costs. Thus, policymakers should quickly incentivize vaccines and other medical treatments.

Our study has several limitations. Since there is no recent data on long-term health quarantines, it is unknown how individuals will react to lengthy restrictions related to infectious disease. Once more information on individuals' responses becomes available, their behavior should be incorporated into later models. We also do not model any individual-level differences in behavior or disease spread. This model could also be modified to incorporate the effects of testing and to have probability of infection depend on job type. Our model does not allow for any differences in disease spread between new and repeated contacts. (26; 27; 28) Additionally, due to the newness of COVID-19, the exact disease parameters and the effects of seasonality are not precisely known. (29; 30) Because of the uncertainty surrounding disease parameters, which change as the COVID-19 situation progresses, our numbers should not be taken as literal predictions, but rather as illustrating the consequences of different policy approaches.

During a fatal infectious disease outbreak of lengthy duration, making policy decisions with longer term consequences in mind is essential. Our model provides a framework for making such decisions that takes into account differences within the population and disease changes that may occur over time. We provide evidence about what quarantine policies may allow for minimal deaths while maximizing economic productivity. We find that once infection levels are somewhat controlled, very gradual relaxation of the restrictions on younger groups can minimize health consequences and economic damage.

Contributors

U.G. designed the study, searched the literature, derived and implemented the epidemiological part of the model, ran the simulations, prepared the figures, analyzed and interpreted the results, and drafted and wrote the manuscript.

D.S. contributed to the design of the study, searched the literature, derived and implemented the economic part of the model, ran the simulations, analyzed and interpreted the results, and drafted and wrote the manuscript.

A.N coordinated the study, contributed to model design, and helped in preparing the manuscript.

U.G. and D.S. contributed equally to this work.

Declaration of interests

We declare no competing interests.

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