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Integrated Assessment of Epidemic and Economic Dynamics

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Integrated Assessment of Epidemic and Economic Dynamics*

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 temporary partial shutdown and intensive testing and isolation of infectious persons for an extended period of time.

Keywords: coronavirus, economic growth, epidemic modeling

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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 during the 1918 flu in the U.S. (Correia et al. 2020). The more aggressive short-run responses are the lower long-run negative effects on output (Ma et al. 2020) may be.

We discuss the economic effects of the disease and of mitigation policies in the standard neoclassical 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 SEIR model into the economic framework (Integrated Epidemic Assessment Model, IntEAM). First, we show that the negative impact of the epidemic on deaths and on output loss depend 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. The feasible optimal combination of the shutdown strength (intensity and duration) and testing strength (intensity and duration) is determined with respect to the minimal number of 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.

2 Integrated Epidemic Assessment Model (IntEAM)

2.1 The economy

The economy develops according to a daily version of the Solow growth model (Solow 1956). Daily production is

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

where productivity grows with constant rate annual rate γ_A:

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

A constant fraction of output is invested

$$Q_t = \gamma_K Y_t$$

[1] We neglect reactions of consumption demand and of labor supply to the epidemic which are analyzed by Eichenbaum et al. (2020).

Table 1: Baseline parameters of the growth model

α	γ_K	γ_A	λ	δ	Pop_0	ρ	σ_U	T
0.36	0.21	0.005	0.545	0.035	100	0.015	1.45	1080

Notes: The capital share parameter α, the investment share γ_K and the depreciation rate δ_K are chosen to approximately match German data.

such that capital accumulation is given by

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

Employment is a constant fraction of population

$$N_t = \lambda Pop_t,$$

where 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 in 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 SEIR model (Atkeson 2020) augmented by 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 population (see Figure 11 in the appendix). In subsection 2.5 we will introduce two additional compartments: documented (tested) and undocumented (not tested) infectious persons. Figure 1 shows a stylized graph of the model structure. The epidemic model consists of the following equations:

$$\begin{aligned}
S_t &= S_{t-1} - \overline{\beta} \frac{S_{t-1}(I_{t-1} + \varphi_t X_{t-1})}{Pop_{t-1}} \\
E_t &= E_{t-1} + \overline{\beta} \frac{S_{t-1}(I_{t-1} + \varphi_t X_{t-1})}{Pop_{t-1}} - \sigma_I E_{t-1} \\
I_t &= I_{t-1} + \xi \sigma_I E_{t-1} - \gamma_I I_{t-1} - \gamma_H I_{t-1} \\
X_t &= X_{t-1} + (1-\xi)\sigma_I E_{t-1} - \gamma_i I_{t-1} \\
H_t &= H_{t-1} + \gamma_H I_{t-1} - \delta_H H_{t-1} \\
R_t &= R_{t-1} + \gamma_I (I_{t-1} + X_{t-1}) + \delta_H H_{t-1} - \mu_t H_{t-1} \\
\mu_t &= \exp\left(\overline{\mu} + b_\mu \exp\left(c_\mu \frac{H_{t-1}/\xi}{Pop_{t-1}}\right)\right) \\
R_t^e &= \frac{R_0}{X_{t-1} + I_{t-1}} \left(\varphi_t X_{t-1} + \frac{I_{t-1}/\gamma_H}{1/\gamma_I + 1/\gamma_H}\right) \\
D_t &= D_{t-1} + \mu_t H_{t-1} \\
Pop_t &= S_t + E_t + I_t + X_t + H_t + R_t
\end{aligned}$$

Figure 1: Structure of the epidemic model

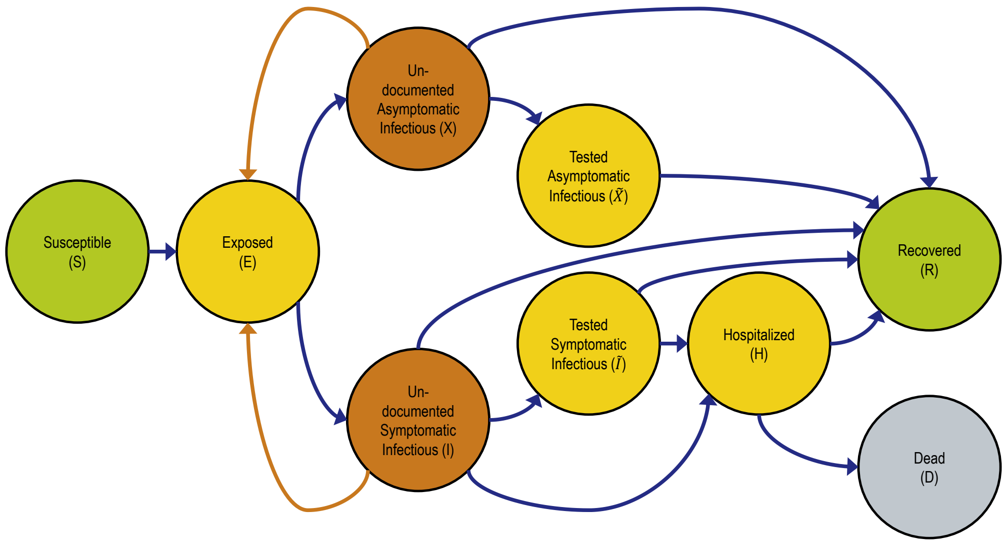


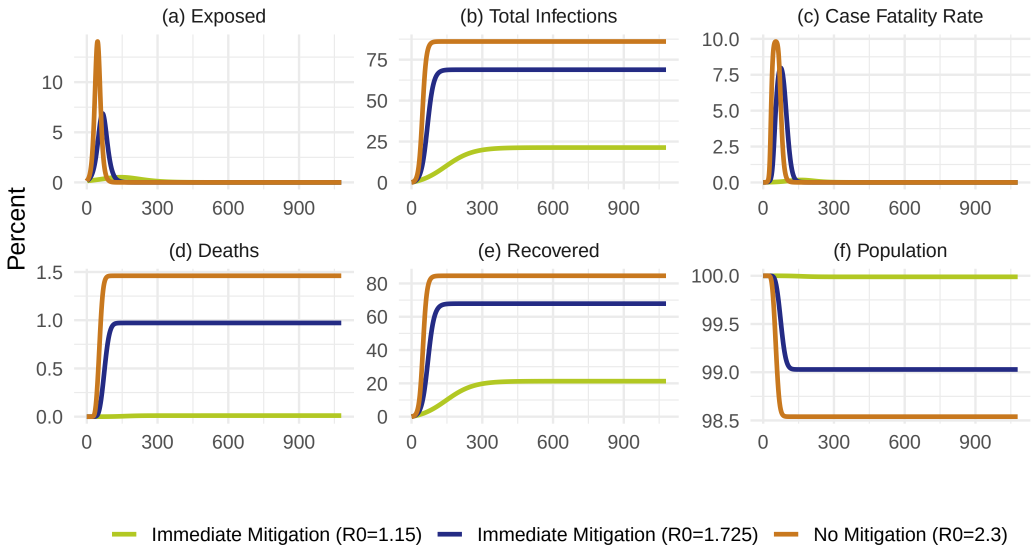
Table 2: Baseline parameters of the epidemic model

R^0	γ_I	σ_I	$\overline{\mu}$	b_μ	c_μ	γ_H	δ_H	φ_t	ξ	E_0	I_0	X_0
2.3	1/2.3	1/5.2	ln 5	−7	−2	1/7	1/17.5	1	1/8	0.1393	0.0087	0.0610

Notes: 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 ($Pop_0 = 100$). We assume that $E_0 = 2(I_0 + X_0)$.

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. Effective reproduction (R^e_t) is time-dependent. The parameter ξ denotes the fraction of infected people who exhibit symptoms at some point. Li et al. (2020) estimate that 86% 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, about 5% of total population will be infectious at the same time during the peak of the epidemic. Hospitals will be overwhelmed and the case fatality rate will rise. While about 85% of the total population will recover, about 1.5% of total population will die, see figure 2; 14% remain susceptible. If the reproduction rate can be immediately reduced from 2.3 to 1.15, the peak of the epidemic will be later and much less pronounced. 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 share of dead people in total population is only 0.01%.

Figure 2: Epidemic with and without mitigation



Notes: Total infections: $I_t + X_t + H_t + R_t + D_t$.

2.3 Integrating the economic and the epidemic model

We now let the epidemic affect employment. Hospitalized people are not available for work:

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

In the immediate mitigation scenario ($R^0 = 1.15$), about 0.05% of total population will be hospitalized during the peak of the epidemic wave after about 150 days, see figure 3. Employment drops accordingly, and output is lower than in the no-epidemic scenario during the peak time due to hospitalized persons. Additionally, some hospitalized patients die. This reduces employment and output permanently. Consumption per capita, however, will temporarily increase 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.[2] The overall relative loss in output is given by

$$L_Y^{(1)} = \frac{\sum_{t=0}^{1080} \left(Y_t^{(1)} - Y_t^{(0)} \right)}{\sum_{t=0}^{1080} Y_t^{(0)}} = 0.0013,$$

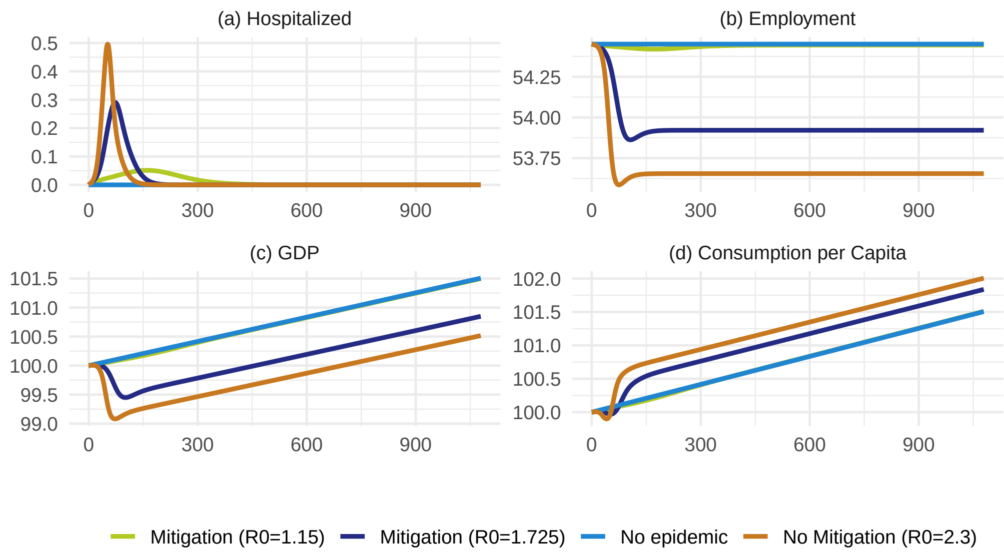
that is 0.1% of GDP is lost due to the epidemic.

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 weak effects of the epidemic on output and deaths (Figure 4). If the basic reproduction number exceeds one, effects will be strong. A basic reproduction number of $R^0 = 2.3$ leads to a loss in total output of about 0.9%; the number of deaths amounts to 1.5% of the initial population.

These calculations are based on the assumption that reducing the reproduction rate comes without economic costs which is actually not the case. In the following subsections we explore two types of mitigation policies: shutdown and testing and isolation.

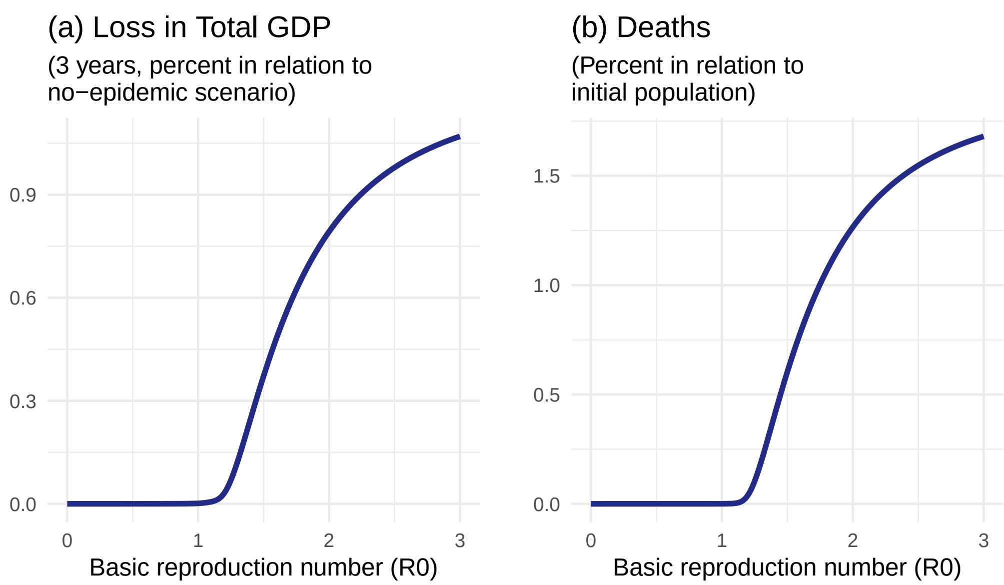
[2] In an extended version of the model, productivity A_t could also be reduced by the epidemic. Furthermore, the capital depreciation rate could be higher in case of an epidemic. These two channels would counteract the positive effect on per-capita consumption.

Figure 3: GDP and Consumption per Capita



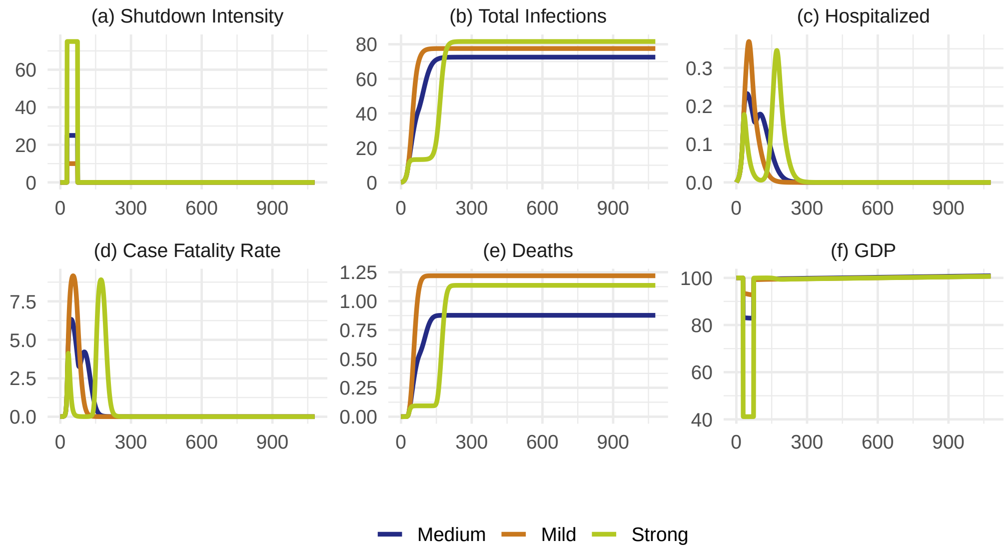
Notes: Model parameters are given in Tables 1 and 2.

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



Notes: Model parameters are given in Tables 1 and 2. R^0 varies from 0 to 3.

Figure 5: Mitigation by shutdown



Notes: Model parameters are given in Tables 1 and 2. Shutdown begin: $T_0 = 30$ and shutdown duration: $\tau = 45$, shutdown intensity (ν_t) is shown in panel (a).

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 (shutdown). 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 (ν_t, shutdown intensity). Employment is now given by

$$N_t = \lambda(1 - \nu_t)(Pop_t - H_t).$$

If the probability of being infectious is independent from 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 is reduced by the fraction ν_t, therefore the spread of the disease is mitigated:

$$\begin{aligned} S_t &= S_{t-1} - \overline{\beta}\frac{(1-\nu_t)S_{t-1}(1-\nu_t)(I_{t-1} + \varphi_t X_{t-1})}{Pop_{t-1}} \\ E_t &= E_{t-1} + \overline{\beta}\frac{(1-\nu_t)S_{t-1}(1-\nu_t)(I_{t-1} + \varphi_t X_{t-1})}{Pop_{t-1}} - \sigma_I E_{t-1} \end{aligned}$$

and the reproduction rate is reduced by the factor $(1 - \nu_t)^2$. This implies that the reproduction rate 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 ($\nu_t = \{0.1, 0.25, 0.75\}$ for $t \in [T_o, T_o + \tau]$ and $\nu_t = 0$ otherwise). We set $T_0 = 30$ and $\tau = 45$. An important result is that the number of deaths is not monotonically decreasing in the shutdown intensity. If the shutdown intensity is higher than a certain threshold, then the immunization of the total population is slowed down 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.

The effects of shutdown intensity and duration on output loss and on the total number of deaths are shown in Figure 6.

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 infected 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 ($\tilde{X}_t$):

$$\begin{aligned}
S_t &= S_{t-1} - \overline{\beta}(1-\nu)^2 \frac{S_{t-1}(I_{t-1} + \varphi_t X_{t-1})}{Pop_{t-1}} \\
E_t &= E_{t-1} + \overline{\beta}(1-\nu)^2 \frac{S_{t-1}(I_{t-1} + \varphi_t X_{t-1})}{Pop_{t-1}} - \sigma_I E_{t-1} \\
I_t &= I_{t-1} + \xi \sigma_I E_{t-1} - \gamma_I I_{t-1} - \gamma_H I_{t-1} - \theta I_{t-1} \\
\tilde{I}_t &= \tilde{I}_{t-1} + \theta I_{t-1} - \gamma_H \tilde{I}_{t-1} - \delta_U \tilde{I}_{1-1} \\
X_t &= X_{t-1} + (1-\xi)\sigma_I E_{t-1} - \gamma_i X_{t-1} - \theta X_{t-1} \\
\tilde{X}_t &= \tilde{X}_{t-1} + \theta X_{t-1} - \delta_U \tilde{X}_{t-1} \\
H_t &= H_{t-1} + \gamma_H I_{t-1} + \gamma_H \tilde{I}_{t-1} - \delta_H H_{t-1} - \mu_t H_{t-1} \\
R_t &= R_{t-1} + \gamma_I (I_{t-1} + X_{t-1}) + \delta_U (\tilde{I}_{1-1} \tilde{X}_{t-1}) + \delta_H H_{t-1} \\
D_t &= D_{t-1} + \mu_t H_{t-1} \\
Pop_t &= S_t + E_t + I_t + X_t + \tilde{I}_t + \tilde{X}_t + H_t + R_t
\end{aligned}$$

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 ($\theta_t = 1/7$ in case of weakly tests). 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 $3.3 \cdot 10^{-5}\%$ of German GDP ($\Phi = 3.3 \cdot 10^{-5}$). We assume that tests are random. Detected infectious persons are quarantined:[3]

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

Employment is now:

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

We model the testing and isolation profile similar to the shutdown by specifying the start date (T_0), the duration (τ) and the intensity (θ) of tests and consider three scenarios ($\theta_t = \{0.1, 0.25, 0.75\}$ for $t \in [T_o, T_o + \tau]$ and $\theta_t = 0$ otherwise).Testing costs reduce consumption:

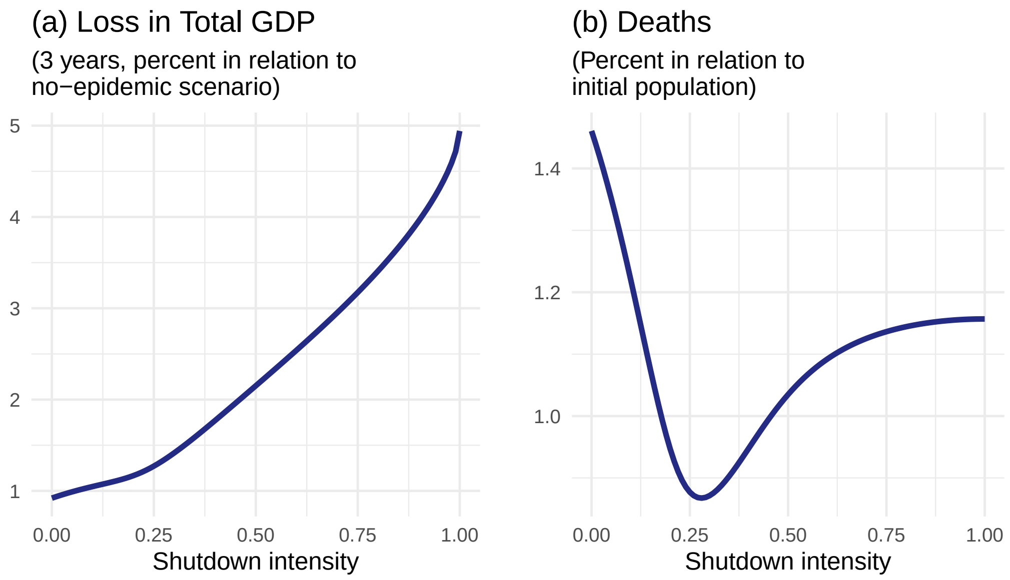
$$C_t = Y_t - Q_t - T_t.$$

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 (Figure 7). The testing-and-isolating strategy reduces the number of deaths while keeping the loss in output smaller than the shutdown strategy. 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 exceed for testing and isolation to be effective.

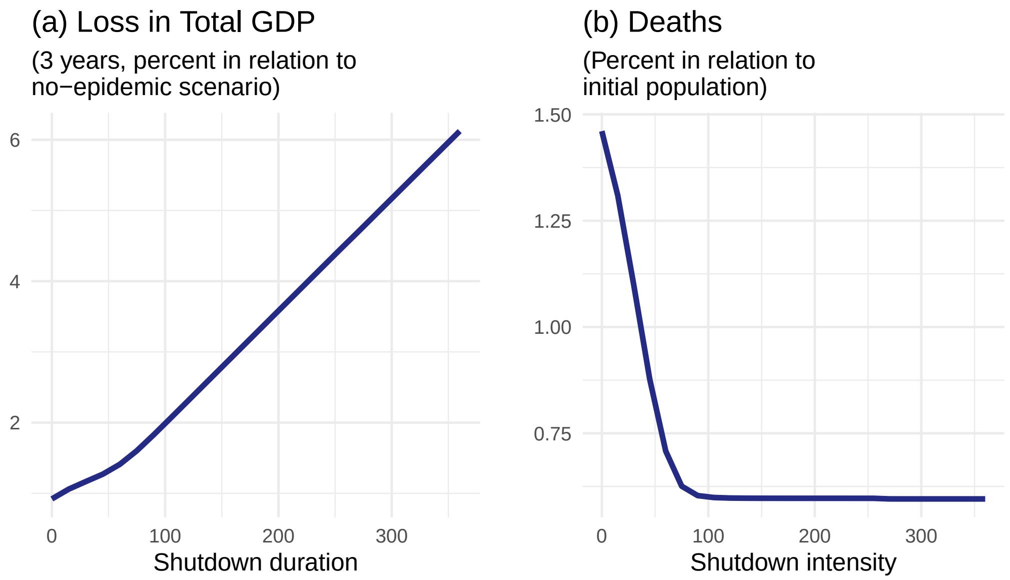
[3] A possible extension is to assume that also family members of infectious persons are quarantined.

Figure 6: Impact of shutdown on GDP and deaths

(a) Shutdown intensity

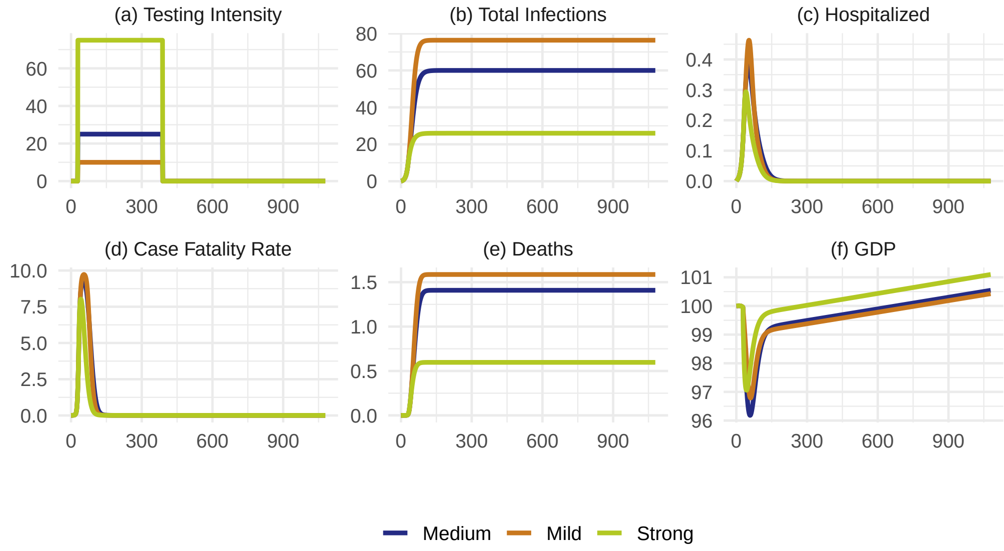


(b) Shutdown duration



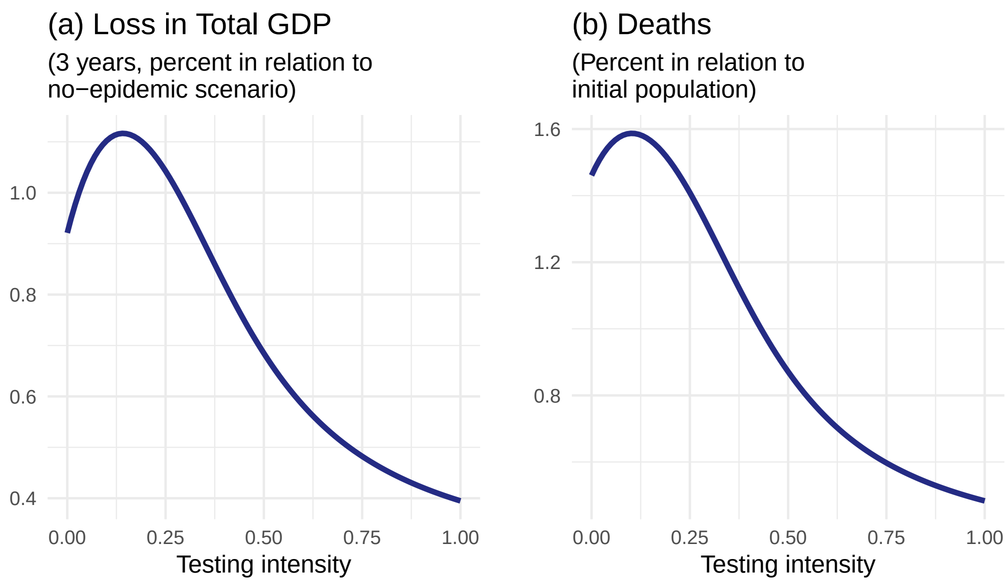
Notes: Model parameters are given in Tables 1 and 2. Shutdown begin: $T_0 = 30$. Shutdown duration: $\tau = 45$ in Figure (a) and shutdown intensity $\nu_t = 0.25$ in Figure (b).

Figure 7: Mitigation by identifying and isolation



Notes: Model parameters are given in Tables 1 and 2. Testing begin: $T_0 = 30$ and testing duration: $\tau = 360$. Testing intensity $\theta = 0.10$ (mild) $\theta = 0.25$ (medium) and $\theta = 0.75$ (strong).

Figure 8: Impact of testing intensity on GDP and deaths



Notes: Model parameters are given in Tables 1 and 2. Shutdown begin: $T_0 = 30$ and shutdown duration: $\tau = 45$.

3 Optimal Policy

In this section, we determine the optimal mitigation policy. Using the instantaneous utility function

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

total wealth is given by

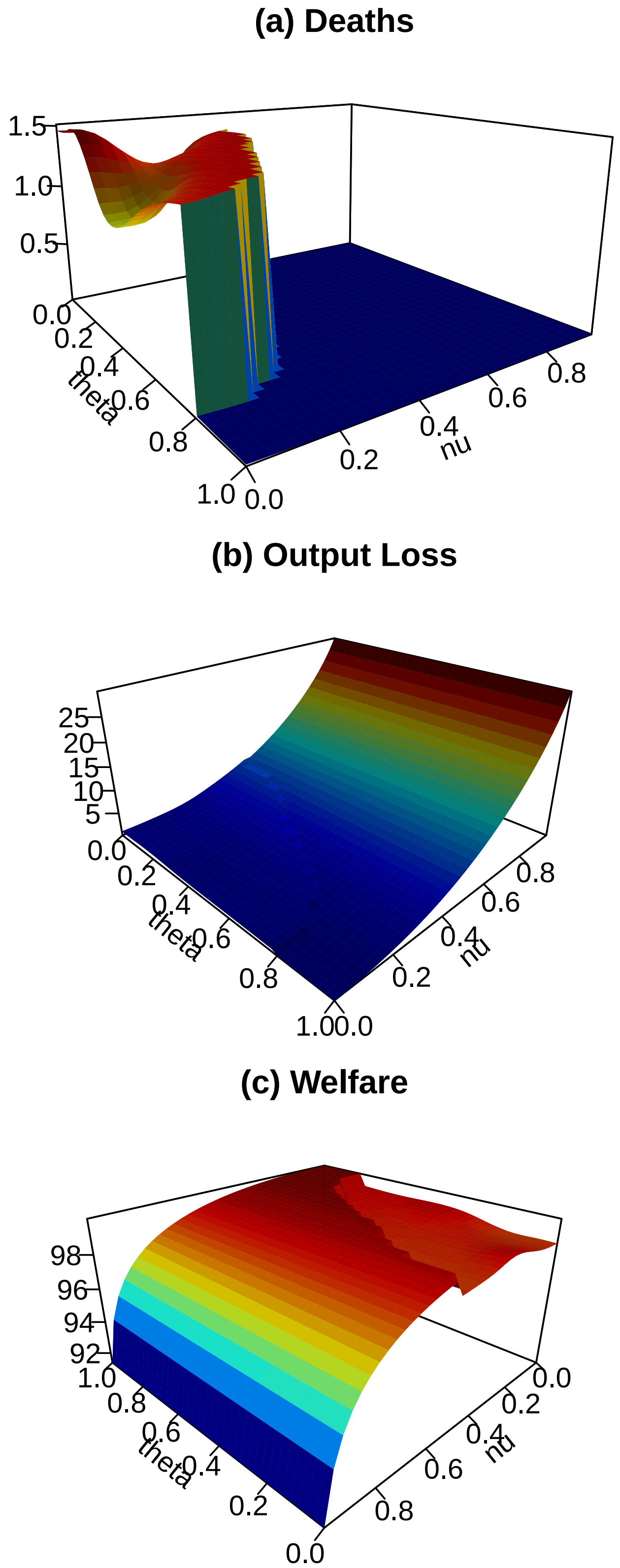
$$W_0 = \sum_{t=0}^{T} \frac{u(c_t) Pop_t}{(1+\rho)^{t/360}}.$$

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 certain 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. As before, the time period considered is three years ($T = 1080$ 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 discount rate is not very influential due to the relatively short simulation horizon. The utility function curvature, however, is a very important parameter because it captures implicitly how the society values consumption and deaths.

We consider four policy parameters: shutdown duration and intensity and testing duration and intensity. Duration varies from 0 to 360 days (step size 30 days) and intensity varies from 0 to 1 (step size 0.1) which implies $11 \times 11 \times 13 \times 13 = 20.449$ mitigation plans. We assume that mitigation policies start on day 15. The epidemic parameters are as in Table 2. In order to summarize the results graphically, we exhibit only a subset of all simulated cases. We choose proportional values for duration and intensity of both shutdown and testing measures ($\nu = \tau/360$ and $\theta = \tau/360$, 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 no shutdown and 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%. In this constrained case, combinations of shutdown and testing are optimal with respect to welfare, see Table 3. The optimal trajectories for the constrained case are presented in Figure 10. Focusing solely on minimizing output loss triggers a second wave of infections after initial mitigation measures have been relieved.

Figure 9: Impact of mitigation policies on welfare



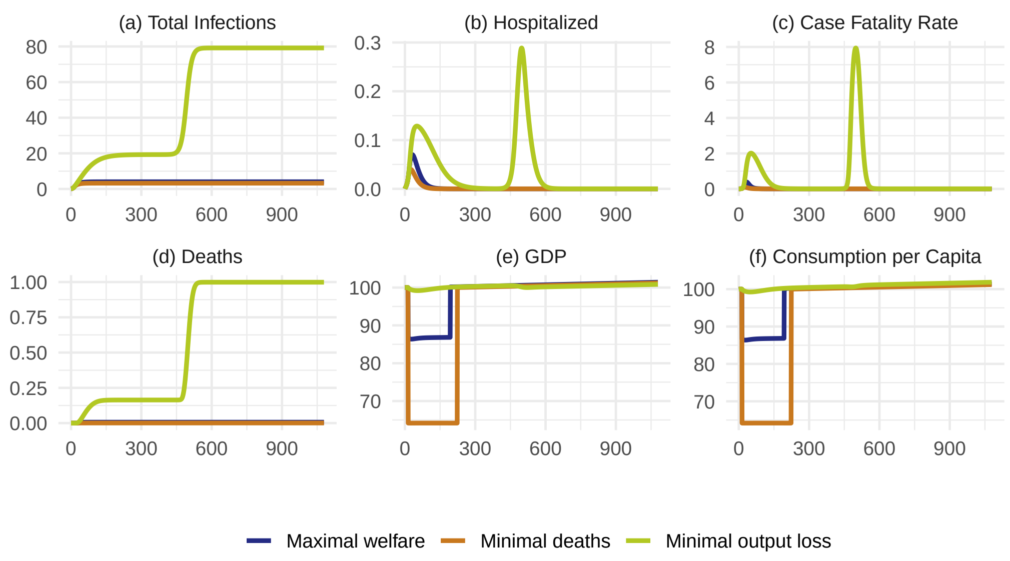
Notes: theta refers to testing strength (duration and intensity) and nu refers to shutdown strength (duration and intensity).

Table 3: Optimal mitigation policies

	Shutdown		**Testing**		**Outcome**		
	Duration	Intensity	Duration	Intensity	Deaths	Output loss	Welfare
	Unconstrained						
Minimal deaths	90	1	0	0	0.0003%	8.5968%	$-\infty$
Minimal output loss	0	0	210	1	0.0117%	0.0285%	99.9875%
Maximal welfare	0	0	210	1	0.0117%	0.0285%	99.9875%
	Constrained ($\theta_t \leq 0.5$, $\nu_t \leq 0.5$)						
Minimal deaths	210	0.5	0	0	0.0009%	7.1799%	99.3529%
Minimal output loss	0	0	360	0.5	0.9985%	0.4892%	99.4110%
Maximal welfare	180	0.2	270	0.5	0.0066%	2.3063%	99.8251%

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

Figure 10: 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 the 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 will come with a second wave of infections once 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. Furthermore, the results presented here depend on the specific calibration. The relationship between asymptomatic and symptomatic infected persons, the case fatality rate, the curvature of the utility function and the time horizon, for example, are crucial parameters. In future versions of the paper, we will provide an intensive sensitivity analysis. Another possible extension that we leave for future work is including individual choice of labor and consumption into the model.

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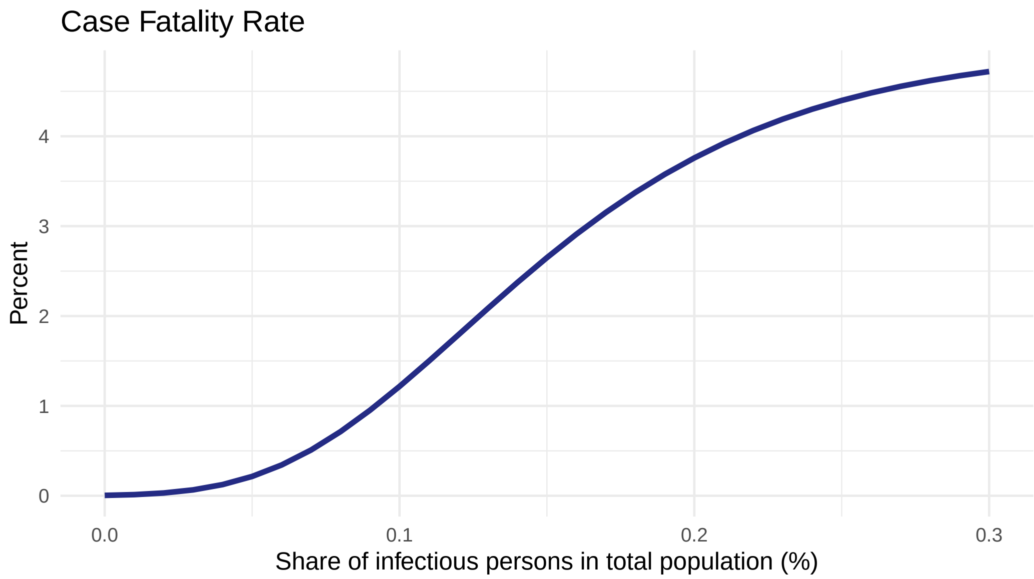
Appendix

Calibration of the case fatality rate

Figure 11: Case Fatality Rate

(a) Observed Deaths

(b) Model Case Fatality Rate



Notes: Panel (a) shows that there is large heterogeneity in the share of deaths. 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% ($\overline{\mu} = 0.1$).

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