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Monetary Policy and COVID-19

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Abstract

We study the macroeconomic effects of the COVID-19 epidemic in a quantitative dynamic general equilibrium setup with nominal rigidities. We evaluate various containment policies and show that they allow to dramatically reduce the welfare cost of the disease. Then we investigate the role that monetary policy, in its capacity to manage aggregate demand, should play during the epidemic. According to our results, treating the observed output contraction as a standard recession leads to overly expansionary policy. Finally, we check how central banks should resolve the trade-off between stabilizing the economy and containing the epidemic. If no administrative restrictions are in place, the second motive prevails and, despite the deep recession, optimal monetary policy is in fact contractionary. Conversely, if sufficient containment measures are introduced, central bank interventions should be expansionary and help stabilize economic activity.

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Contents

1 Introduction

The COVID-19 pandemic poses an unprecedented challenge for both health and economic policy. The two are strongly interrelated as policies that aim at mitigating the spread of the disease, like various forms of lockdown or isolation, have mostly negative consequences for economic activity. Furthermore, governments in many advanced and emerging market economies applied fiscal stimuli of unprecedented scale to prevent persistent loss of production potential, a wave of bankruptcies, financial instability and an increase in economic inequality. These efforts were strongly supported by ultra-loose monetary policy, which included sharp cuts of nominal interest rates and large scale purchases of government debt by central banks. These actions were clearly much needed as they probably helped avoid a complete breakdown of the economic system. However, their direct and indirect effect on aggregate demand, and hence on the intensity of economic interactions by agents, might also have had a non-negligible effect on the pandemic dynamics.

This non-standard and unexplored dimension of macroeconomic stabilization policies poses a huge challenge to the theory and practice of economics, especially that there is very little past experience with economic interventions during an epidemic. In particular, it is far from obvious how monetary policy should react beyond its efforts to preserve financial stability and (possibly) support financing appropriately calibrated fiscal packages. A typical central bank reaction to a recession is to provide monetary stimulus, thus minimizing the drop in economic activity. However, engineering an aggregate demand expansion can prove counterproductive in times of the pandemic since the recession reflects, to a large extent, an intentional and desired reduction in economic activity. This results from the actions of agents who want to decrease the risk of catching the disease, and of policymakers who impose lockdowns and other measures to contain the virus. Optimal aggregate demand management must therefore resolve a trade-off between addressing aggregate demand externalities due to nominal rigidities, which typically call for a policy stimulus during recessions, and agents' failure to internalize the impact of their actions on pandemics, which may suggest an opposite reaction. Prominent policymakers and economists have raised doubts of this nature (see e.g. Bullard, 2020 and Kaplan et al., 2020b). However, to our knowledge, a quantitative analysis of this dilemma in a monetary policy context is still missing, and this is where we see our main contribution.

Against this backdrop, we propose a quantitative analytical framework that connects two modelling concepts. The first is a standard microfounded business cycle model that allows to discuss the effects of monetary policy in its capacity to manage aggregate demand. The second is an epidemic modeling setup that allows to simulate a pandemic resembling

COVID-19 during its early phase, i.e. before the vaccines became widely available. We thus obtain a natural platform that enables experimenting with different policy options and evaluating their welfare effects, including a two-way relationship between economic activity and the spread of the pandemic.

According to our results, the cost of the epidemic is very high – absent regulatory restrictions on economic and social activity, the welfare loss exceeds 1.3% of agents' lifetime consumption. Our simulations show that, thanks to policy interventions (lockdowns) like those introduced in most euro area countries, this cost has been reduced by more than half. We also find that monetary policy should not necessarily react to the pandemic in the usual way, i.e. by responding to deviation of output from trend as during a standard recession. If we assume such a reaction, welfare is reduced regardless of the epidemic containment measures being in place. The reason is straightforward – if monetary policy aggressively counteracts the slowdown, it thus strengthens social interactions and accelerates the pandemic.

The key questions are then: What should, under such special circumstances, monetary policy do? How should it resolve the trade-off between its usual role of providing macroeconomic stability and the side effects described above? The answer is not trivial, and depends on the containment measures introduced by the government. According to our results, if no administrative restrictions are in place, then monetary policy should, in fact, be contractionary, i.e. cool down the economy and flatten the infection curve. This indicates that, under a laissez-faire approach to the pandemic, New Keynesian aggregate demand externalities are less important than externalities associated with agents' reactions to the pandemic. However, once the authorities introduce sufficiently tough lockdowns, the aggregate demand management considerations come back to the forefront and optimized monetary policy becomes expansionary. In general, we show that the policy frontier between stabilizing the economy and reducing the death toll is relatively flat for monetary policy. This means that central bank actions are not efficient at fighting COVID-19, but can relatively effectively limit the economic consequences of lockdowns if they are introduced on an appropriate scale.

The rest of this paper is organized as follows. Section 2 discusses how our study relates to the existing literature. In Section 3 we present our theoretical framework. Section 4 discusses the calibration. In Section 5 we present our main results. Section 6 concludes.

2 Literature review

Our study is most closely related to the literature that attempts to model optimal epidemic policies and their economic consequences. Several papers use stylized frameworks to study the tradeoff between lives saved due to lockdowns and economic costs of them. Atkeson

(2020) compares several scenarios of suppressing the disease through social distancing. Alvarez et al. (2020) formulate a simple planning problem to design an optimal lockdown limiting the spread of the disease. Acemoglu et al. (2020) extend their framework to account for multiple age groups. Finally, Favero et al. (2020) study optimal lockdowns in a stylized economy with multiple sectors and age groups.

An increasing body of the literature implements general equilibrium models to study the optimal public policy response to the pandemic. Eichenbaum et al. (2020b) modify the standard SIR setup by making the probability of infection explicitly dependent on economic decisions made by optimizing agents. They study trade-offs between public health and the economic cost of the pandemic. Jones et al. (2020) employ a similar framework to study optimal mitigation policies in a pandemic. Glover et al. (2020) introduce a quantitative model to examine the interaction between macro-mitigation and micro-redistribution to find that optimal mitigation involves a mixture of such policies. Azzimonti et al. (2020) study infection dynamics and reopening scenarios in a heterogeneous sectors and household network model. Kaplan et al. (2020a) argue that the government policy must face trade-offs between lives and livelihoods and over who should bear the burden of the economic costs. The view that there is a trade-off between health and the economy is challenged by Bodenstein et al. (2020), who show that social distancing measures can reduce large upfront costs of the pandemic and slow down its spread. Krueger et al. (2021) argue that endogenous shifts in private consumption behavior across sectors of the economy can act as a potent mitigation mechanism during an epidemic or when the economy is reopened after a temporary lockdown.

In contrast to the huge effort of modeling optimal containment policies, the question how monetary policy should behave during an epidemic has not received much attention so far. Levin and Sinha (2020), use a simple New Keynesian framework to find that forward guidance has only tenuous net benefits. Lepetit and Fuentes-Albero (2020) study the effects of an unanticipated decline in the interest rate to conclude that monetary policy is likely to be ineffective at the height of the pandemic, but it should help sustain the recovery in economic activity once the virus starts dissipating. Vásconez et al. (2021) augment the DSGE-SIR model with a financial sector as in Gertler and Karadi (2011). They find that while standard monetary policy has a negligible effect on GDP during pandemics, unconventional monetary policy has the potential to lessen total losses in GDP. However, in contrast to our paper, neither of these studies focuses on the optimal response of monetary policy nor takes into account the fact that boosting economic activity can affect the spread of the disease.

On the modeling front our paper connects two streams of the literature. First, we build on the most popular way of modeling epidemics. It draws from the seminal contribution of Kermack and McKendrick (1927) and its extension for the presence of asymptomatic infected agents (Prem et al., 2020). We integrate this modified SIR framework, A-SIR, with the workhorse new Keynesian business cycle model (Clarida et al., 1999). Our complete framework is most similar to Eichenbaum et al. (2020a), who show that a DSGE model with a SIR component has the desired features to study macroeconomic processes during an epidemic. However, our framework features important extensions. First, as mentioned above, we allow some infected agents to be carriers of the disease but experience no symptoms and be unaware of their infection. This modification makes the model more realistic and provides a challenge for public policy since isolation of all infected individuals is not feasible. Second, we allow agents to borrow from each other so that credit market conditions affect agents' balance sheets.

3 Model

As discussed above, our model connects an epidemic framework with a standard New Keynesian setup. From the epidemic perspective agents belong to one of the following groups: susceptible, infected (symptomatic or asymptomatic) or recovered (from being formerly symptomatic or asymptomatic). As regards their economic activity, they decide on consumption and labor supply, and are allowed to borrow from each other. Firms operate in a monopolistically competitive environment and set prices in a staggered fashion, which means that monetary policy can affect real allocations. Additionally, the government conducts epidemic containment policy and the monetary authority sets the interest rate according to a Taylor-type rule. Below we present the framework in more detail.

3.1 Epidemic Model: A-SIR

We modify the classic SIR model along two dimensions. First, following Eichenbaum et al. (2020b), we make probabilities of being infected depend on economic activity. Second, following Prem et al. (2020), infected people are either symptomatic and asymptomatic. The asymptomatic infected are less infectious than symptomatic.[1]

There are five types of individuals in the economy: susceptible S_t, infected asymptomatic A_t, infected symptomatic I_t, formerly asymptomatic recovered V_t and formerly symptomatic recovered R_t. Since infected asymptomatic have no infection symptoms, they behave the same as susceptible individuals, so do formerly asymptomatic infected. Before the pandemic,

[1] The model does not take into account the possibility that during the epidemic a vaccine becomes available. However, our main results remain broadly unchanged if we allow for a gradual decline in the mortality rate after a year since the onset of the pandemic, thus accounting for the effects of the vaccination program introduced in most euro area countries.

all agents are assumed to be identical. Once the virus starts spreading, agents become heterogeneous in whether, when and how they contract the disease, which has consequences for their economic decisions.

There are three channels through which infection spreads. First, susceptible can be infected while consuming, with the probability of infection dependixng on their individual consumption level c_t^S, aggregate consumption of symptomatic infected $I_t c_t^I$ and aggregate consumption of asymptomatic infected $A_t c_t^A$. Since there is evidence that asymptomatic infected are less infectious than symptomatic, we introduce a parameter $0 \leq \kappa < 1$ to account for that. We also allow for possible isolation of symptomatic infected individuals by scaling their infectiousness with parameter $0 \leq \zeta \leq 1$. Second, susceptible agents can be infected while working with the probability of infection depending on their individual hours worked n_t^S, and aggregate hours worked by asymptomatic infected $A_t n_t^A$. We assume that symptomatic infected either do not work or work remotely, so they do not transmit the disease via the labor channel. Finally, infection can spread through other channels (like kindergardens, schools, family meetings etc.), with the probability depending on the number of infected people, both symptomatic and asymptomatic, and on variable ϖ_t which depends on the lockdown measures in place. Summing up, susceptible individual i can become infected (with symptoms or not) with probability $\varpi_{I,t}(i)$ that is given by the following formula

$$\varpi_{I,t}(i) = \varpi_c c_t^S(i)(\zeta I_t c_t^I + \kappa A_t c_t^A) + \varpi_n n_t^S(i)\kappa A_t n_t^A + \varpi_t(I_t + \kappa A_t) \tag{1}$$

where $\varpi_c, \varpi_n > 0$ are constants controlling the relative importance of consumption and labor channels in transmitting the virus.

Since asymptomatic infected experience no symptoms, they do not realize that they are infected. Therefore, while making their decisions, susceptible, asymptomatic infected and formerly asymptomatic recovered behave the same. We call this group supposedly susceptible and their mass is $\tilde{S}_t = S_t + A_t + V_t$. Each member of this group could be susceptible, asymptomatic infected, or formerly asymptomatic recovered, and knows the probabilities of belonging to each category. The evolution of susceptible individuals is given by the following equation

$$S_{t+1} = (1 - \varpi_{I,t})S_t \tag{2}$$

When an individual becomes infected, she is symptomatic with probability ρ and asymptomatic with probability $1-\rho$. Infected asymptomatic recover with probability ϖ_R. Infected symptomatic die with probability $\varpi_{D,t}$ and recover with probability $\varpi_R - \varpi_{D,t}$. The evolution of symptomatic infected, asymptomatic infected, formerly asymptomatic infected and recovered agents is then given by the following equations

$$I_{t+1} = (1 - \varpi_R) I_t + \rho \varpi_{I,t} S_t \tag{3}$$

$$A_{t+1} = (1 - \varpi_R) A_t + (1 - \rho) \varpi_{I,t} S_t \tag{4}$$

$$V_{t+1} = V_t + \varpi_R A_t \tag{5}$$

$$R_{t+1} = R_t + (\varpi_R - \varpi_{D,t}) I_t \tag{6}$$

Finally, the number of deceased D_t evolves according to

$$D_{t+1} = D_t + \varpi_{D,t} I_t \tag{7}$$

3.2 Supposedly susceptible individuals

As we mentioned above, this group consists of susceptible, asymptomatic infected and formerly asymptomatic recovered. The probability that a supposedly susceptible agent i becomes symptomatic infected $\tilde{\varpi}_{I,t}(i)$ equals

$$\tilde{\varpi}_{I,t}(i) = \rho \varpi_{I,t}(i) \frac{S_t}{\tilde{S}_t} \tag{8}$$

Each period agents choose consumption $\tilde{c}_t(i)$, labor supply $\tilde{n}_t(i)$ and nominal bond holdings $\tilde{B}_{t+1}(i)$ that pay a nominal interest rate $\mathcal{I}_t$. Their expenditure is financed with labor income that earns a nominal wage W_t, bond holdings from the previous period $\tilde{B}_t(i)$ and lump sum real transfers from the government Γ_t. For simplicity, we assume that profits from the firms are also collected by the government and transferred to households as a part of Γ_t. Supposedly susceptible agents face the following budget constraint

$$(1 + \tau_{c,t}) P_t \tilde{c}_t(i) + \tilde{B}_{t+1}(i) = (1 - \tau_{n,t}) W_t \tilde{n}_t(i) + \mathcal{I}_{t-1} \tilde{B}_t(i) + P_t \Gamma_t \tag{9}$$

where $\tau_{c,t}$ denotes the consumption tax rate and $\tau_{n,t}$ the labor income tax rate. Following Eichenbaum et al. (2020b), we use these taxes to model administrative restrictions on economic activity (lockdowns). The revenue from these taxes is rebated back to households, therefore, they should not be considere as a part of the fiscal apparatus.

The recursive problem of the supposedly susceptible household is given by

$$\begin{aligned} \tilde{U}_t(\tilde{b}_t(i)) = \max_{\tilde{c}_t(i), \tilde{n}_t(i), \tilde{B}_{t+1}(i), \tilde{\varpi}_{I,t}(i)} & \log \tilde{c}_t(i) + \theta \log(1 - \tilde{n}_t(i)) + \beta(1 - \tilde{\varpi}_{I,t}(i)) \tilde{U}_{t+1}(\tilde{b}_{t+1}(i)) \\ & + \beta \tilde{\varpi}_{I,t}(i) U_{I,t+1}(\tilde{b}_{t+1}(i)) \end{aligned} \tag{10}$$

subject to the probability of becoming infected (8) and the budget constraint (9), where $\tilde{b}_t = \tilde{B}_t/P_{t-1}$ denotes real bond holdings.

The aforementioned problem results in the following first order conditions

$$\frac{1}{\tilde{c}_t} = \tilde{\lambda}_{S,t}(1+\tau_{c,t}) - \tilde{\lambda}_{\varpi,t}\rho\frac{S_t}{\tilde{S}_t}\varpi_c(\zeta I_t c_t^I + \kappa A_t \tilde{c}_t) \tag{11}$$

$$\frac{\theta}{1-\tilde{n}_t} = \tilde{\lambda}_{S,t}(1-\tau_{n,t})w_t + \tilde{\lambda}_{\varpi,t}\rho\frac{S_t}{\tilde{S}_t}\varpi_n \kappa A_t \tilde{n}_t \tag{12}$$

$$\tilde{\lambda}_{\varpi,t} = \beta[U_{I,t+1}(\tilde{b}_{t+1}) - \tilde{U}_{t+1}(\tilde{b}_{t+1})] \tag{13}$$

$$\tilde{\lambda}_{S,t} = \beta[(1-\tilde{\varpi}_{I,t})\tilde{\lambda}_{S,t+1} + \tilde{\varpi}_{I,t}\lambda_{I,t+1}]\frac{\mathcal{I}_t}{\pi_{t+1}} \tag{14}$$

where $\tilde{\lambda}_{\varpi,t}$ and $\tilde{\lambda}_{S,t}/P_t$ are the Lagrangian multipliers on (8) and (9), respectively, $\lambda_{I,t}/P_t$ is the Lagrange mulitplier on the budget constraint of symptomatically infected agents that we define in equation (15) below, $w_t = W_t/P_t$ is the real wage, and we have omitted individual indices i for better clarity. The first two conditions show that supposedly susceptible individuals, while deciding how much to consume and work, take into account the risk of becoming infected during these activities. The pandemic hence endogenously limits their labor supply and consumption. The last term of the first two equations denotes the loss of utility due to infection multiplied by the risk of getting infected during the respective activity. The third equation stipulates that the Lagrangian multiplier $\tilde{\lambda}_{\varpi,t}$ equals the discounted utility loss due to infection. The fourth equation is the Euler equation.

3.3 Symptomatic infected individuals

We assume that, to a certain degree, infected individuals can work remotely, but their productivity is lowered by factor $0 \leq \xi \leq 1$. They choose consumption $c_t^I(i)$, labor supply $n_t^I(i)$, and bond holdings $B_{t+1}^I(i)$. Their return on bond holding equals $\mathcal{I}_t/(1-\varpi_{D,t})$ to account for the fact that a fraction $\varpi_{D,t}$ of infected dies each period. Their budget constraint is as follows

$$(1+\tau_{c,t})P_t c_t^I(i) + B_{t+1}^I(i) = W_t \xi n_t^I(i) + \mathcal{I}_{t-1}B_t^I(i)/(1-\varpi_{D,t-1}) + P_t\Gamma_t \tag{15}$$

The recursive problem of the infected household is given by

$$U_t^I(b_t^I(i)) = \max_{c_t^I(i), n_t^I(i), B_{t+1}^I(i)} \log c_t^I(i) + \theta \log(1 - n_t^I(i)) + \beta(1 - \varpi_R) U_{t+1}^I(b_{t+1}^I(i)) \tag{16}$$
$$+ \beta(\varpi_R - \varpi_{D,t}) U_{t+1}^R(b_{t+1}^I(i)) + \beta \varpi_{D,t} U^D$$

subject to the budget constraint (15), and where U_D denotes disutility associated with dying. Omitting individual indices, the first-order optimality conditions can be written as

$$\frac{1}{c_t^I} = \lambda_{I,t}(1 + \tau_{c,t}) \tag{17}$$

$$\frac{\theta}{1 - n_{I,t}} = \xi \lambda_{I,t} w_t \tag{18}$$

$$\lambda_{I,t} = \beta[(1 - \varpi_R - \varpi_{D,t})\lambda_{I,t+1} + \varpi_R \lambda_{R,t+1}] \frac{\mathcal{I}_t}{\pi_{t+1}(1 - \varpi_{D,t})} \tag{19}$$

where $\lambda_{R,t}/P_t$ is the Lagrange mulitplier on the budget constraint of symptomatic recovered agents defined in equation (20) below.

3.4 Symptomatic recovered individuals

The recovered individuals are not at risk of getting infected, so they are not afraid of it anymore. Their problem is exactly as if there was no epidemic. They choose consumption $c_t^R(i)$, labor supply $n_t^R(i)$, and bond holdings $B_{t+1}(i)$. Their budget constraint is as follows

$$(1 + \tau_{c,t}) P_t c_t^R(i) + B_{t+1}^R(i) = (1 - \tau_{n,t}) W_t n_t^R(i) + \mathcal{I}_{t-1} B_t^R(i) + P_t \Gamma_t \tag{20}$$

The recursive problem of the recovered household is given by

$$U_t^R(b_t^R(i)) = \max_{c_t^R(i), n_t^R(i), B_{t+1}^R(i)} \log c_t^R(i) + \theta \log(1 - n_t^R(i)) + \beta U_{t+1}^R(b_{t+1}^R(i)) \tag{21}$$

subject to the budget constraint (20). Standard first-order conditions follow.

3.5 Firms

Retail firms maximize profit in a perfectly competitive framework. They buy intermediate goods $y_t(\iota)$ at price $P_t(\iota)$ from their producers indexed by ι and combine them into final goods y_t, which they sell to households at a price P_t. They maximize the following profits

$$P_t y_t - \int_{\iota \in [0,1]} P_t(\iota) y_t(\iota) d\iota \tag{22}$$

subject to the technological constraint

$$y_t = [\int_{\iota \in [0,1]} y_t(\iota)^{\frac{\varepsilon-1}{\varepsilon}} d\iota]^{\frac{\varepsilon}{\varepsilon-1}} \tag{23}$$

Solving this problem, we get the following equation describing the demand for intermediate goods

$$y_t(\iota) = \left(\frac{P_t(\iota)}{P_t}\right)^{-\varepsilon} y_t \tag{24}$$

and from the zero-profit condition follows the formula for the aggregate price level

$$P_t = [\int_{\iota \in [0,1]} P_t(\iota)^{1-\varepsilon} d\iota]^{\frac{1}{1-\varepsilon}} \tag{25}$$

We assume that each intermediate good firm ι operating in a monopolistically competitive environment produces its product $y_t(\iota)$ with the following technology

$$y_t(\iota) = Z n_t(\iota) \tag{26}$$

where $n_t(\iota)$ denotes labor demand by firm ι and $Z > 0$ is the level of productivity. Since the total cost is $w_t n_t(\iota)$, production function (26) implies the following expression for the marginal cost

$$mc_t = \frac{w_t}{Z} \tag{27}$$

which is the same for all firms.

Each period an intermediate good firm receives a signal to adjust prices with probability $1 - \delta$ and resets the price to $\tilde{P}_t(\iota)$ to maximize the sum of discounted profits

$$\max_{\tilde{P}_t(\iota), \{y_{t+j}(\iota)\}_{j=0}^{\infty}} E_t \sum_{j=0}^{\infty} (\beta\delta)^j \Lambda_{t,t+j} \left(\frac{\tilde{P}_t(\iota)}{P_{t+j}} - mc_{t+j}\right) y_{t+j}(\iota) \tag{28}$$

subject to demand function (24). Absent the signal the price remains unchanged $P_{t+1}(\iota) = P_t(\iota)$. The discount factor $\Lambda_{t,t+j}$ is computed as a weighted average of marginal utility of consumption across all types of households.

3.6 Government, central bank and the health-care system

The government uses the consumption and labor tax rates $\tau_{c,t}$ and $\tau_{n,t}$ to restrict market activity and slow down the spread of the virus. Since the collected revenue is rebated back to households, these taxes discourage agents from consuming and working, but do not directly affect their average income. Additionally, the government transfers firms' profits to households. As our model describes a one-sector economy, the fiscal authority does not supply rescue packages to industries and workers that are hit most, as it was the case in many countries during the COVID-19 pandemic. Hence, we make an implicit assumption that appropriate income redistribution is in place and that it can be financed without creating market distortions (e.g. with lump sum taxes). Thus, we abstract from income inequality and focus on the aggregate demand management mandate of central banks. The budget of the government can then be assumed to be balanced every period, leading to the following constraint

$$\tau_{c,t} P_t c_t + \tau_{n,t} W_t n_t + P_t y_t - W_t n_t = (\tilde{S}_t + I_t + R_t)\Gamma_t \tag{29}$$

where aggregate consumption c_t and labor n_t will be defined below.

We assume a simple, but operational rule for lockdown policies, that relates the tax rates to the number of infected agents

$$\tau_{c,t} = \Phi_c I_t \tag{30}$$

$$\tau_{n,t} = \Phi_n I_t \tag{31}$$

where $\Phi_c, \Phi_n > 0$. Additionally we assume that the lockdown policy affects transmission via the third channel

$$\omega_t = \omega(1 - \tau_{c,t})^{\Phi_\omega} \tag{32}$$

where $\omega, \Phi_\omega > 0$. This reflects the observation that consumption lockdowns (closures of shops or ski-lifts) were usually introduced simultaneously with non-economic restrictions (e.g. closures of schools).

We assume that the central bank conducts monetary policy according to a Taylor-type rule that responds to the deviation of inflation from the steady state, to the output gap and possibly allows for reaction to the number of infected agents

$$\frac{\mathcal{I}_t}{\bar{\mathcal{I}}} = \left(\frac{\pi_t}{\bar{\pi}}\right)^{\Phi_\pi} \left(\frac{y_t}{y_t^f}\right)^{\Phi_y} \exp(I_t)^{\Phi_I} \tag{33}$$

where $\Phi_\pi, \Phi_y, \Phi_I \geq 0$ and y_t^f denotes the flexible price level of output.

Following the epidemic literature, we assume that the probability of dying depends on the strain put by the pandemic on the heath-care system. We assume a piecewise linear relationship to reflect the notion that the probability increases in the number of infected, but levels off beyond a certain point

$$\varpi_{D,t} = \min\left[\left(1+\frac{I_t}{\nu_0}\right)\varpi_D, \nu_1\varpi_D\right] \tag{34}$$

where $\nu_0, \nu_1 > 0$.

3.7 Market clearing

At the beginning of the epidemic, there is measure one of agents. We denote the set of agents that are supposedly susceptible at time t as $\mathbb{S}_t$, symptomatically infected as $\mathbb{I}_t$, and symptomatically recovered as $\mathbb{R}_t$. Then the final good market clearing can be written as

$$\int_{i\in\mathbb{S}_t} \tilde{c}_t(i)di + \int_{i\in\mathbb{I}_t} c_t^I(i)di + \int_{i\in\mathbb{R}_t} c_t^R(i)di \equiv c_t = y_t \tag{35}$$

The labor market clearing condition has the following form

$$\int_{i\in\mathbb{S}_t} \tilde{n}_t(i)di + \int_{i\in\mathbb{I}_t} n_t^I(i)di + \int_{i\in\mathbb{R}_t} n_t^R(i)di \equiv n_t = \int_{\iota\in[0,1]} n_t(\iota)d\iota \tag{36}$$

Substituting from (26) and (24), we get the aggregate production function

$$\Delta_t y_t = z_t n_t \tag{37}$$

where price dispersion Δ_t is given by

$$\Delta_t = \int_{\iota\in[0,1]} \left(\frac{P_t(\iota)}{P_t}\right)^{-\varepsilon} d\iota \tag{38}$$

Finally, assets by agent type evolve according to

$$\begin{aligned}
\tilde{S}_{t+1}\tilde{B}_{t+1} &= (1-\tilde{\varpi}_{I,t})\int_{i\in\mathbb{S}_t} \tilde{B}_{t+1}(i)di \\
I_{t+1}B_{t+1}^I &= (1-\varpi_R)\int_{i\in\mathbb{I}_t} B_{t+1}^I(i)di + \tilde{\varpi}_{I,t}\int_{i\in\mathbb{S}_t} \tilde{B}_{t+1}(i)di \\
R_{t+1}B_{t+1}^R &= \int_{i\in\mathbb{R}_t} B_{t+1}^R(i)di + (\varpi_R - \varpi_{D,t})\int_{i\in\mathbb{I}_t} B_{t+1}^I(i)di
\end{aligned} \tag{39}$$

and bond market clearing requires

$$\tilde{S}_t \tilde{B}_t + I_t B_t^I + R_t B_t^R = 0 \tag{40}$$

4 Calibration

Our model embeds the pandemic block into an otherwise fairly standard quantitative business cycle setup. To calibrate the former, we draw on the epidemiological literature and particularly on the most recent papers dealing directly with the COVID-19 disease. The parametrization of the macroeconomic block is based on the vast DSGE literature.

We start with the pandemic block. To calibrate the parameters controlling the spread of disease via consumption, labor, and other activities, we follow Eichenbaum et al. (2020c) and set them such that, absent containment measures, each of the two economic channels accounts for one-sixth of the transmission and about two-thirds of the population become infected before the pandemic dies out. The targeted relative role of transmission channels is based on evidence on influenza pandemic described by Ferguson et al. (2006), combined with information from the BLS Time Use Survey. The terminal share of the population that either recovers or dies are consistent with the estimated herd immunity levels of 60-70%, as implied by standard models, see, e.g., Gomes et al. (2020) or Prem et al. (2020).

As in Atkeson (2020) we assume that it takes 18 days (i.e., 7/18 periods in our weekly model) to either recover or die from the disease, which is also consistent with more recent estimates reported by Zhou et al. (2020). This, together with the infection fatality rate of 0.6% suggested by cross-country and meta-studies (O'Driscoll et al., 2020; Ioannidis, 2020), brings us to our calibrated value of basic death probability. The share of symptomatic agents in all infected is calibrated at 0.6, reflecting a compromise between a wide range of estimates reported in the COVID-19 medical literature (Oran and Topol, 2020; Wells et al., 2020; Yanes-Lane et al., 2020). The relative infectiousness of asymptomatically infected is also subject to high uncertainty, so we use the value of 0.5, consistent with a meta-study by Byambasuren et al. (2020), corrected upwards by recent evidence from Bi et al. (2020). The relative productivity of infected agents is set to 0.8. Following Ferguson et al. (2020) and Wilde et al. (2021), we assume that mortality doubles when the number of infected exceeds 1% of the population. Parameters of function (34) are set to extrapolate these assumptions, simultaneously setting a maximum mortality rate of $3 \cdot \varpi_D$.

The parameters related to the macroeconomic part of the model are standard for the business cycle literature. We use well established values, converting them to weekly frequency wherever appropriate. Our calibration of the discount factor is based on its standard value of 0.99 used in quarterly models. The weight on leisure in utility targets 40% of time spent at work-related activities. The elasticity of substitution between intermediate inputs is set to obtain the product markup of 20%. The degree of price stickiness is chosen by expressing the standard value of quarterly Calvo probability of 0.75 in weekly units. The parameters describing the interest rate feedback to inflation and the output gap in the monetary policy reaction function are set to 1.5 and 0.5 (converted to weekly) respectively, as postulated by the standard Taylor rule.

Finally, we set the disutility associated with dying and the three parameters related to lockdowns (U_D, Φ_c, Φ_n and Φ_ω). We proceed as follows. First, we calculate the fallout of GDP in Sweden, which is a country where relatively weak administrative containment measures have been applied. Keeping $\Phi_c = \Phi_n = 0$, we set the disutility of dying such that the model implied recession matches the one in the data. In other words, we assume that the recession in Sweden was driven by private sector decisions (which clearly depend on the fear of dying). Then we move to calibrating the lockdown parameters. To this end we calculate lost output, the change in inflation and the death rate in the euro area. Then Φ_c, Φ_n and Φ_ω are set jointly to match these values given the disutility of death calculated earlier.[2]

5 Simulation results

We are now ready to use our model to analyze the macroeconomics effects of the COVID-19 pandemic. We proceed as follows. First, we study the interplay between epidemic and economic developments, and how various healthcare policies (lockdowns, isolation of infected, etc.) affect the outcomes. Then we discuss the role of monetary policy, focusing both on normative and positive aspects.[3] Our solution method relies on deterministic simulations that take into account the whole nonlinear structure of the model. Since our preferences are homothetic, we can aggregate behavior within each group. Moreover, for evaluation of value functions at arguments off the equilibrium paths, we use a linear Taylor expansion. The resulting equilibrium conditions expressed in terms of aggregates are listed in the online Appendix.

[2]Both in Sweden and in the euro area we calculate the average difference between output in the period 2020q1-2021q1 and an extrapolated trend of real GDP growth (calculated over the previous 20 years). For Sweden the fallout is 3.4% and for the euro area 6.5%. To calculate the change in the inflation rate in the euro area we subtract average inflation in the period 2020q1-2021q1 from average inflation in 2019 (inflation declines by 0.78%). The death rate is calculated as the ratio of excess deaths to total population and amounts to approximately 0.23% (Institute for Health Metrics and Evaluation, 2021).

[3]The optimal response to the pandemic by the central bank is a normative aspect of monetary policy. We are aware that containing the epidemic is not within the usual central bank mandate. The goal of our simulations is to investigatehow monetary policy interacts with other policies fulfilling such a mandate.

5.1 The epidemic and containment measures

We start by constructing and feeding into our model several stylized scenarios, based on different assumptions about containment measures introduced by the authorities. These scenarios help us explain how our model works and, in particular, how it manages the interplay between the epidemic and economic developments. They will also serve us as benchmarks upon which we will later test various monetary policy strategies.

A useful starting point is a laissez-faire scenario, under which the authorities do not impose any containment measures on the economy, i.e. $\Phi_c = \Phi_n = 0$ (solid blue line in Figure 1). The only administrative restrictions consist of subjecting visibly infected agents to a sick-leave. However, in contrast to usual sick-leave procedures, but in line with the COVID pandemic practice, we assume that agents are allowed to work form home, albeit with lower productivity, as described in Section 4. As the epidemic develops and the number of infected agents increases, the economy starts to contract. This happens for several reasons. First, as described above, infected agents are assumed less productive, so income falls. More importantly, however, a large fraction of the remaining society are aware that the risk of getting infected via work and consumption channels increases. This applies not only to susceptible agents, but also to asymptomatically infected and asymptomatically recovered, as they do not know that they cannot fall ill anymore. These groups limit their consumption and work effort, and, as they are much more populous than infected, this is the main reason behind the contraction. Over the first year of the pandemic, output declines by approximately 4.1% and inflation by 0.3%. Total, final fatalities amount to approximately 0.61% of the population.

Output and fatalities

Let us now move to the scenarios that assume some healthcare policy intervention. It should be explained upfront that these policies are generally successful in limiting the fatality rate since they allow to flatten the infection curve, and so limit the strain on the healthcare system. Furthermore, the considered containment measures have also a potential to improve welfare. This is because agents do not fully internalize the cost of the epidemic. In particular, infected agents do not take into account that their individual consumption and work activities affect the spread of the disease. This externality has been described in the epidemic and economic literature so we limit ourselves to a brief mentioning (e.g. Eichenbaum et al., 2020b).

Our baseline policy scenario is our calibrated lockdown, and we present it with red dashed line in Figure 1. Under this scenario the authorities impose administrative measures discouraging economic activity. As discussed in Section 4, we implement this policy using taxes on consumption and labor income which are assumed to respond to the evolution in the number of visibly infected. The lockdown is much more costly for the economy than the laissez-faire variant discussed above as output declines on average by 6.7% during the first year. However, not surprisingly, limiting contacts in the population reduces sharply the number of fatalities. Ultimately the death ratio amounts to slightly less than 0.26% of the population.

Another containment measure we consider is total isolation of the visibly infected agents, which we implement by assuming $\zeta = 0$. As a consequence they spread the disease neither via work nor via the consumption channel. While many countries made efforts to introduce such a policy, we decided not to make it our baseline scenario. Due to practical problems with widespread testing, contact tracking and delays between the incubation and the test result, it seems doubtful whether this policy has historically played a role similar to that implied by our model. We test two variants: one under which this is the only containment policy (yellow, dashed line), and one when it is coupled with the economy-wide lockdown policy described above (purple, dash-dotted line). Pure isolation is relatively uncostly as output declines by only 1.29% in the first year. However, on the epidemic front, it is less successful than the lockdown as it only limits the death toll to 0.42% of the population. In contrast, the mix of isolation and lockdown is highly successful in containing the pandemic (fatalities amount to 0.16%) at a relatively small economic cost (3.39% output decline).

Finally, we consider a lockdown that is much stricter that the one introduced historically (green, dotted line), and we implement it by multiplying the baseline values of Φ_c and $\Phi_n$by three. Here the economy is frozen for over two years, but the policy limits the ultimate death toll to slightly below 0.17%. Such a scenario can be considered attractive in the context of vaccine development, which we abstract from in our model, as the policy has by far the lowest death toll after 6 quarters, a period after which vaccinations have became relatively widespread in developed countries.

Inflation

An interesting feature of our simulations is the behavior of inflation. While output and hours worked always contract in response to the pandemic, inflation can either decline, increase or remain barely affected, depending on what containment measures are introduced. This finding squares nicely with the empirical observation that inflation in most countries declined only moderately in 2020 (despite the huge economic slump), and increased sharply in 2021.

How can the differentiated reaction of inflation be explained? The outcome depends on the relative reaction of consumption demand and labor supply. Both decline during the pandemic, but while the former pushes inflation down, the latter puts an upward pressure on prices. The strongest deflationary effect occurs under the baseline scenario. Recall that we calibrated the model to match the declining inflation rate. However, it is interesting to note that this implied a stronger lockdown on consumption than on labor. In contrast, under the laissez-faire scenario inflation is almost flat. This is because, if left on their own, agents reduce consumption and work effort to a similar degree, and that leaves the aggregate demand and supply effects roughly balanced. The strongest inflationary effect occurs when infected agents are being isolated. As isolation largely reduces the risk of becoming infected via the consumption channel (some risk still remains due to the presence of asymptomatic agents), supposedly susceptible households now become less afraid of consuming, which raises the inflationary pressure.

Welfare

We conclude this part of our analysis by calculating the model-consistent cost of the epidemic. The calculation is based on aggregate welfare as defined in equation (10), evaluated at time 0, which is the period when the first infected agent appears. We compare welfare under the epidemic with welfare in a non-epidemic world, and express the difference in percent of steady state consumption that a susceptible agent would be ready to forego to avoid the epidemic.

Table 2 presents the findings. The laissez-faire scenario generates the highest welfare cost. This amounts to 1.24% of lifetime consumption, several orders of magnitude higher than the usual estimates of business cycle fluctuation costs. This number can be reduced to various degrees by the containment policies described above. For instance, the baseline lockdown cuts the cost by more than half. The most restrictive policies, namely strict lockdown and the mix of lockdown and isolation, are even more successful: the welfare cost declines to about one quarter of that under laissez-faire. While this means a big improvement, one should not forget that the cost still remains high compared to that associated with standard cyclical fluctuations.

5.2 Monetary policy

Let us now move to monetary policy, and especially to the fundamental question on what its role during the pandemic should be. In response to the COVID-19 crisis, central banks around the world assumed an expansionary policy stance (Cantú et al., 2021). This manifested itself in the form of deep interest rate cuts and subsequent rounds of quantitative easing. An important goal of these interventions was to avoid a collapse of the economic and financial system, and alleviate pressure on the governments that were implementing huge rescue plans aimed at preventing a wave of bankruptcies and an increase in economic inequality. Our framework is too simple to appropriately address all of these multiple motives. It does however allow us to capture the role of central banks as powerful institutions responsible for aggregate demand management.

What we want to highlight is that the character of the COVID-19 recession is different from standard. Falling inflation and output usually call for a monetary policy easing. However, the pandemic recession is a mixture of endogenous reactions and administrative policy measures intended to limit social and economic interactions, and hence the spread of the pandemic. From this perspective, an accommodative monetary policy stance could be counterproductive, because it could accelerate the epidemic and bring about more fatalities. In particular, our goal is to evaluate the relative role of two key externalities shaping the pandemic scenario. The first one is a standard New Keynesian aggregate demand externality associated with nominal rigidities, suggesting monetary accommodation in response to a contraction in economic activity. The second externality reflects agents' failure to internalize the effects of their actions on the spread of the disease. Which of these two is stronger will then be reflected in whether monetary policy should take a contractionary or expansionary stance during the pandemic.

Our policy simulations attempt to shed light on these issues. To this end we impose on each of the scenarios described before two types of monetary policy. First, we show what would happen if the monetary authorities reacted to the deviation of output not from its flexible price level (as we have assumed so far) but from the steady state. This alternative formulation, that we will refer to as standard monetary policy, is actually more common in central bank practice as the natural (flexible-price) level output is unobservable. Second, we design monetary policy optimized for the pandemic world. To this end, we return to our baseline assumption that monetary policy reacts to the output gap and search for the monetary policy rule parameter Φ_I that maximizes the social welfare function (10). While such an approach does not produce a globally optimal policy in our model, we believe that relating the interest rate to the number of infected agents allows to realistically capture the idea of reacting to the pandemic while keeping the rule operational.

Figures 2 to 6 and Table 2 document our findings. Let us start with the standard monetary reaction function (red dashed line). As this rule does not take into account the strongly negative effect of the pandemic on the natural level of output, the implied monetary policy stance is clearly more expansionary than under our baseline specification relying on the flexible price-based output gap, which under all scenarios considered is much closer to the steady state than GDP. The difference is weakest in the variant of isolation (Figure 5), as in this case the recession is relatively shallow, and strongest (at least in the first year of the pandemic) for the baseline scenario (Figure 4). The problem with applying this standard monetary reaction in the times of pandemic becomes quite evident if we consider its implications for fatalities. In a sense, monetary policy partly crowds out the effort of other authorities to limit the pandemic. Due to monetary stimulus, output declines less (as a matter of fact, it even increases initially), but the number of fatalities goes up. These observations are complemented by the findings reported in Table 2, which additionally presents the welfare effects. Not only in the baseline, but also in the remaining containment policy scenarios, using the standard monetary policy reaction is detrimental for welfare. To keep things in proportion, it needs to be stated clearly that, in relative terms, these effects are not large, but the direction is unequivocal.

These findings raise the question whether monetary policy can be useful at all in such exceptional circumstances as the pandemic? To provide an answer, we run our second experiment and look for an optimized reaction of interest rates to the number of visibly infected agents. The first column of the optimized policy panel in Table 2 collects the optimized reaction parameters. Clearly, they all differ from zero, which means that policy has some role to play. However, the optimized central bank behavior depends strongly on the underlying containment policy. When containment is absent or weak (isolation), the optimized Φ_I is positive, meaning that monetary policy reaction to the pandemic should in fact be contractionary. Stepping out of its usual shoes, the central bank attempts to support the fight against the pandemic and its fatal consequences. The effects can be observed in Figures 2 and 5 (black dotted line). In both cases the real interest rate is raised sharply, generating a deeper recession. The resulting decrease in economic activity limits the spread of the disease and helps lower the number of fatalities.

Things become different when a sufficiently strong containment policy is in place. Under the remaining scenarios the optimized monetary policy turns out to be more expansionary (although to a relatively small degree) than in normal times – the coefficient on the number of infected in the monetary policy rule is negative. This is documented in Figures 3, 4 and 6, which show a deeper decline in the real interest rates under optimized policy, with positive effects for output and inflation. This means that, when public authorities care sufficiently for containing the epidemic, monetary policy can focus on its standard goal, which is to reduce the externality that arises due to prices stickiness. Given that this externality implies that recessions and deflation are costly, the optimized monetary policy takes an expansionary stance. Nevertheless, it should be noted that, compared with the size of the recession, the impact of monetary policy on smoothing the cyclical fluctuations is relatively small.

All in all, how monetary policy should behave during the pandemic is far from trivial due to a trade-off between stabilizing the economy and containing the epidemic, which in turn depends on the containment policies in place. In what follows we take a closer look at this trade-off.

5.3 The trade-offs

Policymakers always face multiple objective dilemmas, and they should be used to resolving them. However, at least for monetary policy, the trade-off discussed here differs dramatically from the usual one. As we already stressed, if monetary policy attempts to stabilize the economy during the pandemic, it exerts an impact on the number of social interactions, the number of infections and, unfortunately, of fatalities. Monetary policy during the COVID-19 pandemic probably faces the nastiest trade-off ever. We now study how this trade-off looks like and how it compares to that faced by containment policies.

Figure 7 shows the efficient policy frontiers for monetary and lockdown policies. On the horizontal axis we show the cumulative consumption loss during the first 2 years of the epidemic, on the vertical axis we present the percentage of deceased agents. The solid, blue line plots the frontier for lockdown policies, defined as the efficient combinations of coefficients Φ_c and Φ_n in equations (30) and (31), assuming that monetary policy follows the baseline Taylor rule (33) with $\Phi_I = 0$. The yellow dash-dotted and the red dashed lines plot the efficient trade-offs for monetary policy (various levels of Φ_I) under the laissez-faire and baseline lockdown scenarios, respectively.

The first thing to note is that in all cases a trade-off exists – saving lives occurs at an economic cost of foregone consumption. However, there is a striking difference between the effectiveness of lockdowns and of monetary policy. The former has a much steeper profile, meaning that lives can be saved at a lower economic cost. The reason is relatively simple – lockdowns are assumed to reduce the transmission via all three contagion channels, including reduction of social-contacts (school closures, family-meeting restrictions etc.), whereas monetary policy works only by affecting transmission via consumption and work. As a consequence lockdowns are much more efficient in containing the disease.

Nevertheless, as mentioned before, even for monetary policy a trade-off exists: a monetary expansion (contraction) raises (reduces) the number of fatalities. This is more the case when no containment measures are in place: the red dashed line is slightly steeper than the yellow dash-dotted one. It is the consequence of the higher probability of dying because of limited health care capacity in the laissez-faire scenario.

What are the implications of the relatively flat monetary policy trade-off? Monetary policy is not a good tool to help contain the epidemic, as a meaningful reduction in fatalities would require engineering a very deep recession. However, every coin has two sides, and this is also the case here. The relatively flat trade-off, especially when other containment policies are in place, means that a monetary expansion is not very harmful. From this perspective central banks have some freedom to support economic growth at a relatively small cost. This explains why, under some scenarios, optimized monetary policy is expansionary.

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What do all these experiments tell us about monetary policy in the times of pandemic? Abstracting away from fiscal or financial stability considerations, the optimal monetary policy stance depends on whether sufficient containment measures have been introduced. If this is the case, then monetary policy is free to act in its usual role of stabilizing the business cycle, providing monetary stimulus to an economy that suffers a deep recession. Otherwise, the monetary policy stance should be even contractionary as the live-saving motive dominates. Clearly, the latter situation is a third-best option since, as we have shown, central bank instruments are better suited at steering the economy than at decreasing the number of fatalities. This means that saving lives can be brought about only at a huge economic cost.

All of this brings us to a conclusion related to the motives that we abstracted away so far. Since the health cost of a monetary expansion is relatively small, central banks are probably well suited to offer the necessary support to the fiscal authority that introduces packages helping survive those businesses that are particularly affected by the introduced lockdowns. Formalizing this conclusion would, however, require a different modeling strategy, and we leave this issue for further research.

6 Conclusions

After the outbreak of the COVID-19 pandemic monetary policy has been eased in many countries to an unprecedented degree. At the same time several economists have pointed out that in the pandemic central banks face a new trade-off, one between stabilizing the economy and containing the epidemic. While the latter is obviously not the standard goal of central banks, they must be aware that under these very special circumstances monetary policy actions have an impact on the epidemic and its (possibly fatal) consequences. Our paper investigates this trade-off and its consequences for monetary policy. To this end we construct a model that draws from the epidemic modeling literature and the macroeconomic business cycle literature. More precisely, we connect a SIR-type model with a standard new

Keynesian framework. This allows to speak not only about the pandemic (and potential containment measures), but also about macroeconomic effects and monetary policy.

Our simulations explain the moderate reactions of inflation to the epidemic visible in the data during the first year since the outbreak of COVID-19. This happens because reactions of aggregate (consumption) demand are similar to reactions of aggregate (labor) supply. Hence, as in the data, in spite of the unprecedented recession, inflation changes only slightly. Moreover, the direction of inflation reaction depends i.a. on the containment measures applied. In our framework containment measures are relatively efficient in containing the epidemic. In particular, lockdowns can largely reduce the spread of the disease and the number of fatalities, and substantially lower the welfare cost of the epidemic. Their impact on inflation is relatively small and depends on the particular measures introduced.

The pandemic creates new challenges to stabilization policy. Some of them required a massive and unconventional response from central banks to prevent financial turmoil and create favorable market conditions for fiscal packages aimed at protecting the most affected industries and households. Our model abstracts from these considerations, implicitly assuming well functioning financial markets and appropriate safety nets in place that can be provided by the state without creating significant market distortions. In consequence, the only relevant source of economic heterogeneity among households in our model is their health history.

Under these conditions, the implications for monetary policy during the pandemic are that it should not react to a sharp deviation of output from trend as it typically does when faced with standard business cycles. Such policy reduces welfare irrespective of the underlying containment measures. The trade-off faced by the central bank is relatively flat: a decrease in the number of fatalities that can be achieved with monetary policy happens at a relatively large economic cost. This means that, not surprisingly, monetary policy is not a good tool to contain the epidemic, especially when compared to lockdowns. The flip side of this coin is that the side effects of expansionary monetary policy in form of changes in fatalities are relatively small, so that monetary policy may have some freedom to support the economy (or the fiscal side). Nevertheless, such side effects do exist and they are higher if containment measures are absent. As a consequence, monetary policy should be contractionary if appropriate containment measures are not in place. If sufficiently tough measures have been introduced, monetary policy should be eased in order to support the economy.

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Tables and figures

Table 1: Baseline parameters values

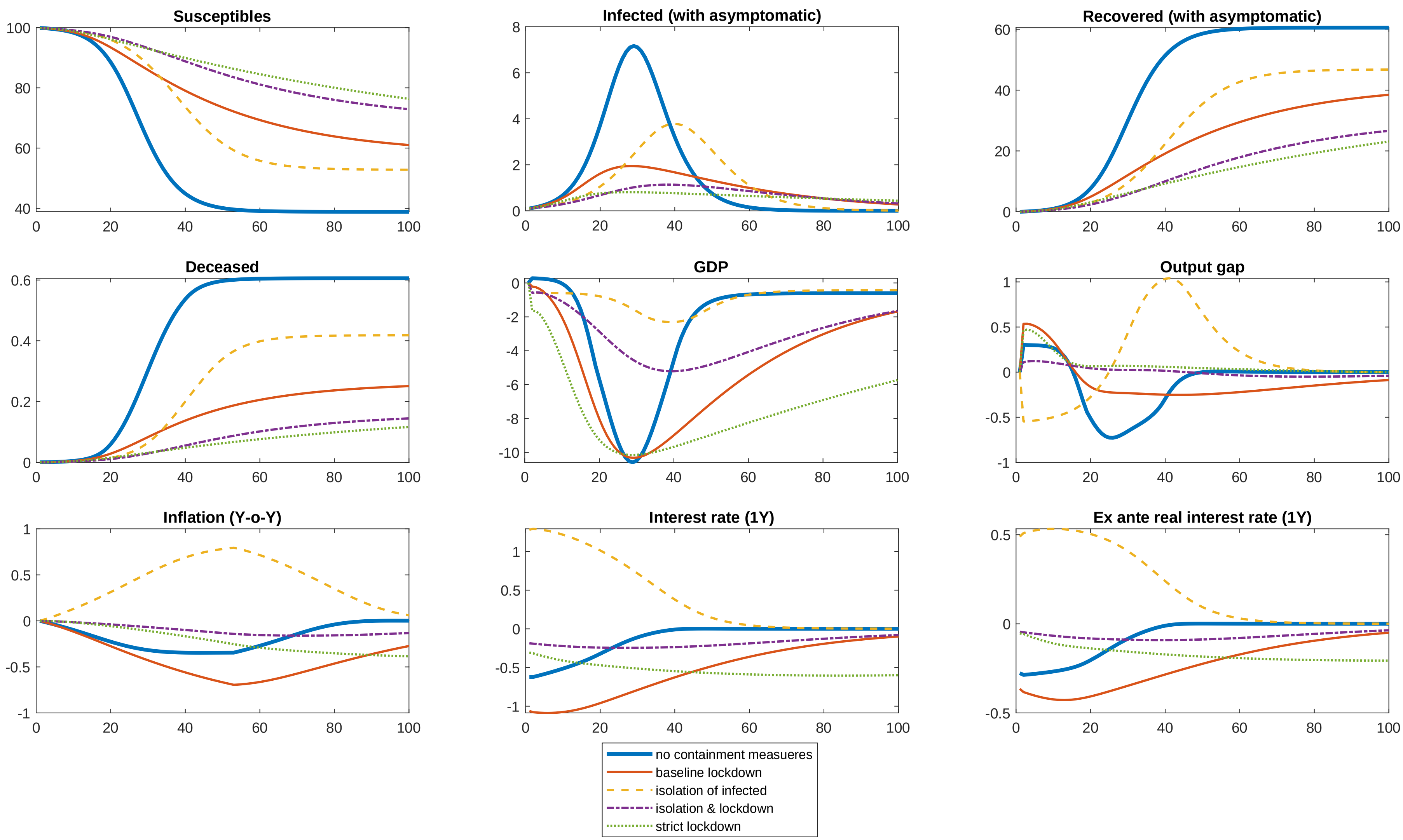
Parameter	Value	Description
		A. Epidemics block
ϖ_c	0.212	Parameter governing infection through consumption activity
ϖ_n	1.185	Parameter governing infection through labor activity
ϖ	0.570	Parameter governing infection through other activity
ϖ_R	0.389	Probability of becoming removed (either death or recovery)
ϖ_D	$\frac{7}{18} \cdot 0.006$	Basic probability of dying
ρ	0.6	Probability of being symptomatic conditional on infection
κ	0.5	Infectiousness of asymptomatic relative to symptomatic
ζ	1	Non-isolation of infected
ξ	0.8	Relative productivity of infected households
U_d	-3863	Disutility of death
ν_0	0.01	Parameter governing capacity constraint on health-care system
ν_1	3	Parameter governing capacity constraint on health-care system
		B. Households
β	$0.99^{1/13}$	Discount factor
θ	1.447	Weight on labor in utility
		C. Firms
Z	2	Productivity
ε	6	Elasticity of substitution between product varieties
δ	$0.75^{1/13}$	Calvo probability
		D. Policy
Φ_π	1.5	Interest rate reaction to inflation
Φ_y	0.5/52	Interest rate reaction to output gap
Φ_I	0	Interest rate reaction to infected
Φ_c	7.65	Consumption channel lockdown
Φ_n	3.8	Work channel lockdown
Φ_ω	3.8	Elasticity of other activities channel to lockdown

Table 2: Cost of the epidemic

	Baseline monetary policy		Optimized monetary policy			Standard monetary policy	
Scenario	Welfare cost	Deaths	Φ_I	Welfare cost	Deaths	Welfare cost	Deaths
No measures introduced	1.240%	0.606%	0.0625	1.230%	0.594%	1.247%	0.610%
Isolation of infected	0.845%	0.418%	0.0629	0.834%	0.409%	0.850%	0.420%
Lockdown (baseline)	0.555%	0.263%	-0.0096	0.554%	0.264%	0.564%	0.268%
Strict lockdown	0.383%	0.169%	-0.0272	0.382%	0.169%	0.456%	0.171%
Lockdown & isolation	0.333%	0.162%	-0.0093	0.333%	0.162%	0.339%	0.163%

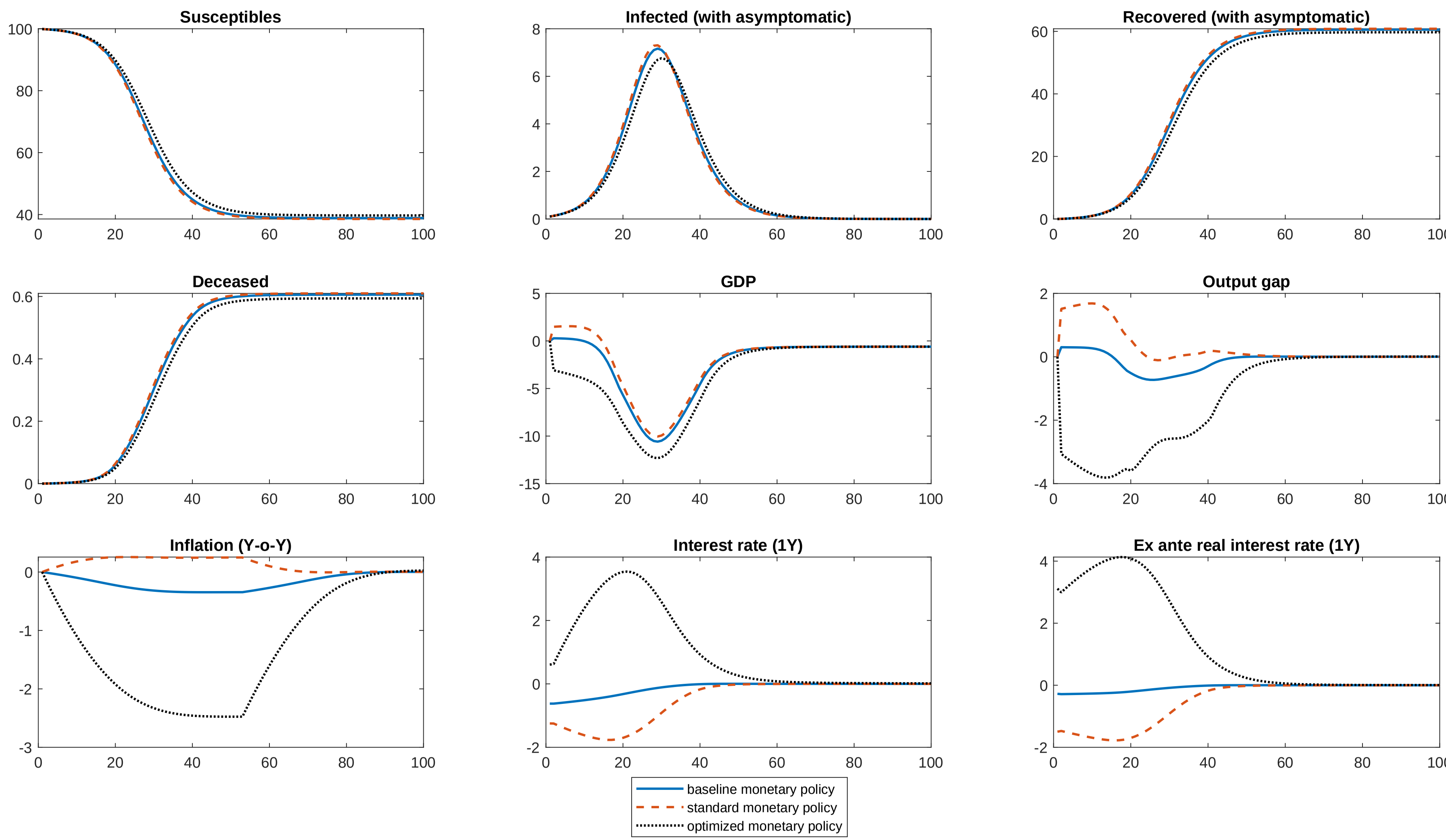
Note: The welfare cost of the epidemic is expressed in per cent of lifetime consumption. Baseline monetary policy refers to the calibration presented in Table 1. Optimized monetary policy responds additionally to the number of symptomatic infected agents. Standard monetary policy responds to inflation (like baseline case) but to output deviations from trend rather than from its level under flexible prices.

Figure 1: Epidemic containment policies



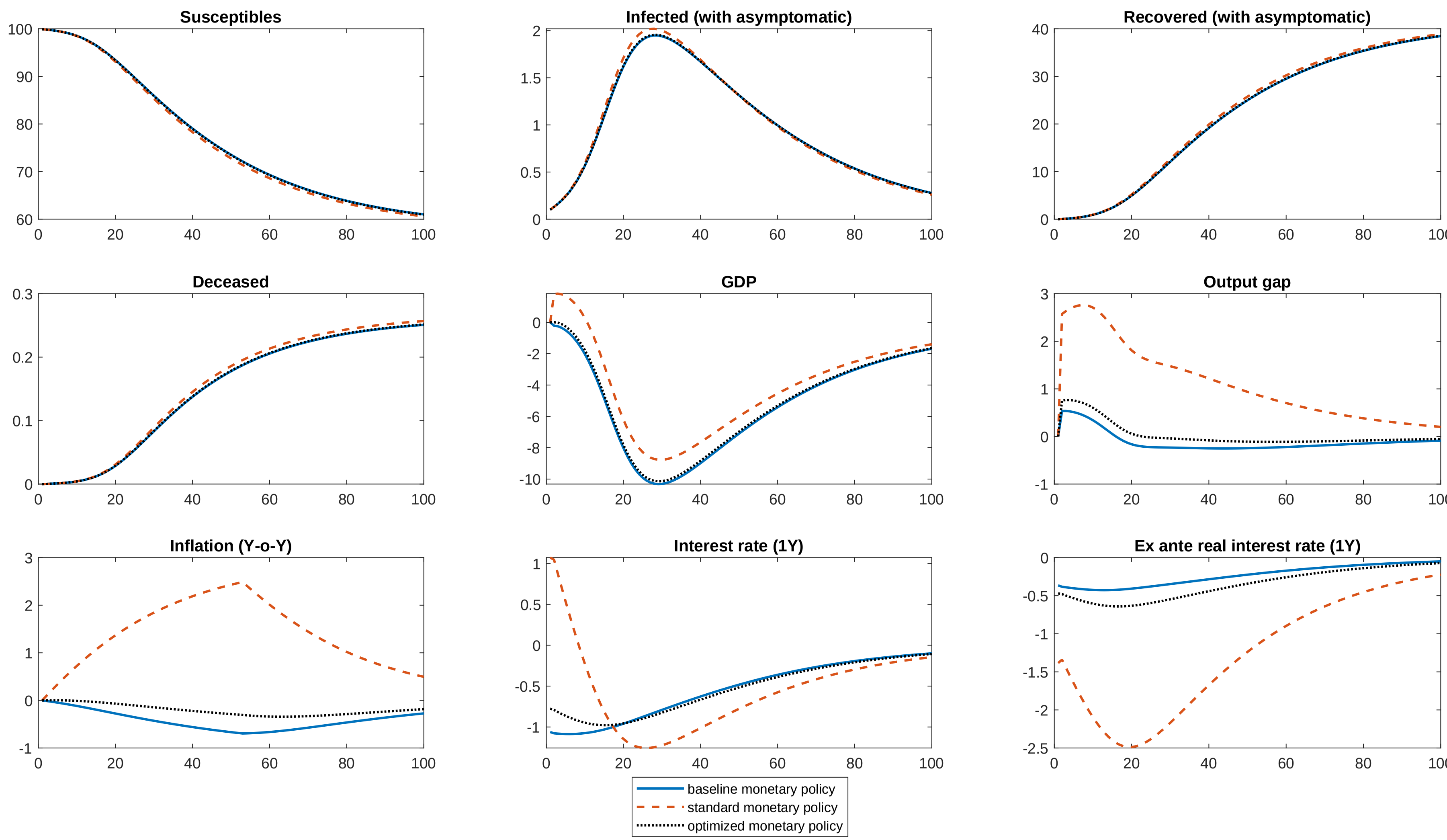
Note: Horizontal axis in weeks, vertical in percent.

Figure 2: Baseline, standard and optimized monetary policy - no containment measures introduced



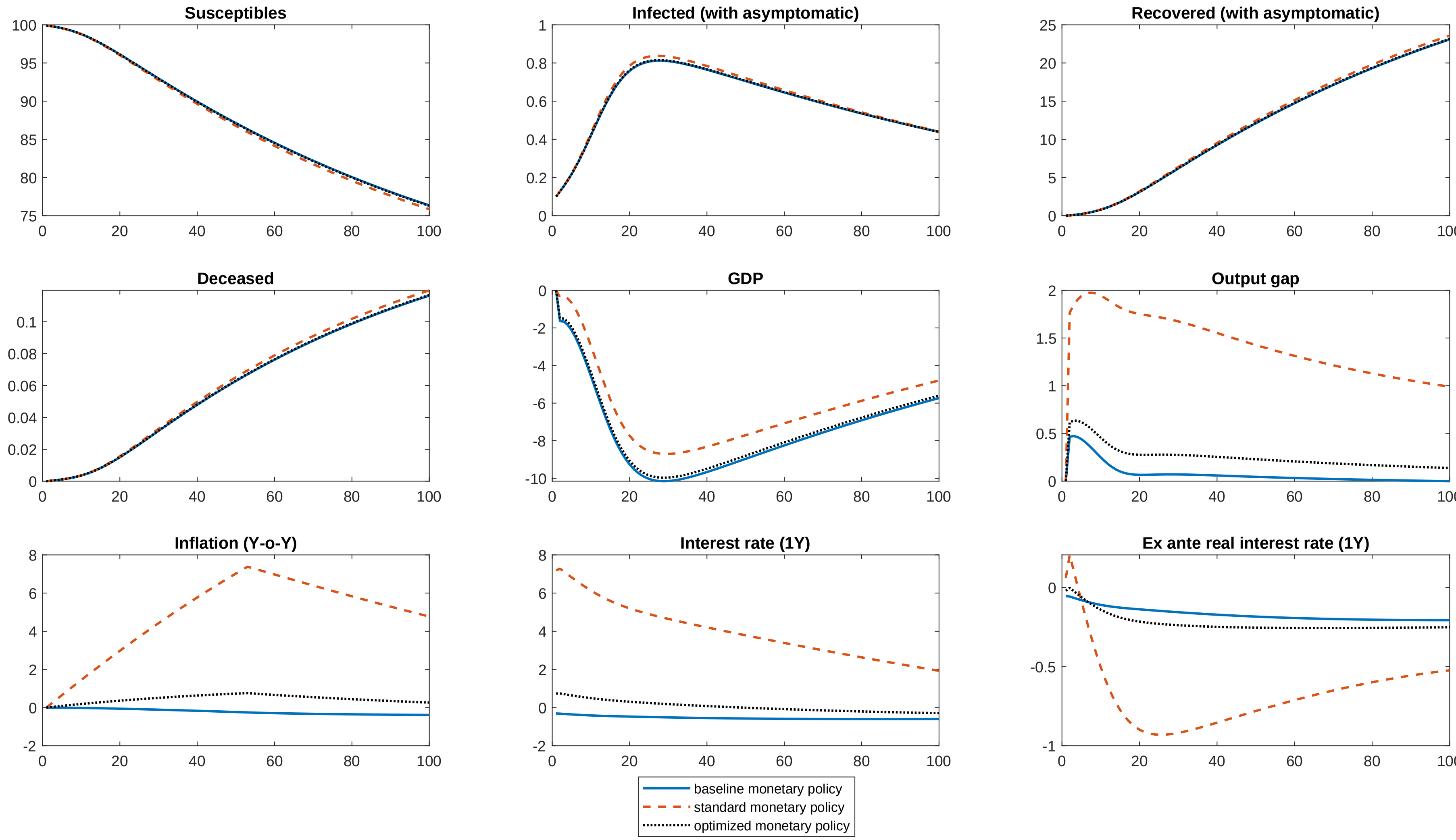
Note: Horizontal axis in weeks, vertical in percent.

Figure 3: Baseline, standard and optimized monetary policy under baseline lockdown



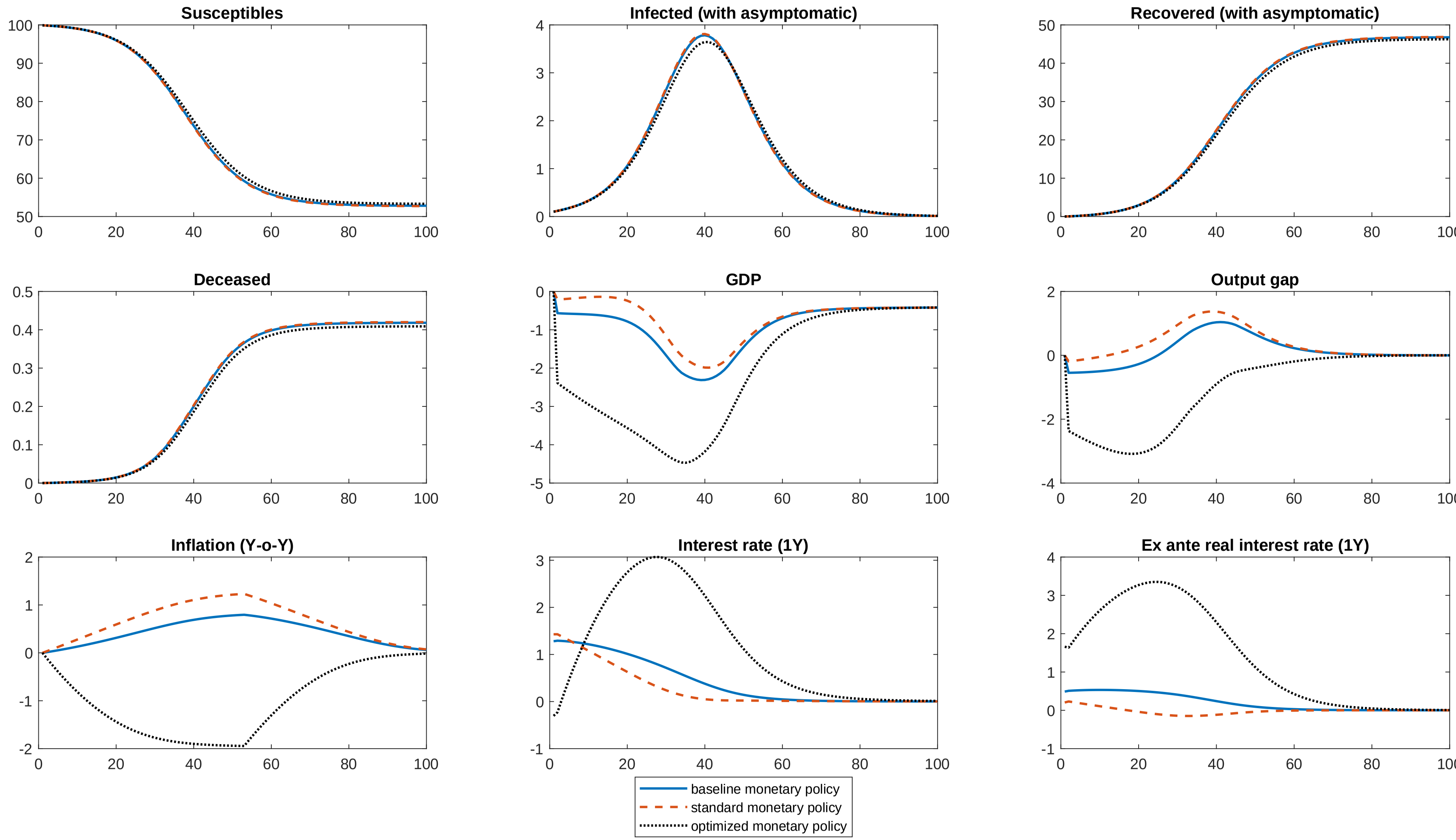
Note: Horizontal axis in weeks, vertical in percent.

Figure 4: Baseline, standard and optimized monetary policy with strict lockdown.



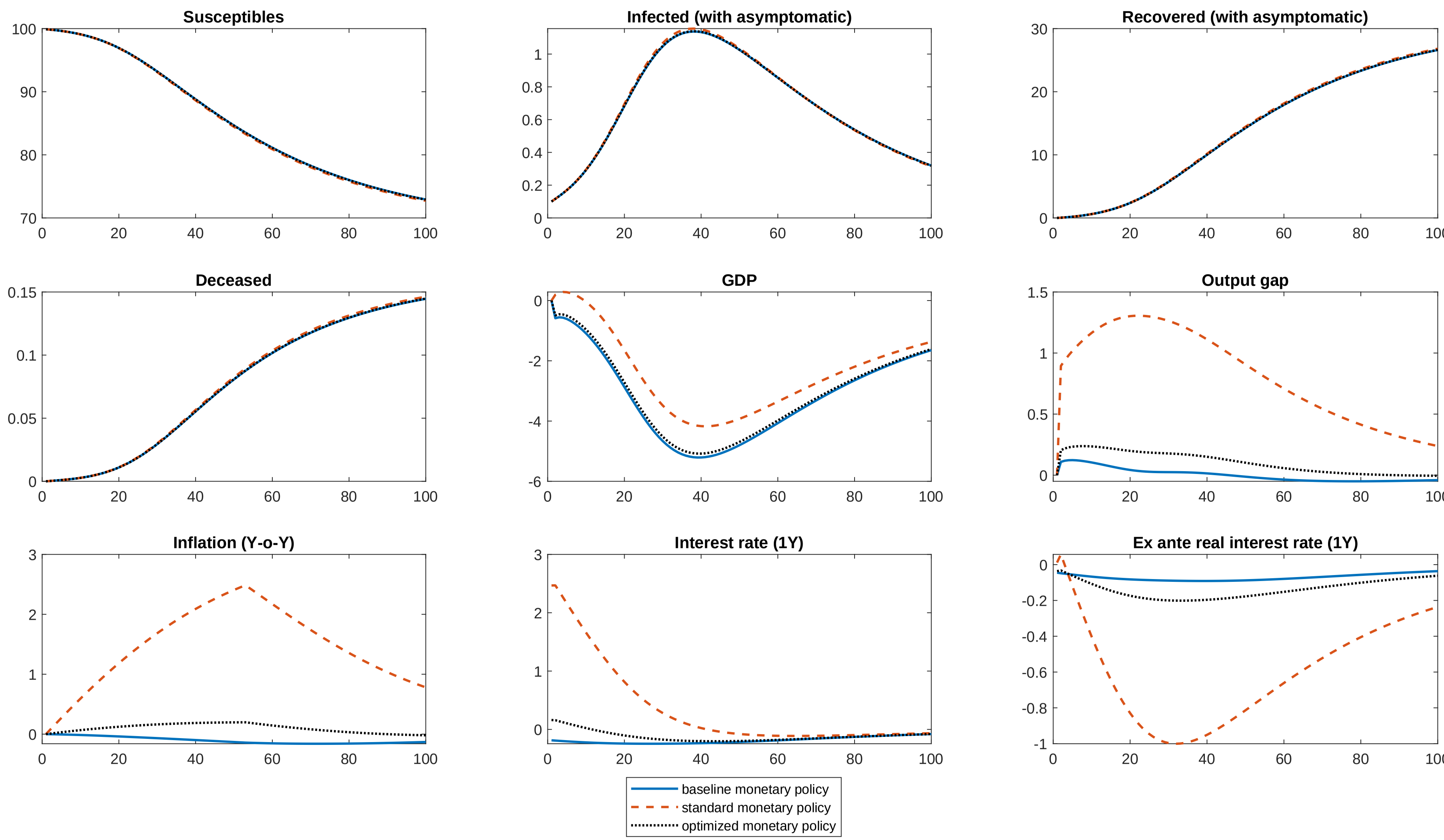
Note: Horizontal axis in weeks, vertical in percent.

Figure 5: Baseline, standard and optimized monetary policy with isolation



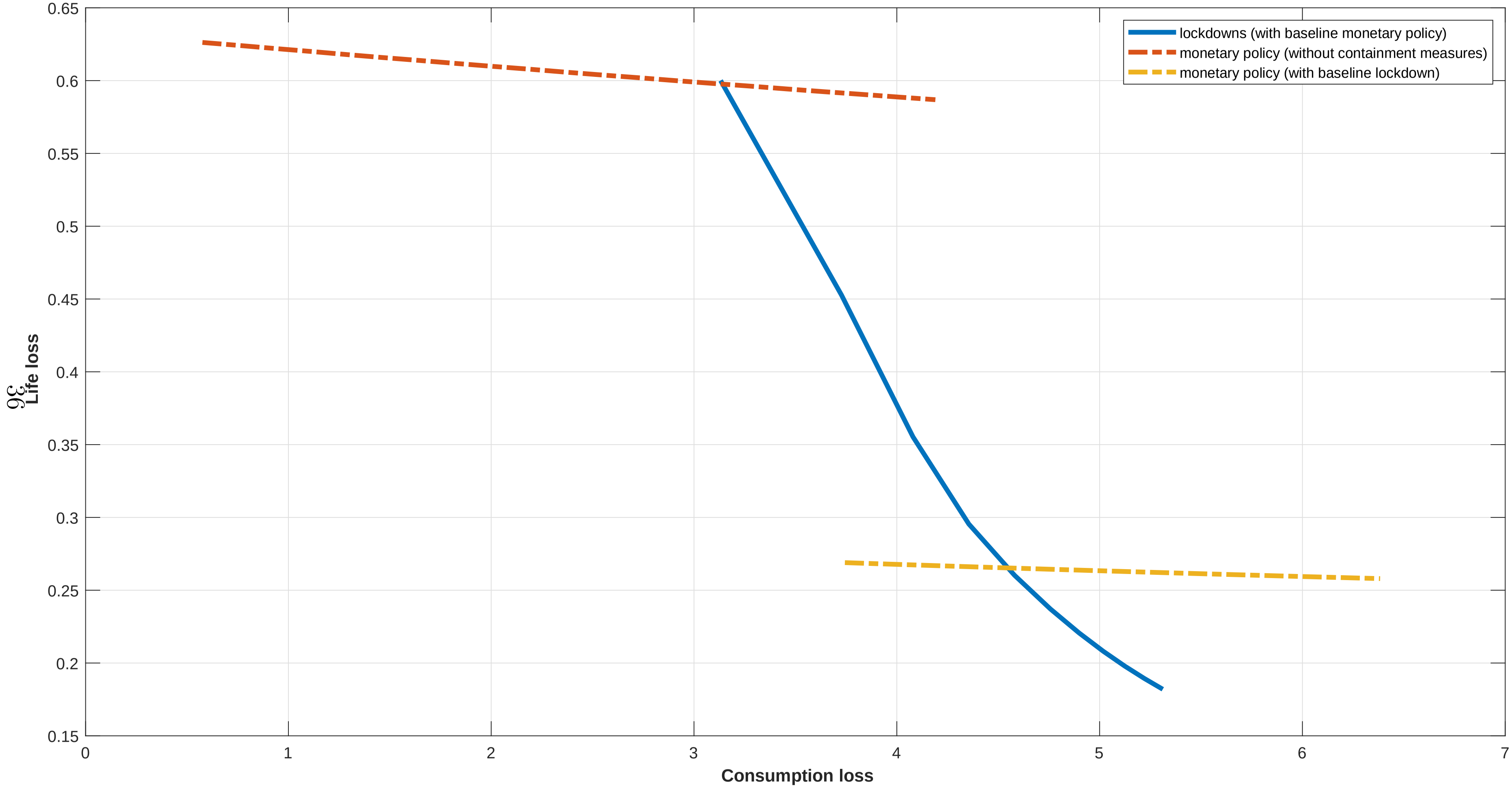
Note: Horizontal axis in weeks, vertical in percent.

Figure 6: Baseline, standard and optimized monetary policy with isolation & lockdown



Note: Horizontal axis in weeks, vertical in percent.

Figure 7: Policy frontiers: lockdown and monetary policy



Note: Both axes scaled in percent. Consumption loss is calculated as average percent deviation from steady state over the first two years of the epidemic. Life loss refers to the final death rate.

Appendix

In this Appendix we present a full list of equations making up the model. Variables with bars denote steady state values.

Epidemic block

Evolution of susceptible individuals

$$S_{t+1} = (1 - \varpi_{I,t})S_t \tag{A.1}$$

Evolution of symptomatic infected

$$I_{t+1} = (1 - \varpi_{R,t})I_t + \rho\varpi_{I,t}S_t \tag{A.2}$$

Evolution of asymptomatic infected

$$A_{t+1} = (1 - \varpi_{R,t})A_t + (1 - \rho)\varpi_{I,t}S_t \tag{A.3}$$

Evolution of formerly asymptomatic infected

$$V_{t+1} = V_t + \varpi_{R,t}A_t \tag{A.4}$$

Evolution of recovered individuals

$$R_{t+1} = R_t + (\varpi_{R,t} - \varpi_{D,t})I_t \tag{A.5}$$

Evolution of deceased individuals

$$D_{t+1} = D_t + \varpi_{D,t}I_t \tag{A.6}$$

Supposedly susceptible individuals

$$\tilde{S}_t = S_t + A_t + V_t \tag{A.7}$$

Infection and death probabilities

Probability of susceptible individuals becoming infected

$$\varpi_{I,t} = \varpi_c\tilde{c}_t(\zeta I_t c_t^I + \kappa A_t\tilde{c}_t) + \varpi_n\tilde{n}_t\kappa A_t\tilde{n}_t + \varpi_t(I_t + \kappa A_t) \tag{A.8}$$

Probability of supposedly susceptible agent becoming symptomatic infected

$$\tilde{\varpi}_{I,t} = \rho \varpi_{I,t} \frac{S_t}{\tilde{S}_t} \tag{A.9}$$

Death probability

$$\varpi_{D,t} = \min \left[\left(1 + \frac{I_t}{\nu_0} \right) \varpi_D, \nu_1 \varpi_D \right] \tag{A.10}$$

Supposedly susceptible individuals

Utility

$$\tilde{U}_t = \log \tilde{c}_t + \theta \log(1 - \tilde{n}_t) + \beta(1 - \tilde{\varpi}_{I,t})\tilde{U}_{t+1} + \beta \tilde{\varpi}_{I,t} U^I_{t+1} \tag{A.11}$$

Budget constraint

$$(1 + \tau_{c,t})\tilde{c}_t + \tilde{b}_{t+1} = (1 - \tau_{n,t}) w_t \tilde{n}_t + \frac{\mathcal{I}_{t-1}}{\pi_t} \tilde{b}_t (1 - \tilde{\varpi}_{I,t-1}) + \Gamma_t \tag{A.12}$$

Optimality conditions

$$\frac{1}{\tilde{c}_t} = \tilde{\lambda}_{S,t}(1 + \tau_{c,t}) - \tilde{\lambda}_{\varpi,t} \rho \frac{S_t}{\tilde{S}_t} \varpi_c (\zeta I_t c^I_t + \kappa A_t \tilde{c}_t) \tag{A.13}$$

$$\frac{\theta}{1 - \tilde{n}_t} = \tilde{\lambda}_{S,t}(1 - \tau_{n,t}) w_t + \tilde{\lambda}_{\varpi,t} \rho \frac{S_t}{\tilde{S}_t} \varpi_n \kappa A_t \tilde{n}_t \tag{A.14}$$

$$\tilde{\lambda}_{\varpi,t} = \beta [U_{I,t+1} - \tilde{U}_{t+1}] \tag{A.15}$$

$$\tilde{\lambda}_{S,t} = \beta [(1 - \tilde{\varpi}_{I,t}) \tilde{\lambda}_{S,t+1} + \tilde{\varpi}_{I,t} \lambda_{I,t+1}] \frac{\mathcal{I}_t}{\pi_{t+1}} \tag{A.16}$$

Symptomatic infected individuals

Utility

$$U^I_t = \log c^I_t + \theta \log(1 - n^I_t) + \beta(1 - \varpi_R) U^I_{t+1} + \beta(\varpi_R - \varpi_{D,t}) U^R_{t+1} + \beta \varpi_{D,t} U^D \tag{A.17}$$

Budget constraint

$$(1+\tau_{c,t})c_t^I + b_{t+1}^I = w_t \xi n_t^I + \Gamma_t + \frac{\mathcal{I}_{t-1}}{\pi_t}\left[\frac{(1-\varpi_R+\varpi_{D,t-1})I_{t-1}}{I_t}b_t^I + \frac{\rho\varpi_{I,t-1}S_{t-1}}{I_t}\tilde{b}_t\right] \quad (A.18)$$

Optimality conditions

$$\frac{1}{c_t^I} = \lambda_{I,t}(1+\tau_{c,t}) \quad (A.19)$$

$$\frac{\theta}{1-n_t^I} = (1-\tau_{n,t})\xi w_t \lambda_{I,t} \quad (A.20)$$

$$\lambda_{I,t} = \beta[(1-\varpi_R-\varpi_{D,t})\lambda_{I,t+1} + \varpi_R\lambda_{R,t+1}]\frac{\mathcal{I}_t}{\pi_{t+1}(1-\varpi_{D,t})} \quad (A.21)$$

Symptomatic recovered individuals

Utility

$$U_t^R = \log c_t^R + \theta\log(1-n_t^R) + \beta U_{t+1}^R \quad (A.22)$$

Budget constraint

$$(1+\tau_{c,t})c_t^R + b_{t+1}^R = (1-\tau_{n,t})w_t n_t^R + \frac{\mathcal{I}_{t-1}}{\pi_t}\left[\frac{R_{t-1}}{R_t}b_t^R + (\varpi_R-\varpi_{D,t-1})\frac{I_{t-1}}{R_t}b_t^I\right] + \Gamma_t \quad (A.23)$$

Optimality conditions

$$\frac{1}{c_t^R} = \lambda_{R,t}(1+\tau_{c,t}) \quad (A.24)$$

$$\frac{\theta}{1-n_t^R} = (1-\tau_{n,t})w_t\lambda_{R,t} \quad (A.25)$$

$$\lambda_{R,t} = \beta\lambda_{R,t+1}\frac{\mathcal{I}_t}{\pi_{t+1}} \quad (A.26)$$

Firms

Optimal price set by reoptimizing firms

$$\tilde{p}_t = \frac{\Omega_t}{\Upsilon_t} \quad (A.27)$$

Auxiliary functions for optimal price setting

$$\Omega_t = (1-\delta\beta)\frac{w_t}{Z}\frac{y_t}{\tilde{S}_t + I_t + R_t}\left(\frac{\tilde{S}_t}{\tilde{c}_t} + \frac{I_t}{c_t^I} + \frac{R_t}{c_t^R}\right) + \delta\beta\pi_{t+1}^{\varepsilon}\Omega_{t+1} \tag{A.28}$$

$$\Upsilon_t = (1-\delta\beta)\frac{y_t}{\tilde{S}_t + I_t + R_t}\left(\frac{\tilde{S}_t}{\tilde{c}_t} + \frac{I_t}{c_t^I} + \frac{R_t}{c_t^R}\right) + \delta\beta\pi_{t+1}^{\varepsilon-1}\Upsilon_{t+1} \tag{A.29}$$

Price index

$$1 = \delta\left(\pi_t\right)^{\varepsilon-1} + (1-\delta)\tilde{p}_t^{1-\varepsilon} \tag{A.30}$$

Price dispersion

$$\Delta_t = \delta\pi_t^{\varepsilon}\Delta_{t-1} + (1-\delta)\,\tilde{p}_t^{-\varepsilon} \tag{A.31}$$

Government and central bank

Containment policies

$$\tau_{c,t} = \Phi_c I_t \tag{A.32}$$

$$\tau_{n,t} = \Phi_n I_t \tag{A.33}$$

$$\omega_t = \omega(1-\tau_{c,t})^{\Phi_\omega} \tag{A.34}$$

Monetary policy rule

$$\frac{\mathcal{I}_t}{\bar{\mathcal{I}}} = \left(\frac{\pi_t}{\bar{\pi}}\right)^{\Phi_\pi}\left(\frac{y_t}{y_t^f}\right)^{\Phi_y}\exp(I_t)^{\Phi_I} \tag{A.35}$$

Market clearing

Final goods market

$$\tilde{S}_t\tilde{c}_t + I_t c_t^I + R_t c_t^R = (\tilde{S}_t + I_t + R_t)y_t \tag{A.36}$$

Labor market

$$\tilde{S}_t\tilde{n}_t + I_t\xi n_t^I + R_t n_t^R = (\tilde{S}_t + I_t + R_t)n_t \tag{A.37}$$

Aggregate output

$$\Delta_t y_t = Z n_t \tag{A.38}$$

Bond market

$$\tilde{S}_t \tilde{b}_t + I_t b_t^I + R_t b_t^R = 0 \tag{A.39}$$

Flexible price block

The flexible price block consists of the same set of equations as above, except that $\delta = 0$. The equilibrium evolution of per capita output in this hypothetical economy, denoted by y_t^f, enters the monetary policy rule A.35.