Integrated Assessment of Epidemic and Economic Dynamics

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Abstract

In this paper, a simple integrated model for the joint assessment of epidemic and economic dynamics is developed. The model can be used to discuss mitigation policies like shutdown and testing. Since epidemics cause output losses due to a reduced labor force, temporarily reducing economic activity in order to prevent future losses can be welfare enhancing. Mitigation policies help to keep the number of people requiring intensive medical care below the capacity of the health system. The optimal policy is a mixture of a temporary partial shutdown and intensive testing and isolation of infectious persons for an extended period of time.

JEL: E1, H0, I1.

Keywords: *Coronavirus, economic growth, epidemic modeling.*

1 Introduction

What are the economic effects of the coronavirus pandemic that spreads globally and what are the economic effects of mitigation measures? The coronavirus causes a disease (COVID-19) that prevents people from working, and a certain share of infected people dies. Therefore, economic output is temporarily reduced by ill people and permanently by deaths. Jordà et al. (2020) show that previous pandemics since the 14th century had severe long-run effects. The number of deaths does not only depend on the number of infected persons but also on the relationship between hospitalized persons and intensive care capacity. If the number of infected persons exceeds a certain threshold, the case fatality rate increases. It is therefore welfare enhancing to mitigate the spread of the virus. Accordingly, the long-run economic effects of non-pharmaceutical measures that depress economic activity in the short-run can be positive like for example in some cities in the U.S. during the 1918 flu (Correia et al. 2020). The more aggressive short-run responses are the lower long-run negative effects on output may be (Ma et al. 2020).

We discuss the economic effects of an epidemic and of mitigation policies in the standard neo-classical growth model.[1] In a no-epidemic baseline scenario, we simulate the trajectories of employment, output and consumption per capita. Then we integrate an extended epidemic SIR (Susceptible-Infectious-Recovered) model into the economic framework (Integrated Epidemic Assessment Model, IntEAM).[2] The extended SIR model includes an incubation period (exposed persons) and distinguishes between symptomatic and asymptomatic infectious persons. In section 2, we first show that the negative impact of the epidemic on excess deaths and on output loss depends on the basic reproduction number of the epidemic. In the next step, we introduce two different mitigation policies into the model: mitigation by shutdown of the economy and mitigation by testing and isolating infectious persons. Shutdown is a brute force method to reduce the overall contact rate in the population. This can be very effective to reduce the number of deaths even if the shutdown only affects a certain fraction of total population. However, a (partial) shutdown of the economy is very costly in terms of output loss. Testing and isolating infectious persons is much cheaper but only as effective as a partial shutdown if it is possible to test the complete population for an extended period of time. We distinguish between the intensity and the duration of the mitigation measures. In section 3, the feasible optimal combination of shutdown intensity and duration and testing intensity and duration is determined with respect to the minimal number of excess deaths, minimal output loss and maximal welfare derived from an aggregate utility function. A temporary partial shutdown of the economy together with an extended period of intensive testing turns out to be the optimal strategy.

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[1] We take the perspective of a central planner and to not explicitly address the reactions of consumption demand and of labor supply to the epidemic which are analyzed by Eichenbaum et al. (2020) and Jones et al. (2020); see Baker et al. (2020) for household spending responses to the coronavirus in the U.S. The impact of social and economic factors on the transmission of the coronavirus is discussed in Qiu et al. (2020).

[2] Alvarez et al. (2020) follow a similar approach but refer to a linear economy and a much simpler epidemic model. Piguillem and Shi (2020) also analyze mitigation policies as an intertemporal optimization problem; however, they do not specify an explicit economic model.

2 Integrated Epidemic Assessment Model

2.1 The economy

The economy develops according to a daily version of the Solow growth model (Solow 1956). A year in the model consists of 360 days. Daily production is

$$Y_t = K_{t-1}^\alpha (A_t N_t)^{1-\alpha},$$

where labor efficiency A grows with constant annual rate γ_A:

$$A_t = A_{t-1}(1 + \gamma_A)^{1/360}.$$

A constant fraction of output is invested

$$Q_t = \gamma_K Y_t$$

such that capital accumulation is given by

$$K_t = (1 - \delta_K)^{1/360} K_{t-1} + \gamma_K Y_t.$$

Employment is a constant fraction of population

$$N_t = \lambda Pop_t.$$

The population is constant as long as there is no epidemic

$$Pop_t = Pop_0.$$

Consumption is therefore

$$C_t = Y_t - Q_t$$

and consumption per capita is

$$c_t = C_t / POP_t.$$

Table 1 shows the parameters of the baseline specification. We start the simulation of the economy at its steady state, such that $\Delta Y_t/Y_{t-1}$, K_t/Y_t and $K_t/(A_t N_t)$ are constant in the no-epidemic scenario.

2.2 The epidemic

The epidemic follows a recursive version of the standard SIR model (Kermack and McKendrick 1927, Atkeson 2020b) augmented by an incubation period, a separation between symptomatic (I_t) and asymptomatic (X_t) infectious persons (Wang et al. 2020), hospitalized persons (H_t) and a variable case fatality rate (μ_t), which depends on the share of hospitalized people in total popula-

Table 1: Baseline parameters of the growth model

	α	γ_K	γ_A	δ_K
Deterministic	0.2976	0.2074	0.0075	0.035
Stochastic	$n(0.2976; 0.0125)$	$n(0.2074; 0.0070)$	$u(0.005; 0.010)$	$u(0.03; 0.04)$

	λ	Pop_0	ρ	σ_U
Deterministic	0.5343	100	0.015	1.45
Stochastic	$n(0.5343; 0.0067)$	100		

Notes: The participation ratio λ, the capital share α, the investment share γ_K and the depreciation rate δ_K are chosen to approximately match German data. $u(a; b)$ denotes a uniform distribution, and $n(\mu, \sigma)$ a normal distribution (values below zero and above one are truncated).

Figure 1: Structure of the epidemic model
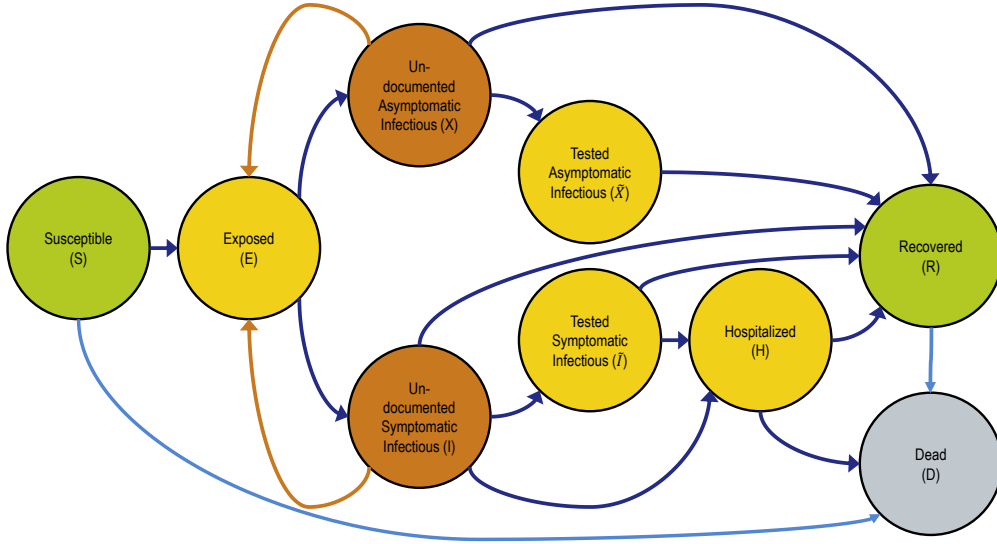
tion (see Figure 12 in the appendix).[3] Exposed persons are already infected but not yet infectious; the infectious period starts after the incubation period. In subsection 2.5 we introduce two additional compartments: documented (tested) and undocumented (not tested) infectious persons. Figure 1 shows the model structure. The epidemic model consists of the following equations:

$$S_t = S_{t-1} - \overline{\beta}\frac{S_{t-1}(I_{t-1} + \varphi_t X_{t-1})}{Pop_{t-1}} - \mu^P S_{t-1} + \mu^P Pop_{t-1}$$

$$E_t = E_{t-1} + \overline{\beta}\frac{S_{t-1}(I_{t-1} + \varphi_t X_{t-1})}{Pop_{t-1}} - \sigma_I E_{t-1} - \mu^P E_{t-1}$$

$$I_t = I_{t-1} + \xi\sigma_I E_{t-1} - \gamma_I I_{t-1} - \gamma_H I_{t-1} - \mu^P I_{t-1}$$

$$X_t = X_{t-1} + (1-\xi)\sigma_I E_{t-1} - \gamma_I X_{t-1} - \mu^P X_{t-1}$$

$$H_t = H_{t-1} + \gamma_H I_{t-1} - \delta_H H_{t-1} - \mu^P H_{t-1} - \mu_t^I H_{t-1}$$

$$R_t = R_{t-1} + \gamma_I(I_{t-1} + X_{t-1}) + \delta_H H_{t-1} - \mu^P R_{t-1}$$

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[3]At the current stage of the pandemic, there is huge uncertainty about the actual fatality rate (Atkeson 2020a).

Table 2: Baseline parameters and initial values of the epidemic model

Parameters						
	R^0	γ_I	σ_I	γ_H	δ_H	φ_t
Deterministic	3.28	$\frac{1}{2.3}$	$\frac{1}{5.2}$	$1/7$	$1/17.5$	1
Stochastic	$u(1.4; 4.39)$	$u\left(\frac{1}{4.6}; \frac{1}{1.5}\right)$	$u\left(\frac{1}{6.4}; \frac{1}{4}\right)$	$u\left(\frac{1}{10}; \frac{1}{4}\right)$	$u\left(\frac{1}{20}; \frac{1}{15}\right)$	1
	μ^P	$\overline{\mu}$	b_μ	c_μ	ξ	
Deterministic	0.0111	10	7.5	1.5	$1/8$	
Stochastic	$n(0.0111; 0.0002)$	$n(10; 1)$	$n(7.5; 0.75)$	$n(1.5; 0.15)$	$u\left(\frac{1}{10}; \frac{1}{6}\right)$	
Initial values						
	E_0	I_0	X_0	POP_0		
Deterministic	0.1393	0.0087	0.0610	100		

Notes: Liu et al. 2020 report a mean basic reproduction number of 3.28 based on several studies. The reported range is $[1.4; 6.49]$, where the upper bound is far above the majority of the studies; we neglect two outliers and set the upper bound to 4.39. The infectious period of 2.3 days and the incubation period of 5.2 days are taken from Wang et al. (2020). World Health Organization (2020) reports that 80% of cases in China have been mild with a duration of about 14 days while severe cases exhibit a duration of 3 to 6 weeks. We use the weighed average: $0.8 \cdot 14 + 0.2 \cdot 31.5 = 17.5$ as hospitalization period. $\xi = 1/8$ implies that $1/8$ of all infections lead to symptoms ($X_0 = 7I_0$). I_0 is calibrated to the value of reported cases in Germany on March 1, 2020 in relation to total population. We assume that $E_0 = 2(I_0 + X_0)$. μ^P has been estimated from the observed death rate in Germany in the period from 2013 to 2017 (Federal Statistical Office Germany). $u(a; b)$ denotes a uniform distribution and $n(\mu, \sigma)$ a normal distribution (negative realizations are discarded).

$$\mu_t^I = \exp\left(\ln\overline{\mu} - b_\mu \exp\left(-c_\mu \frac{H_{t-1}/\xi}{Pop_{t-1}}\right)\right)$$
$$D_t = D_{t-1} + \mu_t^I H_{t-1} + \mu_t^P POP_{t-1}$$
$$D_t^I = D_{t-1}^I + \mu_t^I H_{t-1}$$
$$Pop_t = S_t + E_t + I_t + X_t + H_t + R_t$$

S_t denotes susceptible, E_t exposed but not yet infectious, I_t symptomatic infectious, X_t asymptomatic infectious, H_t hospitalized (ill), and R_t recovered persons. D_t is the number of deaths. $R^0 = \overline{\beta}/\gamma_I$ is the basic reproduction rate of the epidemic. The parameter ξ denotes the fraction of infected people who exhibit symptoms at some point. Li et al. (2020) estimate that 86% [82%; 90%] (approximately 7/8) of all infections in China have been undocumented; we treat undocumented cases as asymptomatic and therefore set $\xi = 1/8$. Undocumented infectious persons may exhibit a lower transmission rate than documented infectious persons, implying $\varphi_t \leq 1$. In a baseline scenario without any mitigation characterized by the parameters in Table 2. μ^P is the regular death rate in the population; we assume a stable population implying that the birth rate is also equal to μ^P. If the number of hospitalized persons increases, the case fatality rate rises due to limited capacities of the health sector, see appendix.

Panel (A) of Figure 2 shows the baseline trajectories of the epidemic model. Without mitigation, the total number of infections (total infections: $I_t + X_t + H_t + R_t + D_t^I$) lies between 75% and almost 100% of the population, mainly depending on the value of the basic reproduction number. The shaded areas in the graphs show central 68%-bands of 1,000 stochastic simulations

with parameter distributions given in Table 2.[4] The deaths rate after three years will be about 1.5 percentage points higher than without epidemic. If the reproduction rate can immediately be reduced to 1.15, the peak of the epidemic will be later and much less pronounced, see Panel (B) of Figure 2. The number of infectious persons during the peak is much lower such that all persons who need intensive care can be appropriately treated in hospitals. Accordingly, the case fatality rate stays low and the death rate lies only slightly above the non-epidemic scenario.

2.3 Integrating the economic and the epidemic model

Now we let the epidemic affect employment. Hospitalized people are not available for work:

$$N_t = \lambda(Pop_t - H_t).$$

In a no-mitigation scenario with $R^0 = 3.28$, the number of hospitalized persons will peak at about 0.75% of population, see Panel (A) of Figure 3. Employment is temporarily reduced as long as people are hospitalized. In addition, employment is permanently lower due to deaths caused by the epidemic. Accordingly, output is also reduced. Consumption per capita, however, temporarily increases above the no-epidemic level after the main infection wave has passed because of a temporarily higher capital intensity due to a lower population caused by the deaths.[5] In the mitigation scenario ($R^0 = 1.15$), only about 0.05% of total population will be hospitalized during the peak of the epidemic wave after about 150 days, see Panel (B) of Figure 3. In this case, there is only a weak effect on employment, GDP and consumption per capita, which is hardly visible.

The overall relative loss in output is given by

$$L_Y^{(1)} = \frac{\sum_{t=0}^{\overline{T}} \left(Y_t^{(1)} - Y_t^{(0)}\right)}{\sum_{t=0}^{\overline{T}} Y_t^{(0)}},$$

where $Y_t^{(0)}$ refers to median output in the no-epidemic baseline scenario, $Y_t^{(1)}$ to median output in an alternative scenario and $\overline{T}$ to the time horizon. The total loss in output and the number of deaths depend on R^0. As long as the basic reproduction number is lower than one, there are only very weak effects of the epidemic on output and deaths (Figure 4). If the basic reproduction number exceeds one, effects are strong. A basic reproduction number of $R^0 = 3.28$ leads to a loss of more than 1% of two-period output ($\overline{T} = 720$); the number of excess deaths amounts to about 2% of the initial population.

Reducing the reproduction rate requires mitigation policies which have economic costs. In the following subsections we explore two types of mitigation policies: shutdown and testing and isolation.

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[4]In addition to mitigation policies, seasonality and immunity of parts of the population affect the transmission of the virus, see Kissler et al. (2020), for example.

[5]In an extended version of the model, productivity A_t could also be reduced by the epidemic. Furthermore, the capital depreciation rate could be higher in case of an epidemic. These two channels would counteract the positive effect on per-capita consumption.

Figure 2: Epidemic scenarios

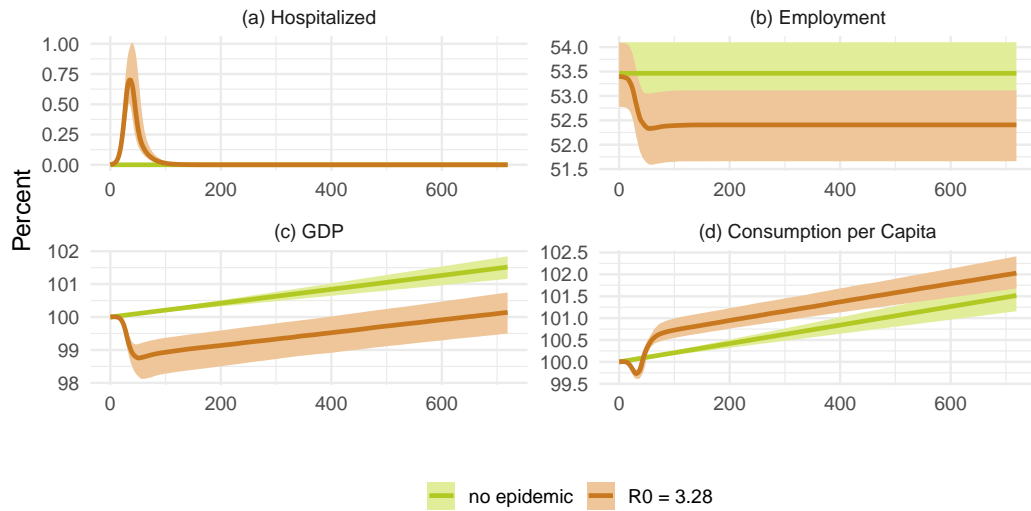(A) Basic reproduction number $R^0 \sim u(1.4; 4.39)$
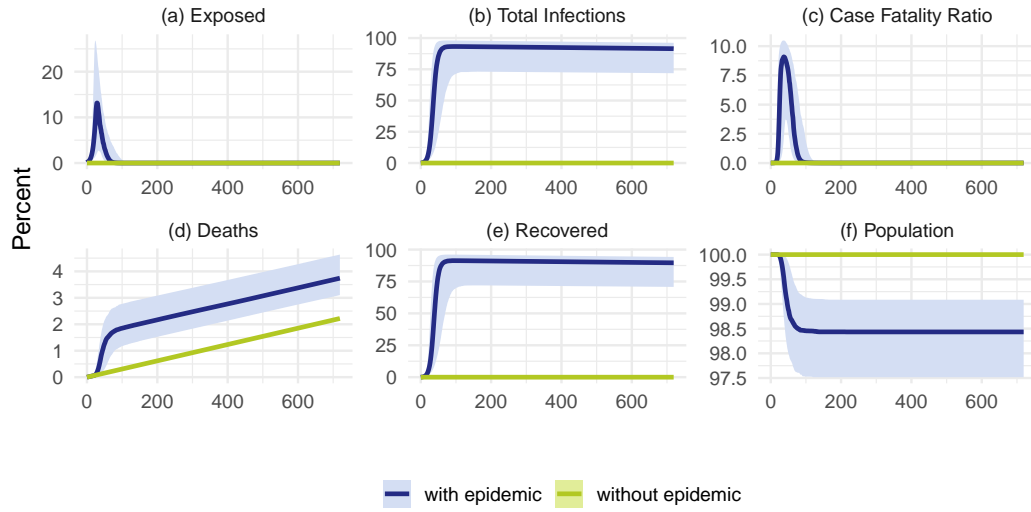
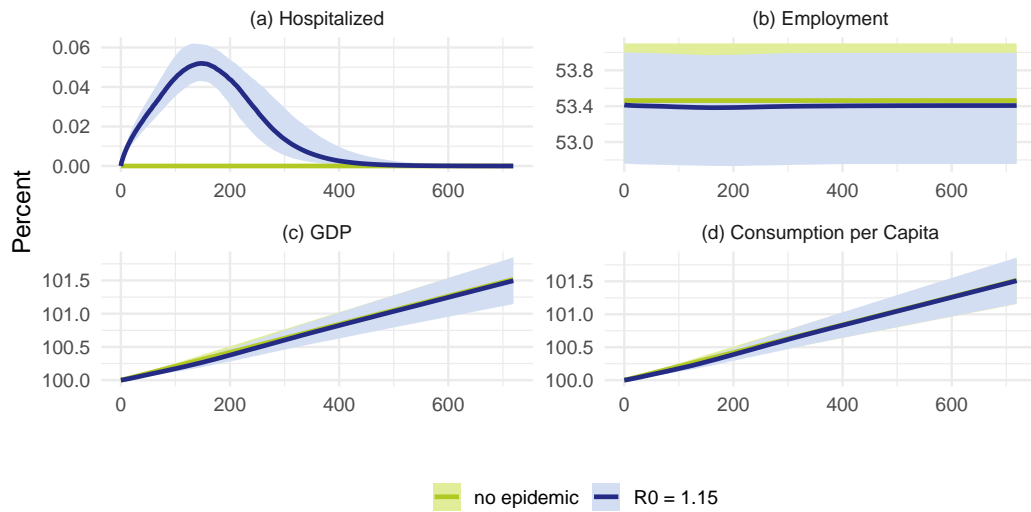(B) High versus low basic reproduction number
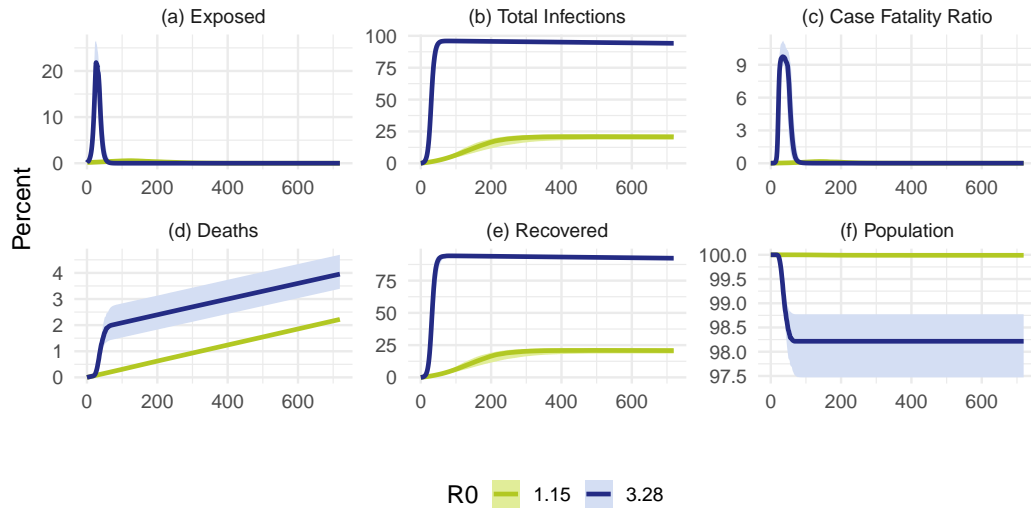
Notes: Model parameters are given in Table 2. Shaded areas show centered 68%-bands of 1,000 replications.

Figure 3: GDP and Consumption per Capita

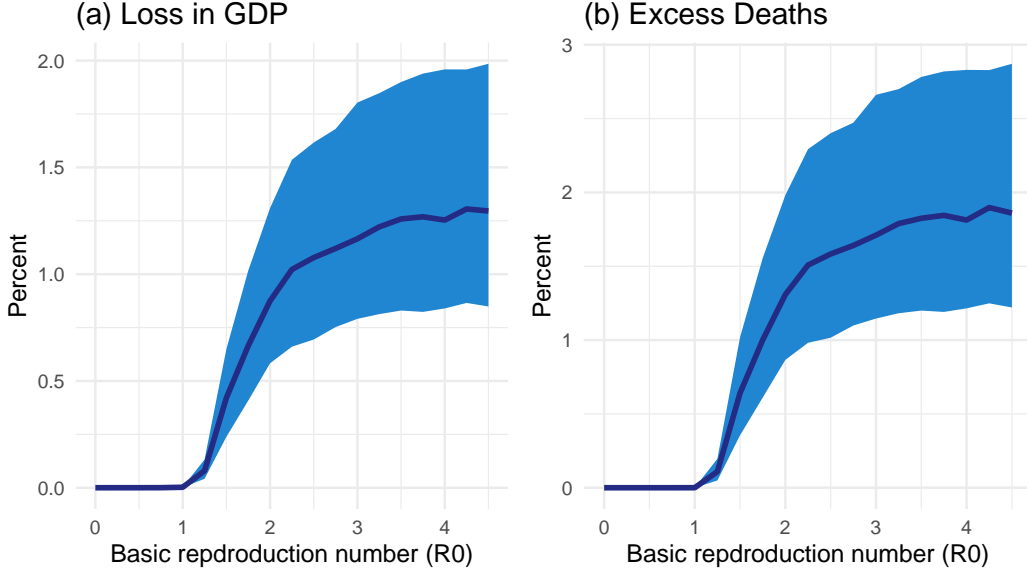(A) Without mitigation (high reproduction number)

(B) With mitigation (low reproduction number)

Notes: Model parameters are given in Tables 1 and 2. Shaded areas show centered 68%-bands of 1,000 replications.

Figure 4: Impact of R^0 on GDP and excess deaths

(a) Loss in GDP

(b) Excess Deaths

Notes: Model parameters are given in Tables 1 and 2. The time horizon is $\overline{T} = 720$ days. R^0 varies from 0 to 4.5. Shaded areas show centered 68%-bands of 1,000 replications.

2.4 Mitigation by shutdown

One possibility to reduce the reproduction rate of the epidemic is to force people to stay at home for a certain amount of time. We call this shutdown of the economy. We model the shutdown with three parameters: the day on which the shutdown begins (T_0), the duration of the shutdown (τ) and the fraction of persons who are not working ($\overline{\nu}$, shutdown intensity). Employment is now given by

$$N_t = \lambda(1 - \nu_t)(Pop_t - H_t), \qquad \nu_t = \overline{\nu} \text{ for } t \in [T_0, T_0 + \tau] \text{ and } \nu_t = 0 \text{ otherwise.}$$

If the probability of being infectious is independent of the probability of staying at home then both the number of infectious people who have to stay at home and the number of susceptible people who have to stay at home are reduced by the fraction ν_t, respectively. Therefore, the spread of the disease is mitigated:

$$S_t = S_{t-1} - \overline{\beta}\frac{(1 - \nu_t)S_{t-1}(1 - \nu_t)(I_{t-1} + \varphi_t X_{t-1})}{Pop_{t-1}} - \mu^P S_{t-1} + \mu^P Pop_{t-1}$$

$$E_t = E_{t-1} + \overline{\beta}\frac{(1 - \nu_t)S_{t-1}(1 - \nu_t)(I_{t-1} + \varphi_t X_{t-1})}{Pop_{t-1}} - \sigma_I E_{t-1} - \mu^P E_{t-1}$$

The reproduction factor is reduced by the factor $(1 - \nu_t)^2$. This implies that the reproduction factor is reduced by 36% if 20% of workers stay at home, for example. The spread of the virus and the overall economic performance depend on the shutdown profile, see Figure 5. We display trajectories for a mild, medium and strong shutdown ($\overline{\nu} = \{0.1, 0.25, 0.75\}$). We set $T_0 = 15$ and

Figure 5: Mitigation by shutdown
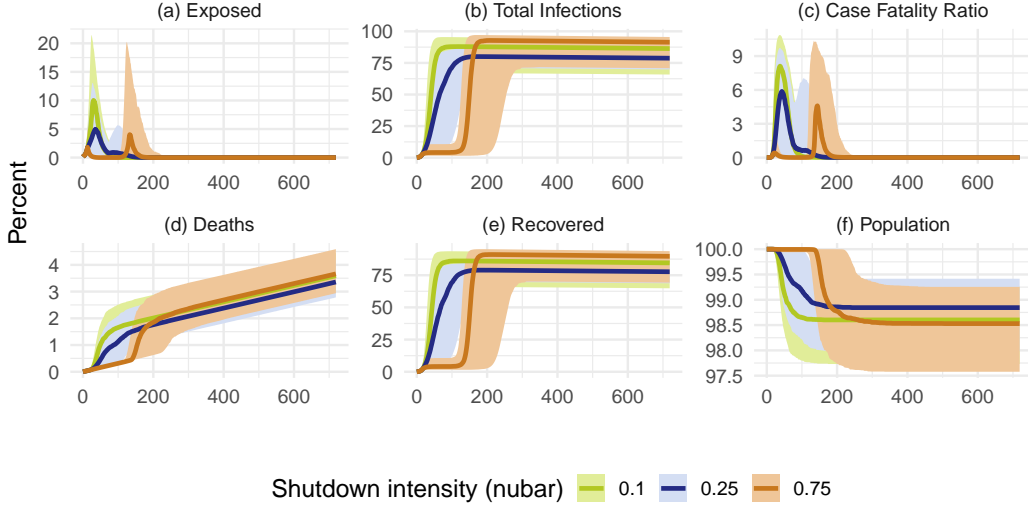
Notes: Model parameters are given in Tables 1 and 2. Shutdown begin: $T_0 = 15$ and shutdown duration: $\tau = 60$. Shaded areas show centered 68%-bands of 1,000 replications.
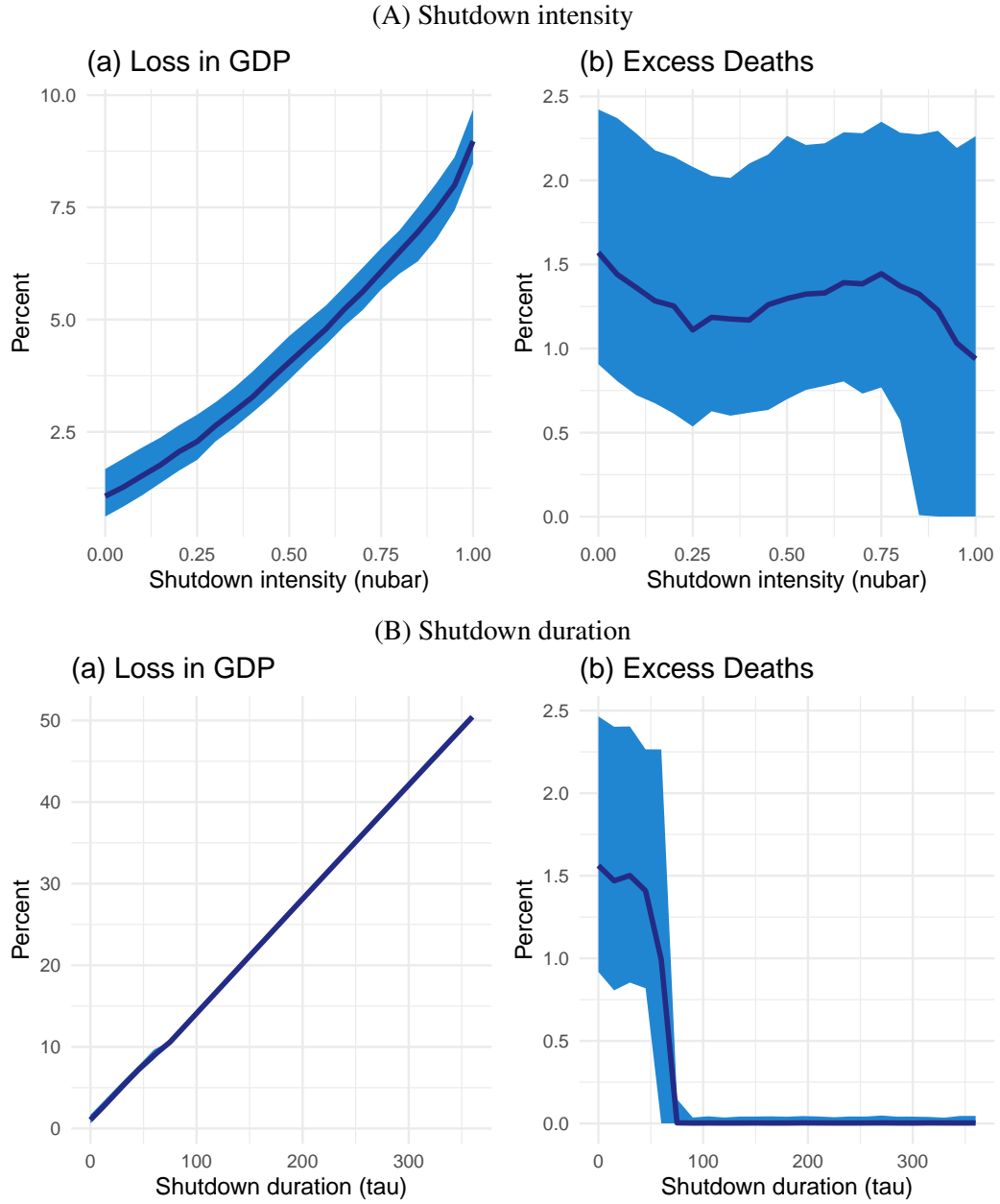
$\tau = 60$. An important result is that the number of deaths is not monotonically decreasing in the shutdown intensity. The number of deaths decreases for intensities from 0 to about 0.25. If the shutdown intensity is higher than this threshold, the immunization of the total population is slowed down during the shutdown and the share of susceptible persons does not decline strong enough to permanently reduce the spread. Once the shutdown is over, the disease spreads again very fast in a second wave which leads to a high number of hospitalized persons and therefore to a higher case fatality rate. Another finding is that the risk of a second wave is very high for a shutdown duration of 60 days, irrespective of the shutdown intensity as shown by the shaded area in Figure 6 (A). On the other hand, the loss in output is strictly increasing in shutdown intensity.

2.5 Mitigation by testing and isolation of infectious persons

Another possibility to reduce the reproduction rate of the epidemic is to identify and isolate infectious people such that the probability of infecting another persons declines (Hellewell et al. 2020, Stock 2020). Similar to Berger et al. (2020), we introduce two new groups of people into the model: positively tested symptomatic infectious persons ($\tilde{I}_t$) and positively tested asymptomatic infectious persons ($\tilde{X}_t$):

$$S_t = S_{t-1} - \overline{\beta}(1-\nu)^2 \frac{S_{t-1}(I_{t-1} + \varphi_t X_{t-1})}{Pop_{t-1}} - \mu^P S_{t-1} + \mu^P Pop_{t-1}$$

$$E_t = E_{t-1} + \overline{\beta}(1-\nu)^2 \frac{S_{t-1}(I_{t-1} + \varphi_t X_{t-1})}{Pop_{t-1}} - \sigma_I E_{t-1} - \mu^P E_{t-1}$$

$$I_t = I_{t-1} + \xi\sigma_I E_{t-1} - \gamma_I I_{t-1} - \gamma_H I_{t-1} - \theta I_{t-1} - \mu^P I_{t-1}$$

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Figure 6: Impact of shutdown on GDP and deaths

(A) Shutdown intensity

(a) Loss in GDP

(b) Excess Deaths

(B) Shutdown duration

(a) Loss in GDP

(b) Excess Deaths

Notes: Model parameters are given in Tables 1 and 2. Shutdown begin: $T_0 = 15$. Shutdown duration: $\tau = 60$ in Panel (A) and shutdown intensity $\bar{\nu} = 0.25$ in Panel (B). Shaded areas show centered 68%-bands of 1,000 replications.

$$\tilde{I}_t = \tilde{I}_{t-1} + \theta I_{t-1} - \gamma_H \tilde{I}_{t-1} - \delta_U \tilde{I}_{1-1} - \mu^P \tilde{I}_{t-1}$$

$$X_t = X_{t-1} + (1 - \xi)\sigma_I E_{t-1} - \gamma_I X_{t-1} - \theta X_{t-1} - \mu^P X_{t-1}$$

$$\tilde{X}_t = \tilde{X}_{t-1} + \theta X_{t-1} - \delta_U \tilde{X}_{t-1} - \mu^P \tilde{X}_{t-1}$$

$$H_t = H_{t-1} + \gamma_H I_{t-1} + \gamma_H \tilde{I}_{t-1} - \delta_H H_{t-1} - \mu_t^I H_{t-1} - \mu^P H_{t-1}$$

$$R_t = R_{t-1} + \gamma_I(I_{t-1} + X_{t-1}) + \delta_U(\tilde{I}_{1-1} + \tilde{X}_{t-1}) + \delta_H H_{t-1} - \mu^P R_{t-1}$$

$$D_t^I = D_{t-1}^I + \mu_t^I H_{t-1}$$

$$D_t = D_{t-1} + \mu_t^I H_{t-1} + \mu^P Pop_{t-1}$$

$$Pop_t = S_t + E_t + I_t + X_t + \tilde{I}_t + \tilde{X}_t + H_t + R_t$$

Detected infectious persons are quarantined for $1/\delta_U = 14$ days and cannot infect other persons anymore:[6]

$$U_t = \tilde{X}_t + \tilde{I}.$$

Employment is now:

$$N_t = \lambda(Pop_t - H_t - U_t).$$

Identifying infectious persons is costly. We assume that these costs depend on the number of susceptible, exposed and unknown infectious persons ($S_t + E_t + I_t + X_t$) in the economy and on the fraction that is tested (θ_t) on day t. The testing costs are

$$T_t = \theta_t(S_t + E_t + I_t + X_t)\Phi.$$

The cost of a single test is assumed to be 1,000 Euro, that is $1.05 \cdot 10^{-5}\%$ of German daily GDP ($\Phi = 1.05 \cdot 10^{-5}$). We assume that tests are random. Testing costs reduce consumption:

$$C_t = Y_t - Q_t - T_t.$$

We model the testing and isolation profile similar to the shutdown by specifying the start date (T_0), the duration (τ) and the intensity ($\bar{\theta}$) of tests and consider three scenarios ($\bar{\theta} = \{0.1, 0.25, 0.75\}$, $\theta_t = \bar{\theta}$ for $t \in [T_o, T_o + \tau]$ and $\theta_t = 0$ otherwise). Mitigation by testing and isolating infectious persons is much cheaper than mitigation by shutdown, if testing and tracing capacities can be set up fast, because testing costs are almost negligible in relation to total output. The testing-and-isolating strategy reduces the number of deaths while keeping the loss in output much smaller than the shutdown strategy, see Figure 7. At the lower end of testing intensity, however, it is not beneficial to increase the testing intensity only gradually, see Figure 8. A certain threshold has to be exceeded for testing and isolation to be effective.

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[6]A possible extension is to assume that also family members of infectious persons, who might already belong to the exposed group, are quarantined.

Figure 7: Mitigation by identifying and isolation of infectious persons
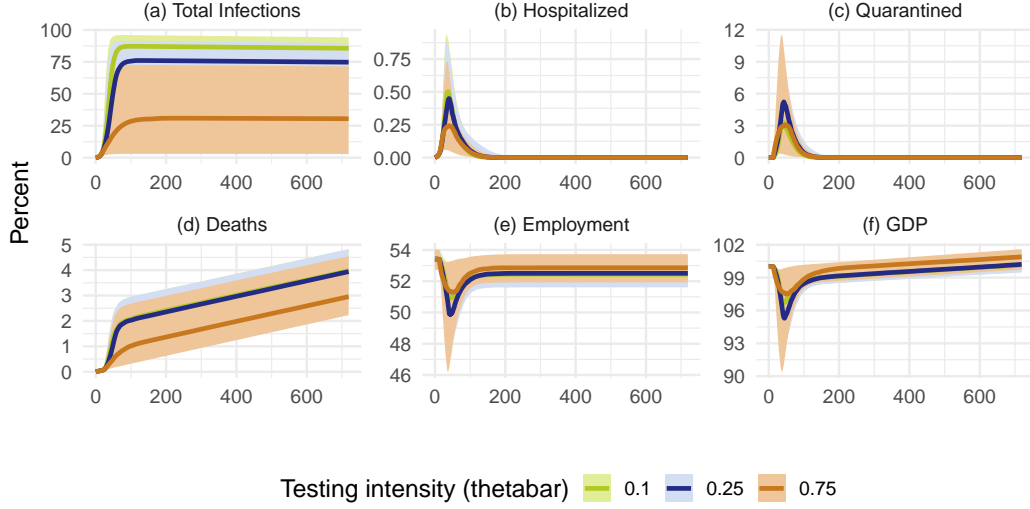
Notes: Model parameters are given in Tables 1 and 2. Testing begin: $T_0 = 15$ and testing duration: $\tau = 720$. Testing intensity $\bar{\theta} = 0.10$ (mild) $\theta = 0.25$ (medium) and $\theta = 0.75$ (strong). Shaded areas show centered 68%-bands of 1,000 replications.

3   Optimal Policy

In this section, we explore the optimal mitigation policy. We consider four policy parameters: shutdown duration and intensity and testing duration and intensity. In our analysis, duration varies from 0 to 720 days (step size 30 days) and intensity varies from 0 to 1 (step size 0.1) which implies $11 \times 11 \times 25 \times 25 = 75.625$ mitigation plans. We assume that mitigation policies start on day 15. The epidemic parameters are as in Table 2.
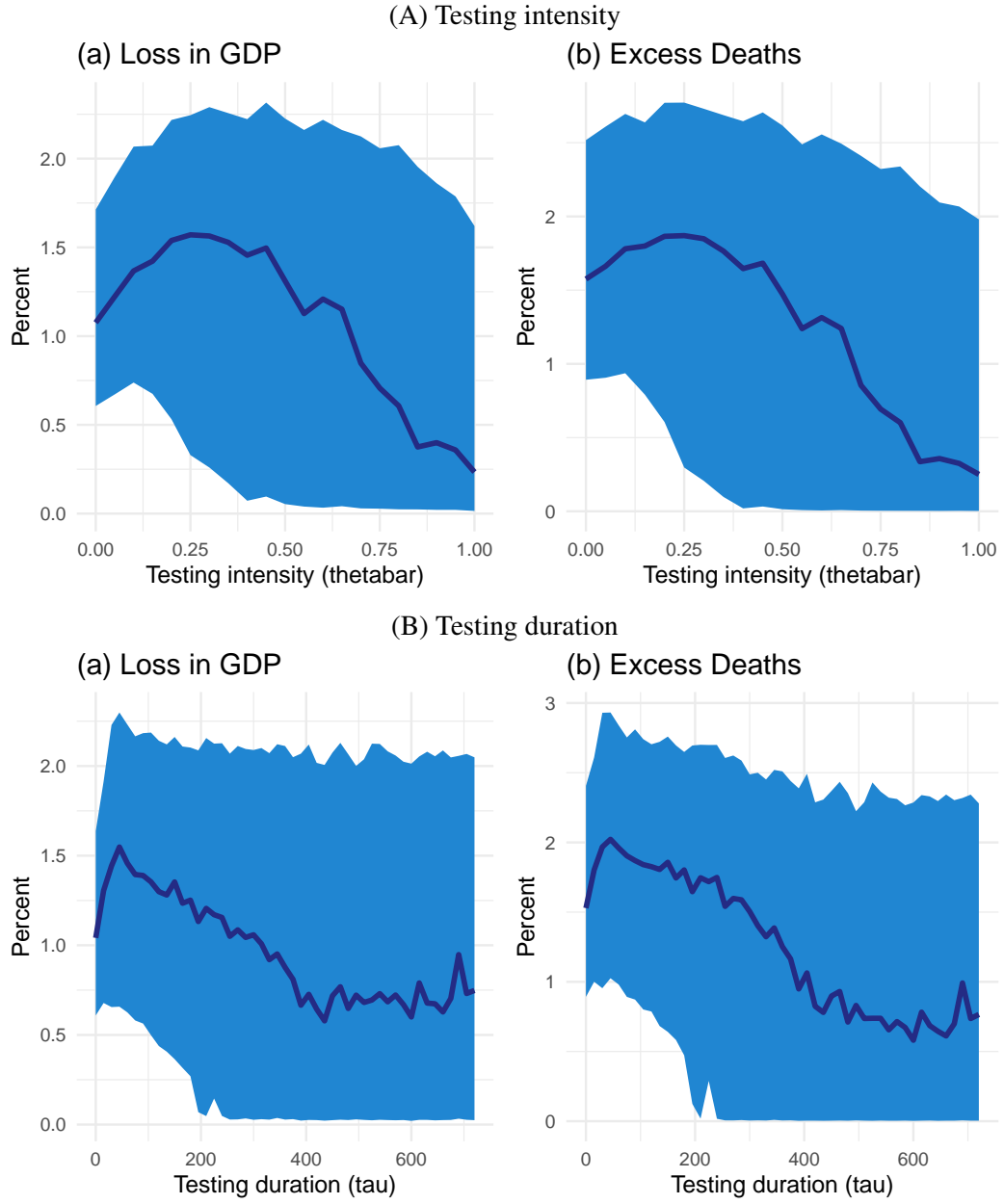
Using the instantaneous utility function

$$u(c_t) = \frac{c_t^{1-\sigma_u} - 1}{1 - \sigma_u},$$

total wealth is given by

$$W_0 = \sum_{t=0}^{\overline{T}} \frac{u(c_t)Pop_t}{(1 + \rho)^{t/360}}.$$

Both, the negative transitory effect of mitigation policies on short-term output and the permanent negative effect of deaths on output are reflected in this aggregate wealth function. Moreover, welfare increases if a given amount of output is consumed by more people due to decreasing marginal utility. In addition, we report the effects of mitigation policies on output and on the number of deaths separately. The time period considered is ten years ($\overline{T} = 3,600$ days). The risk aversion parameter σ_U and the discount rate ρ are given in Table 1; we take values that Nordhaus (2008) applies in climate change assessment. The utility function curvature is a very important parameter because it captures implicitly how the society values consumption and deaths.

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Figure 8: Impact of testing on GDP and excess deaths

(A) Testing intensity

(a) Loss in GDP

(b) Excess Deaths

(B) Testing duration

(a) Loss in GDP

(b) Excess Deaths

Notes: Model parameters are given in Tables 1 and 2. Begin of testing: $T_0 = 15$, testing duration in Panel (A): $\tau = 720$, testing intensity in Panel (B): $\bar{\theta} = 0.75$. Shaded areas show centered 68%-bands of 1,000 replications.

In order to summarize the results graphically, we first exhibit only a subset of all simulated cases. We choose proportional values for duration and intensity of both shutdown and testing measures ($\nu = \tau/720$ and $\theta = \tau/720$, respectively), see Figure 9. Panel (a) shows that the number of deaths is substantially reduced for high shutdown intensities or high testing intensities or a combination thereof. Even if the testing intensity is 1, a further decline in the number of deaths can be achieved by additional shutdown. If the shutdown intensity is very high the number of deaths cannot be reduced further by testing. Panel (b) shows that the shutdown is much more expensive in terms of output loss than testing. Panel (c) reveals that full testing is the optimal strategy if intensity and duration are varied proportionally. However, if full testing of the population is not feasible, a certain shutdown strength is welfare enhancing.

The overall optimal policy cannot be inferred from Figure 9, because duration and intensity of the mitigation policies can vary independently. Moreover, shutdown or testing intensities of one are physically not possible. A complete shutdown of the economy minimizes the number of deaths in our model, but at least some critical infrastructures and public services need to be maintained during a shutdown. Similarly, testing all potentially infectious persons on each day is technically not feasible. Therefore, we set maximum limits for shutdown and testing intensity of 50%. The implications of mitigation plans on output loss and excess deaths is shown in Figure 10. There is a trade-off between minimizing the output loss and minimizing the number of excess deaths. The efficient frontiers reflect all mitigation plans which cannot be improved in the sense that a certain number of excess deaths cannot be achieve with lower output loss.[7] Which of the combinations is optimal with respect to welfare depends on the parameters of the utility function. The larger the time preference rate (ρ), the higher the number of deaths accepted by the society; and the larger the risk aversion parameter (σ_U), the lower the number of accepted deaths in the optimal combination of output loss and excess deaths.

The welfare-optimal combinations of shutdown and testing for the values of ρ and σ given in Table 1 are shown in Table 3. The optimal trajectories for the constrained case are presented in Figure 11. Focusing solely on minimizing output loss triggers a second wave of infections after initial mitigation measures have been relieved.
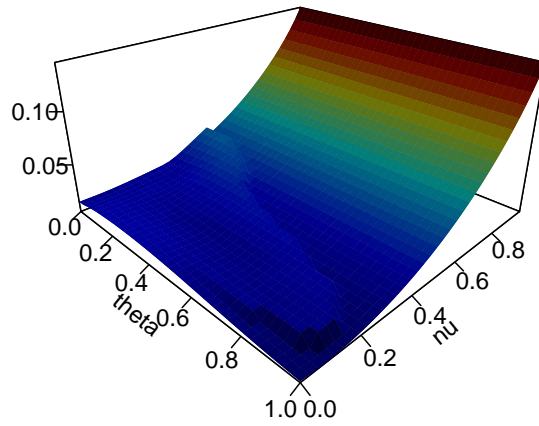
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[7]If it is possible to target mitigation policies to age groups which have different probabilities of dying, the efficient frontier can be shifted to the left, see Acemoglu et al. (2020).
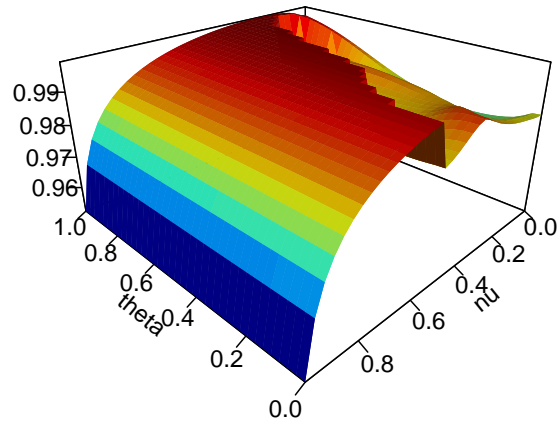
Figure 9: Impact of mitigation policies on welfare
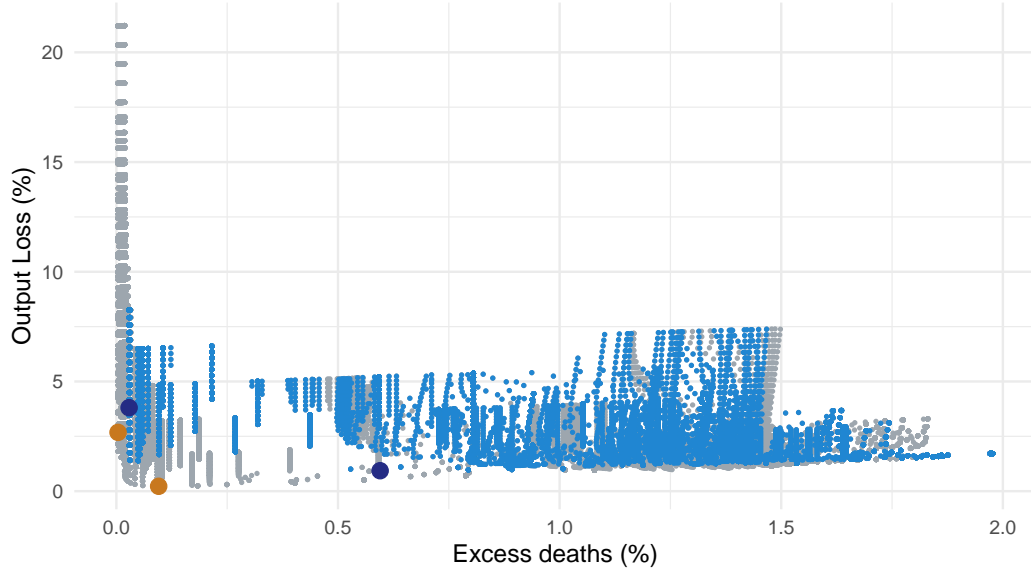
(a) Deaths
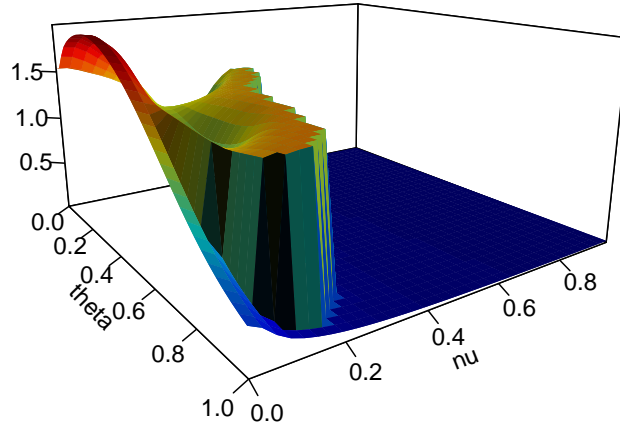
(b) Output Loss

(c) Welfare

Notes: theta refers to testing strength (duration and intensity) and nu refers to shutdown strength (duration and intensity). Time horizon is ten years.
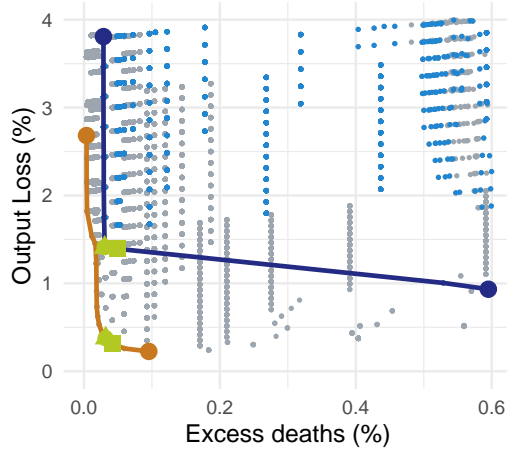
Figure 10: Efficient frontier of mitigation policies
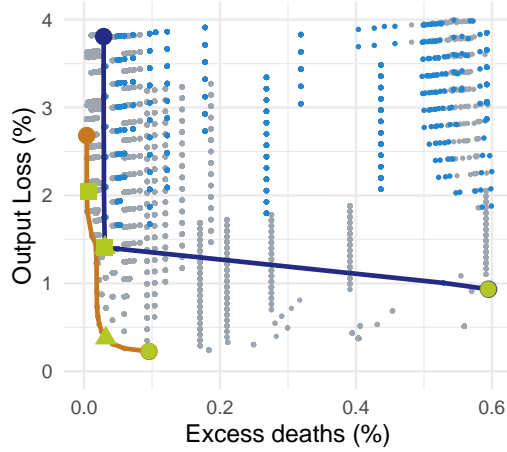
(A) Constrained and unconstrained outcomes

(B) Efficient frontier and optimal welfare

(a) Time preference and welfare

(b) Risk aversion and welfare

rho ● 0 ▲ 0.02 ■ 0.2

sigma ● 0.5 ▲ 1.5 ■ 2.5

Notes: Panel (A) shows output loss and excess deaths for all mitigation plans; feasible combinations in the constrained case ($\overline{\nu} \leq 0.5$, and $\overline{\theta} \leq 0.5$) are colored light blue. Orange circles show minimal output and minimal deaths combinations in the unconstrained case, dark blue circles in the constrained case, respectively. Panel (B) shows the efficient frontiers in the constrained and in the unconstrained case, respectively. The welfare-optimal combination depends on the parameters ρ and σ of the utility function.

Table 3: Optimal mitigation policies

	Shutdown		Testing		Outcome		
	Duration	Intensity	Duration	Intensity	Deaths	Output loss	Welfare
	Unconstrained						
Minimal deaths	90	1	0	0	0.0038%	2.6829%	$-\infty$
Minimal output loss	30	0.2	540	1	0.0955%	0.2261%	99.8839%
Maximal welfare	60	0.4	420	1	0.0417%	0.5801%	99.9050%
	Constrained ($\theta_t \leq 0.5$, $\nu_t \leq 0.5$)						
Minimal deaths	330	0.5	30	0.1	0.0287%	3.8086%	99.6000%
Minimal output loss	60	0.2	480	0.5	0.7941%	0.9731%	99.1286%
Maximal welfare	120	0.5	120	0.5	0.0305%	1.4075%	99.8312%

Notes: Output loss and welfare in relation to no-epidemic scenario. Excess deaths in relation to initial population before the epidemic.

Figure 11: Optimal (constrained) trajectories
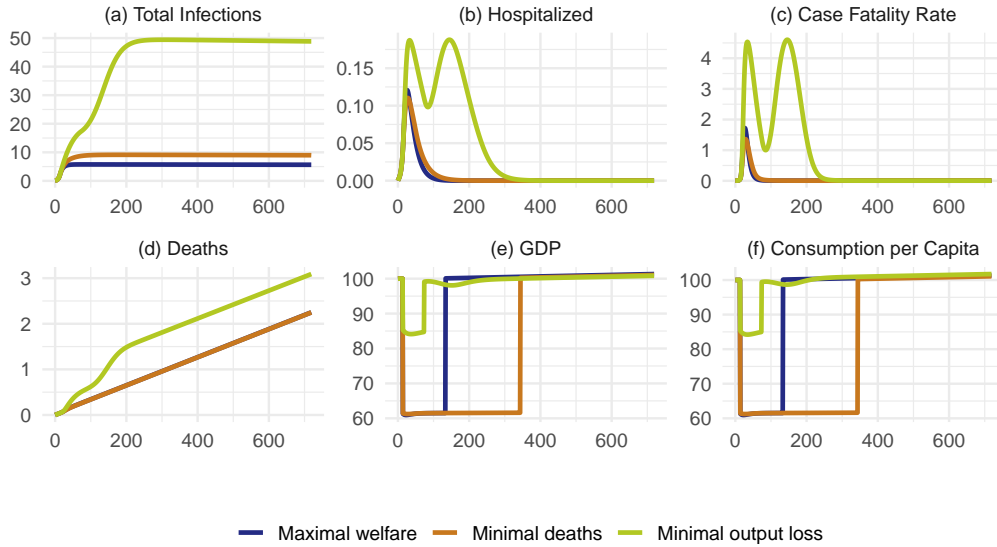
Notes: Trajectories for the three mitigation strategies characterized in Table 3 (constrained case).

4 Conclusions

In this paper, we have explored the properties of epidemic mitigation policies on deaths, output and welfare in an integrated epidemic assessment model (IntEAM). We consider a (partial) shutdown of the economy and testing and isolating infectious persons as mitigation strategies. While shutdown is a brute force mechanism that fights the epidemic at high output costs, a partial temporary shutdown accompanied by intensive testing and isolation of infectious persons for an extended period of time is an efficient mitigation strategy. Minimizing output loss, on the other hand, is a dangerous strategy because this may come with a second wave of infections when transitory mitigation measures are relieved. It has to be stressed that the model is extremely simple. However, the simulations are still useful for understanding the interaction of economy and epidemic. Of course, the welfare-maximizing strategy depends on the specific calibration. The relationship between asymptomatic and symptomatic infected persons, the case fatality rate, the curvature of the utility function and the discount rate, for example, are crucial parameters.

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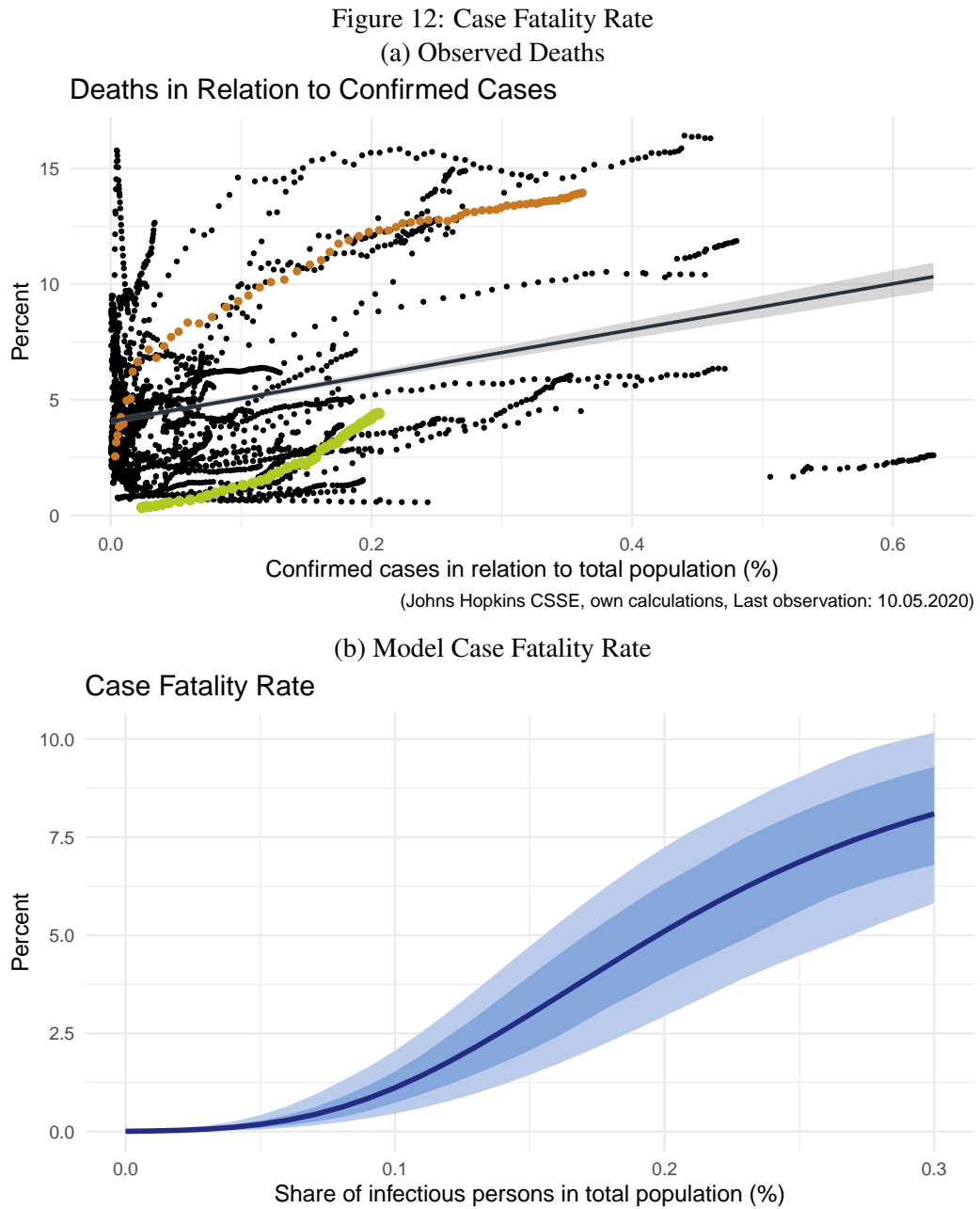
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Appendix

Calibration of the case fatality rate

Figure 12: Case Fatality Rate
(a) Observed Deaths

(Johns Hopkins CSSE, own calculations, Last observation: 10.05.2020)

(b) Model Case Fatality Rate

Notes: Panel (a) shows that there is large heterogeneity in the death rate. Observations from Germany are depicted in green, observations from Italy in orange. We calibrate the case fatality rate such that it mimics the German situation with a relatively low share of deaths. The case fatality rate in panel (b) follows a Gompertz function with a limit of 10% ($\overline{\mu} = 10$), see Table 2.