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Endogenous Cycles, COVID-19 Pandemic, Bounded Rationality, Heterogenous Expectations

JEL Classification

E3, E7, I1

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Belief-Driven Dynamics in a Behavioral SEIRD Macroeconomic Model with Sceptics

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Abstract

The reluctance of a significant number of individuals in the current COVID-19 pandemic to adhere to social distancing measures – and even to get vaccinated – seems to be one of the major obstacles for the long-term success of public health policies around the world. Against this background we study the impact of boundedly rational perceptions for the dynamics of epidemics such as the COVID-19 pandemic in a standard epidemic model extended by a stylized macroeconomic dimension similar to Atkeson et al. (2021). We show through which channels misperceptions or even "scepticism" concerning the infectiousness of the decease or its mortality rate may undermine in the long-run the effectiveness of lockdowns and other public health policies.

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*Corresponding author. E-mail: christian.proano@uni-bamberg.de. We would like to thank Augusto de la Torre, Blake LeBaron, Tiziana Assenza, Herbert Dawid, Giorgos Galanis and other participants at the CEF 2021 conference for helpful comments and suggestions on previous drafts of this paper. The usual disclaimers apply.

1 Introduction

While the epidemiological dynamics of diseases such as COVID-19 have been modelled extensively e.g. in the literature on compartmental epidemiological models based on the seminal work by Kermack and McKendrick (1927), the role of behavioral factors based on economic conditions in the evolution of such epidemics was much less investigated until recently, where works by Atkeson et al. (2021) and Eichenbaum et al. (2020) and others led to a outright explosion of studies in the new field of "Pandenomics" (Cliffe, 2020).

A current and quite relevant example of this phenomenon is the existence of a non-irrelevant fraction of "sceptics" among the population who either doubt the mere existence of the COVID-19 virus (or explain their existence through conspiracy theories), or are reliant of adhering to the social distance measures ordained by governments around the world. This sceptics, known e.g. in Germany as "Querdenkern", have not only obtained a certain amount of prominency in the political discourse, but may even compromise the long-run effectiveness of the vaccination campaigns by hindering the accomplishment of "herd immunity" through vaccination.

Given the numerous and continuously increasing amount of studies that has emerged since the COVID outbreak by the end of 2019 a throughout survey is an also impossible task to undertake. Nonetheless, there are a few studies worth highlighting. At the behavioral sphere, studies such as Eksin et al. (2019) and Di Guilmi et al. (2020) endogenize the reaction of susceptive individuals on physiological measures, Dasaratha (2020), for instance, extends a standard SIR model with endogenous meeting rates based on game-theoretic considerations.[1]

At the intersection between epidemiology and economics, Eichenbaum et al. (2020) were among the first to investigate the main economic transmission mechanisms of an epidemic such as COVID-19 in a model with forward-looking utility maximizing representative agents with rational expectations. Using the more elaborated heterogenous agents New Keynesian (HANK) approach, Kaplan et al. (2020) investigate the distributional consequences of social distancing measures in terms of income and wealth in a model calibrated for the United States. Using medium-scale agent-based models, Delli Gatti and Reissl (2020) and Dawid and Harting (2021) analyze the joint dynamics of the epidemic and the economy in model with various types of agents' heterogeneity.

Regarding the role of scepticism in the context of the COVID-19 pandemic, Allcott et al. (2020) documents the correlation between political orientation of COVID scepticism and compliance to containment measures with the political orientation. Bursztyn et al. (2020) study the role of misinformation in mass media broadcasts and the adoption of preventative measures by the population, and Charron et al. (2020) study the impact of political polarization, see also Milosh et al. (2020). Mellacher (2020) also investigates the role of sceptics for the transmission of the disease in a theoretical

[1] See Funk et al. (2015) for a discussion of nine challenges in incorporating the dynamics of behavior in epidemiological models.

model similar to ours, but in a purely epidemic model only. To the best our knowledge, our paper is thus the first one to highlight the trade-off between the economic and epidemiological impacts of COVID-19 and its role on the endogenous emergence of "sceptics" in a SEIRD-macroeconomic model. Our study links thus the COVID-scepticism with the epi-macro literature discussed above.

The remainder of this paper is organized as follows: In section 2 we describe the basic epidemiologic SEIRD model and our baseline behavioral extensions. We modify then our model by incorporating sceptics into the model in section 3. We investigate then how the dynamics of the model change when alternative reference measures are used by the government and the public in section 4. Finally, we draw some conclusions from this paper in section 5.

2 A Baseline Reduced-Form Behavioral SEIRD-Macroeconomic Model

For the description of the epidemiological dynamics we use a compartmental model which describes the evolution of a disease such as COVID-19 by dividing the total population into five categories: susceptible (S), exposed (E), infected (I) recovered (R) and deceased (D) similarly as in Kaplan et al. (2020).

In discrete time, the baseline SEIRD model reads

$$\Delta S_{t+1} = -\beta_t S_t I_t / N_t \tag{1}$$
$$\Delta E_{t+1} = \beta_t S_t I_t / N_t - \sigma E_t \tag{2}$$
$$\Delta I_{t+1} = \sigma E_t - (\gamma_R + \gamma_D) I_t \tag{3}$$
$$\Delta R_{t+1} = \gamma_R I_t \tag{4}$$
$$\Delta D_{t+1} = \gamma_D I_t \tag{5}$$
$$N_{t+1} = N_t - D_t, \tag{6}$$

where N denotes the initial population, N_t the current population size, S_t the number of susceptible persons at period t, E_t the number of exposed persons, I_t is the number of infected people at t, R_t is the number of recovered people and D_t the number of deceased persons. Please note that all the level variables are also subject to non-zero constraints. β_t is the number of extended contacts per day or transmission rate and $\gamma = \gamma_D + \gamma_R$ is the average duration of the disease.

While a purely epidemiological approach would consider the transmission rate as constant, a more realistic approach would take into account behavioral as well as policy-induced effects on this variable. In a similar vein as Atkeson et al. (2021) and Flaschel et al. (2021) we thus endogenize β_t as follows

$$\beta_t = \beta_0 - \phi_g G_t - \phi_h H_t. \tag{7}$$

where β_0 is the baseline contact rate and G_t and H_t represent social distancing measures enforced by the government and households respectively. Note thus that an increase in y_t leads to an increase in β_t, and thus by extension to an increase in the infection rate I_t/N.

As discussed by Eichenbaum et al. (2020), the two main channels through which economic activity is related and in fact influences the number of transitions are a) the amount of time spent by people at their working places with other workers and b) the amount of time spent by them in consuming (buying) goods and services.[2] As a disease affects an increasing fraction of the population, both types of activities may become less feasible either because people are too sick to leave homes, or because people decide to stay at home and avoid being infected. Aggregate economic activity (represented here by the output gap y_t) depends thus unambiguously negatively on the infection rate, i.e.

$$y_t = \alpha_y y_{t-1} - \alpha_i I_t/N + \alpha_b(\beta_{t-1} - \beta_0) \tag{8}$$

where α_i represents the impact of I_t/N on y_t due to purely *physiological* factors, α_y the intrinsic persistence of the output gap process and and α_b represents the impact of the meeting or contact rate on economic activity. Social distancing policies affect thus directly the meeting rate β through the imposition of social distancing measures or eventual lockdowns which in turn have a negative impact on economic activity.

When not otherwise stated, the following simulations are based on the parameter values reported in Table 1. For the epidemiological part of the model we use parameter values used in standard studies such as Atkeson (2020), Wang et al. (2020) and Fauci et al. (2020). In particular, following Atkeson (2020) and Wang et al. (2020) we assume an incubation period of 5.2 days and an average duration of the disease of 18 days. Further, we assume for the basic reproduction ratio, defined as

$$\mathcal{R}_0 = \beta_0/\gamma,$$

the value of 2.25 proposed by Fauci et al. (2020).[3]

In numerous countries such as Germany a key measure for the evolution of the COVID-19 epidemic is the so-called incidence rate $\mathcal{I}_{t-1}$, namely the number of new cases σE_t per 100.000 persons.[4] Figure 1 illustrates the baseline dynamics of the model under a constant $\mathcal{R}_0$ and under the assumption that $G_t = \mathcal{I}_{t-1}$.

[2] This is of course an oversimplification which is qualified by the capability of working from home (available of course only to a fraction of the working population), as well as by the use of delivery and take-away services for the purchase of goods and to some extent, services.

[3] While Wang et al. (2020) propose a value of 3.1 for the description of the outbreak in the Chinese city of Wuhan, estimates for Western countries range between 2 and 3 (European Center for Disease Control). With a value of 2.25 we are thus on the lower end of the values proposed so far.

[4] In Germany, the 7-day average incidence rate has been prominently used as a threshold value for the implementation of sharp social distancing public policy measures.

Table 1: Baseline Parameters

σ	incubation period	1/5.2	Atkeson (2020), Wang et al. (2020)
$\gamma = \gamma_R + \gamma_D$	duration of illness	1/18	Atkeson (2020)
$\gamma_D = 0.08$	Death rate	0	Own parametrization
α_y	Autoregressive output gap coefficient	0.95	Own parametrization
α_i	Infection rate impact on output gap	0.005	Own parametrization
β_0	Baseline meeting rate	0.175	Wang et al. (2020)
β_y	Output gap impact on β_t	5	Own parametrization
$R_0 = \beta_0/\gamma$	Baseline transmission rate	2.25	Fauci et al. (2020)

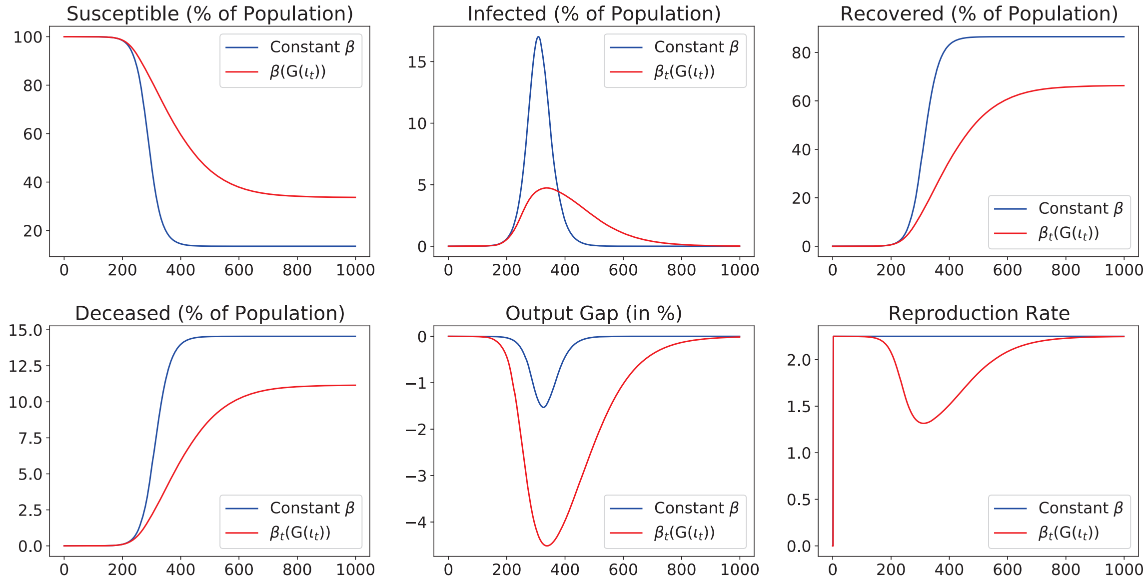

Figure 1: The baseline behavioral SIR model with exogenous (baseline) and endogenous (scenario 1) number of extended contacts per day β_t following an initial infection of 100 persons of the population.

The epidemiologic dynamics are well known by now not only to epidemiologists, but to a broader public including economists. An initial infection of a small fraction of the population leads ceteris paribus, and in particular under an unchanged reproduction rate $\mathcal{R}_0$ (resulting from an unchanged number of daily extended contacts $\beta_t = \beta_0$ and represented by the baseline blue lines in the individual graphs in Figure 1) to a rapid infection of an increasing number of susceptible persons (which we assume are the totality of the population). Without any public policy aimed at the reduction of the transmission rate β_t and thus of the reproduction rate $\mathcal{R}_0$, the epidemic enters in an exponential growth phase which leads to a swift spread of the disease over the population in a short period of time. Given the (still constant) mortality rate assumed so far, the rapid increase in the number of infected leads also to a significant number of deceased persons.

Since the rate of infection (number of infected persons relative to the population) affects negatively the level of economic activity – represented in our model by the output gap variable, see equation 8 – the spread of the disease leads to a negative output gap. Given our parametrization, this impact is relatively small, leading at the peak of the infection to about a 1% decrease in economic activity due to purely physiological reasons, i.e. solely due to the sickness related reduction of productivity in the economy.

When the number of daily extended contacts β_t is endogenized as a function of economic activity according to (13), the reproduction rate

$$\mathcal{R}_t = \beta_t/\gamma. \tag{9}$$

decreases from about 2.25 (Fauci et al. 2020) to about 1.5, as the increase in the infection rate I_t/N affects the output gap negatively through the physiological channels represented by α_i^p.

When a social distancing policy is implemented, the transmission and the basic reproduction rates β_t and $\mathcal{R}_0$, respectively, are reduced. This has opposite effects on the epidemic and economic spheres: On the epidemic sphere, the containment policy leads to a significant reduction in the number of newly infected persons per day and, given the constant mortality rate of the epidemic, also to a lower number of deceased persons in the long run. On the economic sphere, by contrast, the slump in economic activity which in the previous case was only due to the pure physiological effects of the epidemic, is magnified by the containment policies.

3 Incorporating Sceptics

So far, we have assumed that the population does not react by itself to the spread of the disease ($\phi_h = 0$), and that the contact rate β and the reproduction rate R_t^0 vary only due to government-imposed social distancing measures. Further, we have also implicitly assumed that these measures are followed and accepted by the totality of the population, what leads to a successful containment of the disease, as discussed in the previous section.

As discussed in the introduction, a non-trivial phenomenon that may undermine the success of public health policies and even threaten the achievement of herd immunity in the long-run is the emergence of COVID-19 "sceptics" who do not adhere to social-distancing measures.

We incorporate this dimension in our baseline SEIRD model by assuming that a fraction of "sceptics" in the population who do not support the governments containment policies determined by the

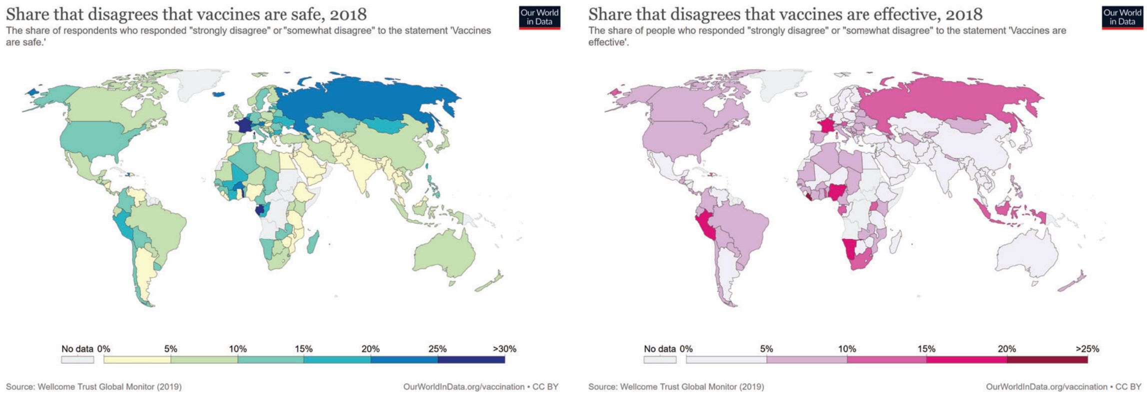

Figure 2: Vaccine scepticism around the world. Source: Welcome Trust Global Monitor 2018 through Our World in Data.

relative valuation of the public health vs the economic situation by the population. More specifically, we assume that the fraction of "sceptics" in the population is given by

$$\omega_t = \frac{\exp(-\mu_y y_{t-1})}{3 + \exp(-\mu_y y_{t-1}) + \exp(\mu_i \mathcal{I}_{t-1})}. \tag{10}$$

with $\partial\omega_t/\partial y_{t-1} < 0$ and $\partial\omega_t/\partial\iota_{t-1} < 0$. Accordingly, the "sceptics" share in the population is given by the relative weighted economic and epidemiologic impact of the epidemic, where the former is represented by the output loss (the negative of the output gap) and the latter by the incidence rate.[5] Note that for $y_{t-1} = 0$ and $\mathcal{I}_{t-1} = 0$, $\omega^o = 1/(3+1+1) = 0.2$, i.e. that 20% of the population does not support the government's containment policies.

Assuming a 20% number of sceptics in the steady state may seem quite exaggerated. However, as Figure 2 illustrates, the share of the population that disagrees that vaccines (in general, not only COVID-19 vaccines) are safe or are effective goes in some countries like France up to 20-30%.

The presence of sceptics in population affects primarily the effect of the public health measures on the transmission rate. We model this through the following specification:

$$\beta_t = \beta_0 - (1-\omega_t)\phi_g G_t - \omega_t \phi_h y_{t-1}, \quad \beta_t \geq 0, \tag{11}$$

with the share of sceptics given by eq.(10). While the first term $(1-\omega_t)\phi_g G_t$ highlights the fact that containment policies depend on public's support, the second term $-\omega_t\phi_h y_{t-1}$ is based on the notion that contrarian behavior depends directly on economic impact of containment policies.

Figure 3 illustrates the dynamics of the model for $\phi_g = \phi_y = 0.25$ and $\mu_y = 100$, $\mu_i = 1.5$. As

[5] In the next section we investigate alternative specifications where e.g. ω_t depends not on the incidence rate, but on the mortality rate of the disease.

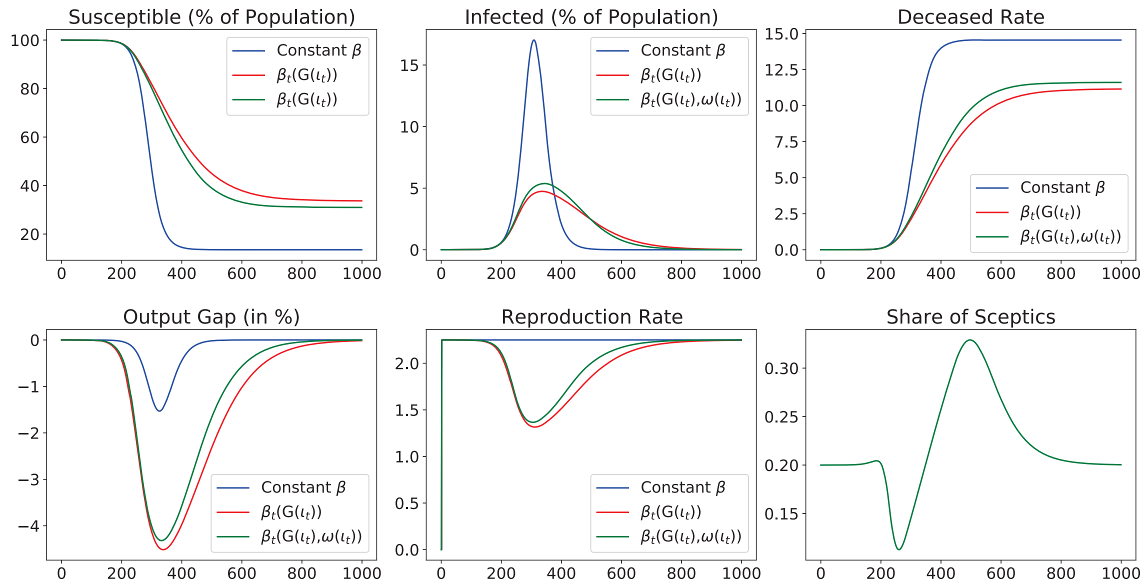

Figure 3: The SEIR model with endogenous transmission rate β_t and a varying fraction of sceptics in the population with $\phi_g = \phi_y = 0.25$ and $\mu_y = 100$, $\mu_i = 2.5$.

it can be observed, for the chosen parameter constellation, the share of sceptics in the population, after a very slight initial increase, decreases from 20% down to nearly 10% in the initial phase of the epidemic where the number of new infections increases significantly and the output gap is decreasing. However, as the latter increases even further and the percent of infected persons in the population decreases, the popular sentiment changes and the share of sceptics increases, leading to a slight increase in the reproduction rate relative to the baseline scenario where no sceptics were present, i.e. where the transmission rate (and by extension the reproduction rate) depended solely on the government's containment policies ($\beta_t(G_t)$).

When public health is relatively less valued by the population ($\mu_i/\mu_y = 0.015$) relative to the previous parametrization ($\mu_i/\mu_y = 0.025$), the share of sceptics increases in relation to the previous case (which we depict here again for better comparison), as is illustrated in Figure 4.

The smaller reduction in the reproduction rate resulting from the compromised effectiveness of the government's containment policies due to the sceptics has non-trivial results for this second parametrization. Regarding the economic sphere, the sceptics non-adherence to the social distancing measures reduces to some extent the fall in the output gap, as it can be clearly observed. However, this comes at a great cost, as the disease's mortality rate (deceased persons as percent of the total population) in the long-run increases by about 1.5 percent points, from about 11% to about 12.5%.

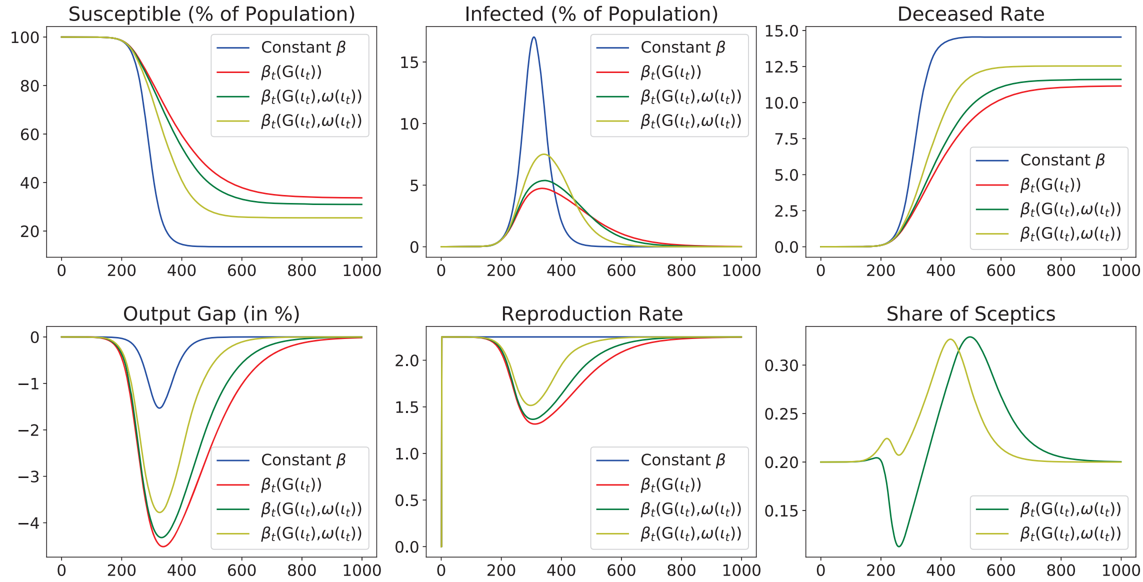

Figure 4: The SEIR model with endogenous transmission rate β_t and a varying fraction of sceptics in the population with $\phi_g = \phi_y = 0.25$ and $\mu_y = 100$, $\mu_i = 2.5$ (green lines) and $\mu_i = 1.5$ (yellow lines).

To the best of our knowledge, Faia et al. (2021) is the only study which focuses on agents' perceptions of public health and economic or financial conditions. Using a survey experiment, Faia et al. (2021) investigate how the ability of individuals to select public health- and economics-related information is related with their prior beliefs. However, they do not focus on the perceived trade-off between these two dimensions.

4 Alternative Reference Measures

Given the ad hoc formulation of the share of sceptics in the population, it is worthwhile to investigate what the dynamics of the model may look like for alternative specifications.

To begin with, we modify the specification of the share of sceptics as follows:

$$\omega_t = \frac{\exp(-\mu_y y_{t-1})}{3 + \exp(-\mu_y y_{t-1}) + \exp(\mu_i \mathcal{D}_{t-1})}. \tag{12}$$

Accordingly, as investigated also by Cochrane (2020), the share of sceptics is now determined by the relative evolution of the daily number of new deaths $\gamma_D I_t$ per 100.000 persons $\mathcal{D}_t$ instead of the incidence rate $\mathcal{I}_t$ and of the output gap.

Figure 5 illustrates the resulting dynamics for the same parametrization used in Figure 4.

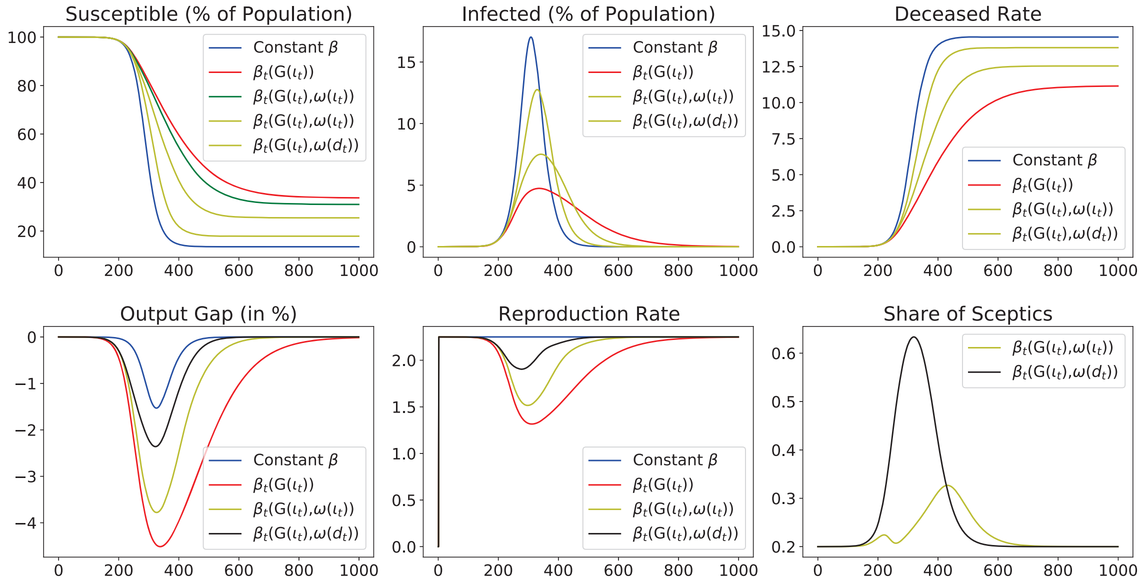

Figure 5: The SEIR model with endogenous transmission rate β_t and a varying fraction of sceptics in the population with $\phi_g = \phi_y = 0.25$ and $\mu_y = 100$, $\mu_i = 2.5$.

As it can be clearly observed, when sceptics react to the number of new deaths instead of the number of newly infected people, its share increases dramatically relative to the case where the incidence rate is the reference measure for the share of sceptics. As in the previous case, the increase in the sceptics'sshare lessens the government containment policies, leading to an increase in the number of infected people and by extension, of the deceased rate in the long-run.

Finally, we consider the case where both the government as well as the share of sceptics depend on the number of new deaths rate instead of the incidence rate, so that

$$\beta_t = \beta_0 - (1 - \omega_t)\phi_g \mathcal{D}_t, \quad \beta_t \geq 0. \tag{13}$$

For better comparison, we depict this final case with the two previous ones in Figure 6.

The differences in the dynamics between this last scenario and the previous ones are striking. First and foremost, for the chosen parametrization of this last scenario concerning the two most important variables, the infection and the deceased rates, have dynamics quite similar to the baseline case where the transmission rate was constant. The reason for this outcome can be traced back to the choice of the government' reference variable for its containment policy: Since the number of newly deceased reacts with some delay to the overall evolution of the epidemic, the government reaction is by extension also too slow and too insufficient, what leads only to a very small decrease in the reproduction rate. As the

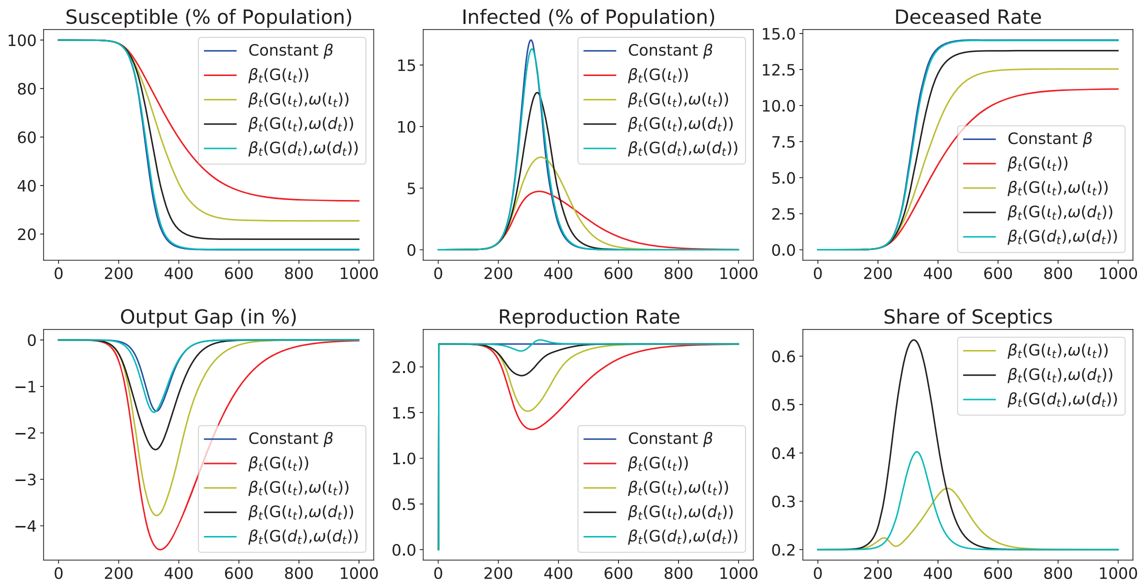

Figure 6: The behavioral SEIR model with endogenous transmission rate β_t and a varying fraction of sceptics in the population.

share of sceptics is also boosted by the delayed reaction of the newly deceased relative to the evolution of the output gap, the reproduction rate becomes even larger than its baseline level β_0, highlighting the non-compliance and even protest behavior of the sceptics.

5 Concluding Remarks

In this short simulation study we investigated the role of sceptics in the effectiveness of governmental containment policies through a reduced-form specification of the trade-off between the public health and the economic dimensions in an epidemic such as COVID-19.

Despite of the parsimony of our behavioral SEIRD model, we could model in a reasonable manner how policy or disease scepticism affects the transmission rate, the reproduction rate and thus the general evolution of the disease, as well as the economic sphere. Additionally, we showed that focusing on the incidence rate – as done in many countries around the world during the COVID-19 pandemic – is a superior strategy than using the number of new deaths, for example.

The current framework can be extended in various directions. First and foremost, it would be interesting to estimate the model or to calibrate it on the basis of real data. Further, one could introduce the public-health vs. economics trade-off in the government's policy function, as well as model the economic dimension in a more detail manner. We intend to tackle these and other issues in future work.

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