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The trade-off between public health and the economy in the early stage of the COVID-19 pandemic

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Abstract

How does contagion risk affect the business cycle? We find that the presence of contagion risk significantly alters the transmission of standard macroeconomic shocks. Relative to the first-best equilibrium, the contagion externality significantly reduces the response of output to a technology shock. We also argue that the magnitude of the trade-off between health and the economy crucially depends on how the proba-bility of infection is specified. If the probability of infection only depends on agents' endogenous choices, a weaker trade-off emerges. In such a framework, and relative to the laissez-faire equilibrium, suboptimal policies such as zero COVID strategies, health insurance, or mandatory testing substantially attenuate recessions that are caused by epidemics. Therefore, policies primarily aimed at preserving public health do not necessarily come at the cost of deeper recessions.

- **JEL:** E1, H0, I1
- **Keywords:** Contagion Externality, Lockdown Policies, Risk Sharing, Incomplete Markets.

Non-technical Summary

The COVID-19 shock has profoundly affected the design of stabilisation policies. Relative to the recessions witnessed in the last decades, a major difference is that the COVID crisis also caused millions of fatalities globally. Since vaccines take time to be developed, lockdown policies are the first line of defence against epidemic outbreaks. But since lockdowns reduce economic activity, the costs and benefits of these policies are a source of debate. The main contention of this article is that the so-called trade-off between health and the economy could in fact be weaker than previously thought. Indeed, in our environment, policies that save lives also reduce the economic cost of an epidemic outbreak.

We study the trade-off between health and the economy using a modified version of the workhorse macroeconomic model with susceptible, infected and recovered (SIR) agents. Our results suggest that the magnitude of this trade-off crucially depends on how the probability of infection is specified. Indeed, relative to the findings documented in the literature, a weaker trade-off emerges if the probability of infection only depends on agents' endogenous choices.

With this alternative specification, we find that suboptimal policies such as zero COVID strategies, health insurance, or mandatory testing not only save lives but also attenuate recessions that are caused by epidemics. This result suggests that policies primarily aimed at preserving public health do not necessarily come at the cost of deeper recessions.

The second objective of this paper is to analyze how the presence of contagion risk affects the propagation of standard macroeconomic shocks. Indeed, in most countries, public authorities opted for a mitigation strategy, which implies that the virus was never completely eliminated. If a fraction of the population remains infected, fluctuations in economic activity could affect the transmission of the virus by stimulating economic interactions. An important question, therefore, is whether contagion risk affects the transmission mechanism of standard macroeconomic shocks. We study this question in a stochastic version of the workhorse macroeconomic model with SIR agents.

Our second result is that it does. Indeed, the presence of contagion risk considerably alters the response of output to supply shocks. Relative to the first-best equilibrium, which corresponds to the allocation that a social planner would choose, the contagion externality significantly reduces the response of output. The reason is that contagion risk is akin to a tax on labor supply. This implicit tax affects the propagation of supply shocks by reducing labor supply when the number of infected individuals, and hence the risk of contagion, increases.

1 Introduction

The COVID-19 epidemic caused a recession of an unprecedented magnitude. In many countries, the decline in activity caused by the shock was even greater than that observed during the 2007-2009 financial crisis. A crucial difference between the two crises, however, is that the epidemic also caused millions of fatalities globally. In addition to the economic damage caused by the crisis, stabilization policies must therefore be designed with the death toll from epidemics in mind.

Since developing vaccines takes time, in the early stages of the crisis, imposing strict containment policies was the only available option to reduce contagion. But a main argument against containment policies, such as lockdowns, is that these measures reduce economic activity. During an epidemic, a trade-off between business cycle stabilization and public health may therefore emerge.

This possible trade-off between lives that can be saved and the damage caused by lockdowns could explain the different mitigation strategies observed across countries. In the early stages of the crisis, countries such as Sweden, followed a rather laissez-faire approach and refrained from implementing strict measures. At the other end of the spectrum, countries such as China stood out by adopting some of the most restrictive policies.

As illustrated by Chart A.1, however, at first glance, until the first quarter of 2021 the existence of a trade-off between public health and economic activity is far from evident. Indeed, in a sample of OECD economies, the countries hardest hit by the epidemic also seem to have experienced deeper recessions. Moreover, as noted by Aghion, Artus, Oliu-Barton, and Pradelski (2021), Australia, Japan, New Zealand, and South Korea are examples of countries which managed to contain the effect of the virus on their population while experiencing milder recessions than many OECD economies.

According to Aghion et al. (2021), this is not a coincidence and this success could well be the result of good policies rather than good luck. Indeed, countries such as New Zealand or Australia stood out by adopting what is sometimes referred to as a zero COVID strategy. In contrast to the approach observed in many countries, the aim of the zero COVID strategy is to completely eradicate the virus by imposing severe restrictions each time a new cluster is detected.

Motivated by this difference in approach across countries, this paper studies the relationship between health and the economy from the perspective of an otherwise standard business cycle model. The objective is to investigate this possible trade-off by evaluating different types of mitigation strategies.

Relative to the seminal work of Eichenbaum, Rebelo, and Trabandt (2021) (ERT 2021), we argue that the trade-off between health and the economy could in fact be weaker than previously thought. The key contribution of ERT (2021) is to link the propagation of the disease to economic activity within a general equilibrium model. The novel part is that the probability of infection depends on agents' endogenous decisions. Susceptible agents catch the virus by interacting with infected ones when making consumption decisions or in the workplace. In the original formulation of Kermack and McKendrick (1927) (KMK 1927), in contrast, the probability of infection only depends on the number of infected agents in the economy. This specification therefore implies that the probability of contagion is exogenous with respect to agents' decisions.

ERT (2021) maintain the original assumption by assuming that contagion has two components: one that mechanically increases with the number of infected agents in the economy, as in KMK (1927), and another one that depends on agents' choices. In this study, instead, we consider an extended version of the ERT (2021) model in which the probability of contagion only depends on agents' choices. According to our specification, the difference is that individual agents therefore have greater control over their own probability of contagion.

Our motivation to study this case is firstly that there is no consensus in the literature regarding the exact specification of the infection probability. For example, Kaplan, Moll and Violante (2020) or Krueger, Uhlig, and Xie (2020) exclude the KMK (1927) component by positing that new infections solely depend on economic interactions. Second, using this alternative specification significantly alters the model's main policy implications. Indeed, without the exogenous component, the trade-off between health and the economy improves substantially.

This point is firstly illustrated by evaluating a policy akin to the zero COVID strategy by which the government seeks to minimize fatalities. Although this approach was followed by several countries, to our knowledge, very few studies have provided a quantitative evaluation of the zero COVID strategy. Taking the practical considerations into account is achieved by assuming that the authorities can only force agents to reduce hours worked, without the possibility to discriminate healthy from sick workers. This lockdown strategy is captured by imposing a tax on labor supply that is uniformly applied to all agents.

We find that a swift initial increase in this tax, followed by a gradual reduction, allows the government to fully neutralize the effect of the shock on new infections. Interestingly, although the policy is suboptimal, it also allows the government to contain the effect of the shock on output. Indeed, whereas the recession is inevitable, it is of several orders of magnitude lower than that obtained under a laissez-faire system. In ERT (2021), in contrast, the best containment policy saves lives but comes at the cost of a sizeable increase in the magnitude of the recession.

We also evaluate the zero COVID strategy by asking whether the model can jointly reproduce the dynamics of output growth and health variables observed in the data. Given the low fatality rate observed in Australia, we study the response of the Australian economy during the COVID crisis. The magnitude of the recession observed from the second quarter of 2020 to the first quarter of 2021 as well as the low number of cases can be jointly reproduced. In our setting, the lockdown strategy that completely eliminates the virus is equivalent to increasing this uniform tax on labor supply from 0 to 17% when the shock hits. Since our analysis focuses on the early stages of the COVID crisis, we do not take into consideration vaccination or the emergence of new variants.

Second, to evaluate some of the policies observed in European economies in recent months, we study the case of compulsory testing. This scenario assumes that a testing technology such as antigen tests, is available.[1] We find that imposing sanctions to deter firms from employing infected workers is also an effective strategy. Relative to the laissez-faire case, the key is that the measure incentivizes firms to test workers to avoid possible sanctions. Once infected individuals are identified, it is then possible to reduce contagion risk in the workplace without cutting hours worked by healthy agents.

If the source of the shock is an increase in new cases, the main takeaway from this article is thus that the trade-off between public health and business cycle stabilization could be weaker than previously thought. Containment policies, even if they are suboptimal, can be powerful tools to mitigate the effect of an epidemic shock. One tool turns out to be sufficient to minimize new infections while at the same time mitigating the damage to the economy.

To illustrate the importance of market incompleteness, we next study the case of redistributive policies. Indeed, besides the presence of contagion risk, the absence of risk sharing in the laissez-faire equilibrium is another important source of inefficiency. The objective of this experiment is to capture the effect of measures that are akin to health insurance. This is achieved by introducing a tax on susceptible agents that is used to finance a transfer to infected agents. We find that this measure reduces contagion risk by encouraging contaminated agents to stay at home when infected. Reducing contagion risk in the workplace in turn mitigates the recession by avoiding the large contraction in hours worked by healthy

[1] Antigene tests are widely used in Germany since the Summer of 2021. Proof of a negative test is for example necessary to check in at hotels. Compulsory tests were also introduced in schools in April 2021.

agents observed under a laissez-faire system.

Next, to highlight the difference with other shocks, we also study shocks that are known to generate efficient business cycle fluctuations. Under the first-best policy, we find that the response of the economy to a technology shock is very similar to that obtained in the baseline neoclassical growth model. Output, aggregate hours worked, and consumption as well as investment all increase, as in the textbook model. Under laissez-faire, the main difference is that the contagion externality attenuates the effect of technology shocks on output. A social planner therefore chooses to increase the fluctuations in output induced by technology shocks. In contrast, a social planner finds it optimal to completely eliminate those caused by epidemic shocks.

Relative to ERT (2021), the difference is that we study the transmission of macroeconomic shocks in a model in which there is a very small number of infected agents in the steady state. A rise in economic activity therefore triggers an increase in infections because the shock stimulates interactions between susceptible and infected agents .

Finally, our mechanism provides a potential explanation for the puzzling dynamics of labor productivity observed in the euro area during the COVID crisis. Indeed, as illustrated in Chart A.2, hourly compensation as well as hourly labor productivity increased substantially when the epidemic shock hit. This rise in labor productivity suggests that the dramatic decline in hours worked observed during this period was mostly driven by a reduction in labor supply, and not by a fall in labor demand. Our theory explains this rise in labor productivity by the effect of contagion risk, which is akin to a tax on labor supply. Consequently, a shock that increases the number of infected agents reduces the labor supply of agents susceptible to catching the virus. This effect in turn generates the co-movement between hours worked and hourly labor productivity observed in the data during the COVID crisis.

The work ERT (2021) is the starting point of this newly emerging literature on the macroeconomic implications of epidemics. These authors extend the classic model of susceptible, infected, and recovered (SIR) agents (e.g. Kermack and McKendrick (1927); Atkeson, 2020) to endogenize contagion risk. Relative to their seminal contribution, we consider a model with capital accumulation and study shocks in a stochastic environment, as typically done in the business cycle literature. ERT (2021) also derive the first-best policy by solving the planner's problem, a case which is referred to as the smart containment policy.

Eichenbaum, Rebelo, and Trabandt (2020a) study the effect of social distancing and mask use in a model in which a testing technology is available. Relative to ERT (2021), a main innovation is to consider the case in which agents do not know their true health state. Combining testing with social distancing measures provides a more efficient solution than lockdowns.

Eichenbaum, Rebelo, and Trabandt (2020b) introduce investment into the analysis in a setting in which there is perfect risk-sharing between agents. Marginal utility of consumption is therefore equalized across agents. Those authors find that the neoclassical growth model cannot rationalize the positive co-movement between consumption and investment observed in the data. Relative to their approach, we consider an environment with imperfect risk sharing. Workers and capital owners therefore have different stochastic discount factors. We find that this version of the neoclassical growth model generates the positive co-movement between investment and aggregate consumption observed in the data.

Our results could potentially suport the view that, in the early phase of the pandemic, elimination could have been the best strategy to deal with the virus. Indeed, as argued by Baker, Wilson, and Blakely (2020) and Oliu-Barton, Pradelski, Aghion, Artus, Kickbusch, Lazarus, Sridhar and Vanderslott (2021) countries that adopted this strategy by aiming to stop community transmission as quickly as possible generally had better outcomes than countries in Europe or the United States, which opted for mitigation.

To our knowledge, the work of Alvarez, Argente, and Lippi (2020) is one of the first studies that derives the optimal lockdown policy of a planner. Their study features a trade-off between health and the economy. Relative to their approach, we consider a model in which the probability of infection depends on consumption as well as labor supply decisions. In our case, the difference between the planner's problem and the decentralized equilibrium is that the planner can choose the number of hours worked and consumption so as to fully internalize the effect of individual choices on contagion risk.

Relative to ERT (2021), Krueger, Uhlig, and Xie (2020) consider an economy composed of heterogeneous sectors. This modification is motivated by the fact that some sectors are more exposed to contagion risk than others. Consequently, if the economy is sufficiently flexible, the COVID crisis can induce a reallocation of resources towards less contagious sectors of the economy. Given the rather laissez-faire approach adopted by the Swedish authorities in the early stages of the crisis, these authors calibrate their model using Swedish data. They also derive the first-best policy by solving the planner's problem. As in ERT (2021), under the first-best allocation, the COVID shock only has a small output cost.

Glover, Heathcote, Krueger, and Rios-Rull (2020) study mitigation policies in a model composed of agents with different age profiles. Taking this dimension into account is necessary to capture the differentiated effect of lockdown policies across age cohorts. Indeed, severe complications are less likely to occur among young agents. At the same time, younger agents are more likely to suffer the consequences of lockdown policies, as they face unemployment risk.

Kaplan, Moll and Violante (2020) study the effect of the COVID crisis on income and wealth distributions. Although the costs are large and heterogenous, households in the middle of the wealth distribution are the most affected.

Guerrieri, Lorenzoni, Straub, and Werning (2020) develop a theory of supply shocks that triggers large declines in aggregate demand. Negative supply shocks can therefore be Keynesian in the sense that they generate recessions that are mainly driven by a decline in aggregate demand. This type of Keynesian supply shock can only arise in economies with multiple sectors, and not in one-sector models.

Garriga, Manuelli, and Sanghi (2020) study the trade-off between economic activity and infection transmission when agents expect a vaccine to become available and when the vaccine is available. Vaccinating the entire population is a time consuming process. They show that this constraint significantly affects the optimal policy, even before the vaccine is available. Given that it takes time to develop vaccines, Glover, Heathcote, and Krueger (2022) find that vaccinating older adults in priority mitigates the effect of the pandemic on both public health and the economy.

There is also evidence that the COVID crisis had a stronger effect on labor supply than labor demand. The results documented in Brinca, Duarte, and Faria-e-Castro (2020) for instance suggest that two-thirds of the decline in aggregate hours worked can be attributed to labor supply.

Brzoza-Brzezina, Kolasa, and Makarski (2021) study the effects of the COVID crisis in a model with nominal rigidities. In the absence of containment measures, they find that the optimal monetary policy is contractionary.

Alveda, Ferguson, and Mallery (2020) argue that saving lives is the best strategy to limit the economic damage from pandemics. The facts that they document suggest that countries which focused on COVID elimination experienced smaller recessions. Fang, Nie, and Xie (2022) find that higher unemployment insurance increases unemployment but saves lives by reducing infections at work.

Under the planner's problem, our model reduces to a standard real business cycle model as markets are complete and the contagion externality is eliminated in this case. Under the first-best allocation, technology shocks therefore have an effect which is very similar to that documented in King and Rebelo (1999) for example. Since our model also features an extensive labor margin, one notable difference is that we obtain more persistent responses to technology shocks. Under laissez-faire, we also find that augmenting the neoclassical growth model with susceptible, infected and recovered agents considerably amplifies the model's endogenous propagation mechanism (e.g. Beaudry, Galizia, and Portier, 2020; Chang, Gomes, and Schorfheide, 2002).

Our work is also related to Di Tella and Hall (2020) who show that risk premium shocks can cause inefficient fluctuations. They reach this conclusion by showing that risk premium shocks cause a fall in output and employment that is too large relative to that obtained in the efficient allocation.

Relative to the textbook neoclassical model, we use the solution method developed by Andreasen, Fernández-Villaverde, and Rubio-Ramírez (2018) and that is implemented in the dynare software platform (e.g. Adjemian et al., 2021) to study these questions. Given the non-linear nature of the types of models used to study epidemics, we use a third-order approximation as well as pruning techniques to solve the model and derive impulse responses.

2 The laissez-faire equilibrium

This section derives the allocation under laissez-faire, which corresponds to the decentralized equilibrium. As in ERT (2021), the economy is composed of susceptible (S), infected (I) and recovered (R) agents. These three types of agents are hand-to-mouth (e.g. Weil, 1992) in the sense that they consume exactly what they earn and do not save. Firms are owned by entrepreneurs, which are modelled as a separate type of agent. The representative entrepreneur hires S, I, and R agents and makes investment decisions so as to maximize lifetime utility.

2.1 Susceptible agents

Susceptible agents maximize utility, which depends on both consumption and leisure, and which are denoted by c_S and l_S, respectively. As in ERT (2021), their decision is affected by the probability of being infected.

For an S agent, the probability of catching the virus depends on the number of hours worked and quantity of good that is consumed when interacting with I agents. Consequently, the probability of infection is given as follows:

$$p_{It} = \varkappa_h h_{St}(n_{It} h_{It}) + \varkappa_c c_{St}(n_{It} c_{It}) \tag{1}$$

where $\varkappa_h$ and $\varkappa_c$ denote the probability of infection when working and consuming, respectively.

One important difference is that we abstract from the MKK (1927) component. Indeed, since contagion risk is endogenously determined, there is no clear justification for this term. A susceptible agent or a family who is confined at home is very unlikely to be infected. Consequently, an increase in the number of infected individuals in the economy does not mechanically increase the risk of contagion.

In this expression, n_I denotes the total number of I agents in the economy. From the standpoint of an S agent, the probability of infection when working h_S hours or consuming an amount c_S firstly depends on hours worked and consumption of I agents, which are denoted by c_I and h_I, respectively. This probability in turn depends on the total number of I agents they meet at work or in shopping malls.

The value function of an S agent is denoted by υ_S and depends on both consumption and leisure. The time endowment is normalized to 1. Consequently, leisure time for an S agent is given as follows:

$$l_{St} = 1 - h_{St}$$

In equation (2) below, the first component is standard and denotes the utility flow enjoyed by agents in period t. Following the real business cycle literature (e.g. King and Rebelo, 1999), we assume a log utility specification that is separable in consumption and leisure. ψ_S is a labor supply parameter that determines the steady state allocation of time spent between hours worked and leisure activities.

Relative to the neoclassical growth model, the difference is that the continuation value of an S agent depends on the probability of infection. An S agent remains healthy with probability $1 - p_I$ and falls sick with probability p_I. Consequently, the value function of an S agent is given as follows:

$$\upsilon_{St} = \log c_{St} + \psi_S \log(1 - h_{St}) + \beta E_t \left[p_{It} \upsilon_{It+1} + (1 - p_{It}) \upsilon_{St+1} \right] \tag{2}$$

where υ_I denotes the continuation value of an I agent. The continuation value of an S agent therefore integrates the risk of falling sick and becoming infected with probability p_I.

S agents are hand-to-mouth and their budget constraint is given as follows:

$$w_t h_{St} = c_{St} \tag{3}$$

where w denotes the wage received from entrepreneurs. The problem of an S agent consists of choosing the optimal trajectory for c_S, h_S and p_I so as to maximize expected lifetime utility subject to constraints (1) and (3):

$$v_{St} = \max_{c_{St}, h_{St}, p_{It}} \left\{ \begin{array}{c} \log c_{St} + \psi_S \log(1 - h_{St}) + \beta E_t \left[p_{It} v_{It+1} + (1 - p_{It}) v_{St+1} \right] \\ +\lambda_{St} \left[w_t h_{St} - c_{St} \right] + \eta_t \left[p_{It} - \varkappa_h h_{St}(n_{It} h_{It}) - \varkappa_c c_{St}(n_{It} c_{It}) \right] \end{array} \right\}$$

where λ_S is marginal utility of consumption and η the Lagrange multiplier associated with constraint (1). The subjective discount factor is denoted by β and is common to all agents.

The first-order conditions with respect to c_S, h_S, and p_I are given by equations (4),(5), and (6), respectively.

$$\frac{1}{c_{St}} = \lambda_{St} \left(1 + \frac{\eta_t}{\lambda_{St}} \varkappa_c (n_{It} c_{It}) \right) \tag{4}$$

$$\psi_S \frac{1}{1 - h_{St}} = \lambda_{St} \left(w_t - \frac{\eta_t}{\lambda_{St}} \varkappa_h (n_{It} h_{It}) \right) \tag{5}$$

$$\eta_t = \beta E_t v_{St+1} - \beta E_t v_{It+1} \tag{6}$$

Relative to a real business cycle model, the difference is that the probability of infection alters both consumption and labor supply. As illustrated by equations (4) and (5), the risk of infection is akin to a tax on consumption and labor, where this tax is given by:

$$\tau_t^C = \frac{\eta_t}{\lambda_{St}} \varkappa_c (n_{It} c_{It}) \tag{7}$$

and:

$$\tau_t^L = \frac{1}{w_t} \frac{\eta_t}{\lambda_{St}} \varkappa_h (n_{It} h_{It}) \tag{8}$$

An increase in the number of I agents or an increase in the consumption and hours worked of I agents raises the probability of infection. This effect is internalized by S agents and acts as a tax on consumption and labor. Similarly, a shock that increases the probability of infection p_I tightens the constraint (1). This in turn reduces both the quantity consumed as well as the number of hours worked of an S agent via the effect of the Lagrange multiplier η associated with constraint (1).

Finally, and as illustrated by equation (6), the Lagrange multiplier η depends on the difference in expected lifetime utility between S and I agents. A higher difference in expected utility implies a stronger impact of contagion risk on the demand for consumption goods and the supply of labor.

Whereas S agents do internalize the risk of contagion, their choice is however not fully optimal. Indeed, they only take into account the effect of their decisions on their individual probability of catching the virus. They do not take into account that their behaviors will also affect the proportion of S vs. I agents. Indeed, since S agents have a higher expected lifetime utility than I agents, an increase in the number of infected agents also has a negative impact on aggregate welfare via this channel. As the total number of agents varies, an additional effect akin to an extensive margin therefore also operates in this type of model.

2.2 Infected agents

Each period, I agents choose the quantity to consume as well as the number of hours worked to supply. If an agent I recovers from the disease, this agent integrates into the pool of R agents. I agents recover from the virus with probability p_R. In contrast to S agents, the crucial difference is that I agents face a probability of dying from the disease given by p_D. In this case, we assume that the lifetime utility of a deceased agent is zero. The probability of remaining infected next period is denoted by $1 - p_R - p_D$ and the value function υ_I of an I agent is therefore given as follows:

$$\upsilon_{It} = \log c_{It} + \psi_I \log(1 - h_{It}) + \beta E_t \left[(1 - p_R - p_D)\upsilon_{It+1} + p_R \upsilon_{Rt+1}\right]$$

where c_I and h_I denote consumption and the number of hours worked chosen by an I agent, respectively. The continuation value of an I agent that recovers is denoted by υ_R.

Normalizing the time endowment to 1, non-working time of an I agent is therefore given by $l_I = 1 - h_I$. I agents are hand-to-mouth and maximize utility subject to their budget constraint, which at time t is given as follows:

$$w_t h_{It} = c_{It}$$

as well as the time allocation constraint by solving the following dynamic programming problem:

$$\upsilon_{It} = \max_{c_{It}, h_{It}} \left\{ \begin{array}{c} \log c_{It} + \psi_I \log(1 - h_{It}) + \beta E_t \left[(1 - p_R - p_D)\upsilon_{It+1} + p_R \upsilon_{Rt+1}\right] \\ +\lambda_{It} \left[w_t h_{It} - c_{It}\right] \end{array} \right\}$$

where λ_I is the marginal utility of an I agent.

The first-order conditions with respect to consumption and leisure are given as follows:

$$\frac{1}{c_{It}} = \lambda_{It} \tag{9}$$

$$\frac{\psi_I}{1 - h_{It}} = \lambda_{It} w_{It} \tag{10}$$

In contrast to S agents, the risk of contagion has no effect on the optimality conditions of an I agent. Hence, I agents do not internalize the impact of their economic choices on the probability of transmitting the disease to S agents. This contagion externality is the main market failure that distorts the allocation of resources.

2.3 Recovered agents

Following ERT (2020), we assume that an I agent that recovers from the disease cannot catch the virus again. To ensure the existence of a unique steady state, we assume that recovered agents face a probability of death that is given by ϕ. Each period these agents consume a quantity of good denoted by c_R and enjoy leisure l_R.

Recovered agents allocate all their income to consumption and do not save. At time t, the budget constraint of a recovered agent is therefore:

$$w_t h_{Rt} = c_{Rt}$$

The value function of an R agent is given as follows:

$$v_{Rt} = \log c_{Rt} + \psi_R \log(1 - h_{Rt}) + (1 - \phi)\beta E_t v_{Rt+1}$$

where h_R is the fraction of time that recovered agents spend working in the representative firm.

As in the case of an I agent, the risk of contagion has no effect on the optimality conditions of recovered individuals. The first-order conditions with respect to consumption and hours worked are therefore standard:

$$\frac{1}{c_{Rt}} = \lambda_{Rt}$$

$$\psi_R \frac{1}{1 - h_{Rt}} = \lambda_{Rt} w_t$$

where λ_R is marginal utility and ψ_R is a labor supply parameter.

2.4 Entrepreneurs

In contrast to workers, entrepreneurs are not subject to contagion risk. They are able to consume a fraction of what the firm that they own produces. They also do not meet workers during business hours and are therefore not at risk of catching the disease from the workers. These agents own the representative firm and need hours worked as well as capital to produce the economy's output good y. They also own the economy's capital stock and employ S, I, and R agents.

The output good is produced via a Cobb-Douglas production function. Since the total number of S, I, and R agents is denoted by n_S, n_I, and n_R, respectively, the production function takes the following form:

$$y_t = ak_{t-1}^{\alpha}(n_{It}h_{It} + n_{St}h_{St} + n_{Rt}h_{Rt})^{1-\alpha} \tag{11}$$

where k denotes the capital stock, α is the capital share parameter, and a is a technology parameter. This illustrates that total labor input consists of both an extensive margin, i.e. the number of agents of a given type, as well as an intensive margin, i.e. the number of hours worked by agents of each respective type.

Every period, the objective of entrepreneurs is to choose the mix of hours worked and investment that maximizes their consumption c_E and their budget constraint is given as follows:

$$\begin{aligned} c_{Et} &= ak_{t-1}^{\alpha}(n_{It}h_{It} + n_{St}h_{St} + n_{Rt}h_{Rt})^{1-\alpha} - w_t\left(n_{It}h_{It} + n_{St}h_{St} + n_{Rt}h_{Rt}\right) \\ &\quad -(k_t - (1-\delta)k_{t-1}) \end{aligned} \tag{12}$$

where k denotes the capital stock and δ is the depreciation rate of capital. Assuming a log specification for the utility function of entrepreneurs, their value function is given as follows:

$$\upsilon_{Et} = \max_{\substack{c_{Et}, k_t, h_{It}, h_{Rt} \\ h_{St}, n_{It}, n_{St}, n_{Rt}}} \left\{ \begin{array}{c} \log c_{Et} + \beta E_t \upsilon_{Et+1} \\ +\lambda_{Et}\left[\begin{array}{c} a_t k_{t-1}^{\alpha}(n_{It}h_{It} + n_{St}h_{St} + n_{Rt}h_{Rt})^{1-\alpha} - w_t\left(n_{It}h_{It} + n_{St}h_{St} + n_{Rt}h_{Rt}\right) \\ -(k_t - (1-\delta)k_{t-1}) - c_{Et} \end{array} \right] \end{array} \right\}$$

where λ_E is marginal utility of consumption.

Entrepreneurs choose consumption, hours worked, the number of agents of each type, and investment to maximize lifetime utility. The optimality conditions corresponding to this dynamic problem are given as follows:

$$\frac{1}{c_{Et}} = \lambda_{Et} \tag{13}$$

$$\lambda_{Et} = \beta E_t \lambda_{Et+1}(1-\delta) + \beta E_t \lambda_{Et+1} \alpha \frac{y_{t+1}}{k_t} \tag{14}$$

$$w_t = (1-\alpha)\frac{y_t}{n_{It}h_{It} + n_{St}h_{St} + n_{Rt}h_{Rt}} \tag{15}$$

where to derive equation (14), we use the envelope condition, which implies:

$$\lambda_{Et} = \beta E_t \frac{\partial \upsilon_{Et+1}}{\partial k_t}$$

2.5 Evolution of the number of S, I, and R agents

The total number of S agents in the economy in period t, which we denote by n_S, evolves according to the following law of motion:

$$n_{St} = n_{St-1} + b - p_{It} n_{St} - \log \varsigma_t \tag{16}$$

where n_{St-1} is the number of S agents in period $t-1$. The number of S agents in period t therefore depends on new infections in the current period. New infections represent the share of S agents who catch the virus and is denoted by $p_I n_S$. Since the model is calibrated at a quarterly frequency, this timing implies that new infections occur within the period. To ensure the existence of a steady state, we assume that new agents enter each period. The flow of new entrants, which is constant, is denoted by b.

As regards the law of motion of I agents, it depends on the flow of newly infected individuals $p_I n_S$, as well as the probability of recovery but also death:

$$n_{It} = (1 - p_R - p_D)\, n_{It-1} + p_{It} n_{St} + \log \varsigma_t \tag{17}$$

Relative to the number of I agents in period t, a fraction p_R recovers whereas a fraction p_D disappears. These agents therefore leave the group of I agents.

An epidemic shock is captured by introducing an exogenous disturbance that increases the number of infected agents.[2] The exogenous health shock is denoted by $\log \varsigma_t$, and follows an autoregressive process of order one:

$$\log \varsigma_t = \rho_\varsigma \log \varsigma_{t-1} + \varepsilon_{\varsigma t}$$

where the innovation $\varepsilon_{\varsigma t}$ is normally distributed with mean 0 and standard deviation $std(\varepsilon_{\varsigma t})$. The persistence of the shock is governed by the parameter ρ_ς. Finally, the evolution of R agents is given as follows:

$$n_{Rt} = (1 - \phi) n_{Rt-1} + p_R n_{It-1} \tag{18}$$

where $p_R n_I$ is the fraction of infected agents who recovered in period $t-1$. Recovered agents face a probability of disappearing given by ϕ.

[2] Given that the shock is so small, introducing it in the law of motion of susceptible agents in equation (16) has essentially no impact.

2.6 Market clearing

The economy's market clearing condition implies that all goods produced are either consumed or invested. The aggregate consumption of workers also depends on the number of agents in each group.

$$y_t = n_{It}c_{It} + n_{St}c_{St} + n_{Rt}c_{Rt} + c_{Et} + k_t - (1-\delta)k_{t-1} \tag{19}$$

3 Calibration and results

The fluctuations induced by the COVID crisis turned out to be more persistent than initially envisaged. In most economies, the shock generated recessions that lasted several quarters. Epidemics are therefore phenomena that are relevant from a business cycle perspective. To ensure comparability with standard business cycle models, we choose a quarterly frequency and one period corresponds to three months.

Standard parameter values

The subjective discount factor β is common across agents and this parameter is typically calibrated to reproduce a realistic value for the risk-free interest rate. Given the persistent decline in real rates observed in the last decades, we set β to 0.995, which implies an annualized risk-free real rate of 2%. The value typically used in the literature, i.e. 0.99, which would imply an average value for the risk-free rate of 4% in this model, seems somewhat too low. As for the depreciation rate of capital and the capital share parameters, i.e. δ and α, we choose standard values and set these two parameters to 0.025 and 0.36, respectively.

Labor market

Following standard practice in the real business cycle literature, we fix the number of hours worked by each agent and then use the model's optimality conditions to find the values for the 3 labor supply parameters ψ_S, ψ_I, and ψ_R that are consistent with the steady state allocation of time. Given that the time endowment is normalized to one, we assume that S and R agents spend around 20% of their time on remunerated work-related activities. This is the value consistent with available evidence on time of use. The steady state fractions of time spent working for S and R agents, which are denoted by h_S and h_R, are therefore set to 0.2.

For I agents, we set the steady state fraction of time spent working to 10%. This choice can be justified by evidence suggesting that about half of all infected agents are asymptomatic (e.g. ERT, 2020). In contrast, infected agents that suffer from symptoms are unable to work and typically stay at home. An I agent therefore spends on average 10% of his or her time working in the final good sector, which implies a value for h_I of 0.1.

Laws of motion for the number of agents

The evolution of I and R agents is given by equations (17) and (18). Their evolution firstly depends on the two parameters p_D and p_R, which stand for the probability of recovery but also death from COVID, respectively.

The facts documented by Roser, Ritchie, Ortiz-Ospina, and Hasell (2020) suggest that the mortality rate in eurozone economies was exceptionally high during the early phases of the epidemic and varies widely across age ranges. In Italy and Spain, these authors report a fatality rate of 0.14% and 0.3% for ages from 30 to 39 years. For persons of age 80 and older, this rate reaches 15.6% and 20.2%, respectively. Since our model only focuses on active labor force participants, we set the fatality rate to 0.35%. This is the average mortality rate for a patient of age between 40 and 49 years that is reported by Roser et al. (2020). This choice also reflects the fact that the median age in most European economies stands between 40 and 46 years.

Since in our setting one period corresponds to 3 months, we assume that 99% of all I agents recover within the period and set p_R to 0.99. Therefore, the fraction of patients that remains infected after 90 days is 0.0065. There is indeed accumulating evidence suggesting that a small fraction of persons who caught the virus still suffer from symptoms 3 months after having been infected. This condition is often referred to as "long COVID". There is still considerable uncertainty about this parameter value, especially for active labor force participants.

To ensure the existence of a unique steady state, we also need to introduce a flow of new entrants as well as a probability of leaving the labor force because of other reasons than COVID. Other reasons for instance include other causes of mortality or a decision to retire or leave the labor force. To our knowledge detailed data about the probability of leaving the labor force are not available at the euro area level. Given this lack of a priori knowledge, we set ϕ to 0.0005, which therefore implies a very small probability of leaving the labor force for reasons that are not COVID related. Finally, the flow of new entrants b, which is constant, is calibrated to normalize the steady state number of I agents to 1.

Infection probabilities

The model dynamics critically depends on the two parameters governing the probability of infection in equation (1), $\varkappa_h$ and $\varkappa_c$. One main challenge is that there is considerable uncertainty about the value of these two parameters. These coefficients determine how consumption decisions and time spent at work impact the probability of infection p_I. But to our knowledge, no study has managed to clearly identify how patients suffering from the disease became infected. We will therefore use additional model implications to infer plausible values for these two parameters.

Given that the parameter b is chosen to normalize the steady state number of I agents to 1, $\varkappa_h$ and $\varkappa_c$ firstly determine the incidence rate. In our environment, the incidence rate can be computed as follows:

$$INC_t = \frac{p_{It} n_{St}}{n_{It} + n_{Rt} + n_{St}}$$

This incidence rate corresponds to the fraction of agents who catch the virus during a 90-day period. To obtain an incidence rate that is comparable to that used by governments, we multiply it by 7/90 to convert it into a weekly frequency. Given that the steady state of the economy corresponds to a situation in which COVID is not a concern, we target a weekly incidence rate of 2 per 100,000. In Germany, compulsory lockdown measures are triggered when the incidence rate reaches 35 cases per 100,000 inhabitants. In France, regions or cities are confined when this rate exceeds 400 cases per 100,000 inhabitants.

Contagion risk affects the steady state of the model by acting as an implicit tax on consumption. Indeed, the optimality condition with respect to c_S can be rewritten as follows:

$$c_{St} = \lambda_{St} \left(1 + \tau_t^C\right)$$

where τ^C denotes this implicit tax. Since the steady state value of τ^C in turn depends on $\varkappa_c$, this parameter determines the level of this implicit consumption tax. In a steady state in which the incidence rate is only 2 per 100,000, the effect of contagion risk on consumption is likely to be small. We therefore set a value for $\varkappa_c$ that implies an implicit consumption tax of 1%. It is possible to reproduce an incidence of 2 per 100,000 and the magnitude of this implicit consumption tax by setting $\varkappa_h$ and $\varkappa_c$ to 0.0001 and 0.00005, respectively.

Output per capita

Following ERT (2021), SIR models are calibrated to produce realistic values for output per capita. In 2019, the eurozone gross domestic product per capital stood at 33,000 euros. Setting the technology parameter in the production function a to 3.5 allows us to reproduce this magnitude, where in the model output is expressed in thousands of euros.

Shock process parameter

In our environment, a COVID shock is captured by introducing an exogenous component into the law of motion of I agents, which is given by equation (17). To illustrate how the number of infected agents impacts the real economy, we simulate a shock which generates a recession that lasts around 8 quarters. This magnitude can be reached by setting the persistence parameter ρ_ς to 0.8. The shock standard deviation $std(\log \varsigma_t)$ in equation (17) determines the strength of the shock and in particular the magnitude of the recession. We select this parameter to generate a peak increase in the 7-day incidence rate in the laissez-faire equilibrium from 2 to 30. Replicating an increase of this magnitude can be achieved by setting the shock standard deviation to 0.01.

It is important to note that the objective of this section is not to replicate one episode in particular. Indeed, given that all eurozone economies adopted confinement measures, the laissez-faire equilibrium has no direct counterpart in the data. As we illustrate in the next section, the aim of the exercise is to compare how different policies affect the propagation of a shock of a given magnitude. For the case of Australia, a comparison between the model and the data is shown in section 5.

Table 1 SIR parameters

h_S	h_I	h_R	p_R	p_D	ϕ	$\varkappa_h$	$\varkappa_c$	$std(\varepsilon_{\varsigma t})$	ρ_ς
0.2	0.1	0.2	0.99	0.0035	0.0005	0.0001	0.00005	0.01	0.8

3.1 The COVID shock in the laissez-faire equilibrium

The effect of the COVID shock on output is shown in the upper left panel of Figure 1. Figure 1 and 2 report variables in log deviation from steady state. The peak of the recession is reached two quarters after the shock hit and corresponds to a decline in output relative to the trend of 3%. Output then increases above the trend for a few quarters before converging towards its steady state value. The upper right and lower right quadrants of Figure 1 illustrate that the arrival of newly infected agents in the economy leads to a sharp reduction in consumption and hours worked of S agents. This dramatic decline in labor effort in turn reduces the marginal productivity of capital. This explains the substantial fall in investment shown in the lower left panel, the decline of which reaches 4% at the peak of the recession.

The effect of the shock on consumption and hours worked of S agents is driven by the implicit tax induced by contagion risk in equations (7) and (8). A COVID shock raises the tax on both hours worked and consumption, as S agents understand that their probability of catching the disease depends on how much they interact with I agents. This implicit tax firstly increases because of the direct effect of the shock on the number of I agents, which is denoted by n_I.

In equations (7) and (8), the second effect comes from the term denoted by the ratio η/λ_S. This term can be interpreted as the impact of contagion risk on consumption and labor supply decisions. On impact, the rise in this ratio is mainly driven by a decline in the marginal utility of consumption of S agents. Indeed, the presence of contagion risk implies a decline in both consumption and marginal utility. Relative to a standard model, the key is thus that contagion risk reduces agents' willingness to consume.

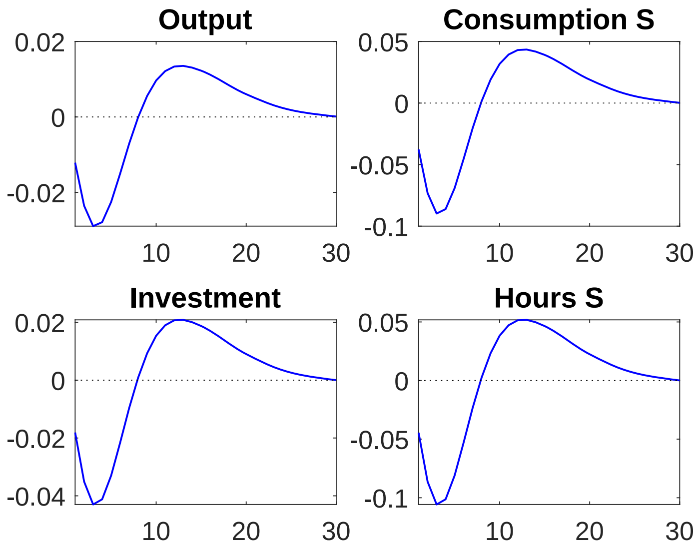

Figure 1. x axis: quarters after the shock. y axis: log deviation from steady state.

This lower willingness to consume also exacerbates the decline in labor supply. As in any business cycle model, labor supply is determined by both a wealth and a substitution effect. The higher tax is akin to a decline in real wages. This latter effect is then exacerbated by the decline in marginal utility, which induces a negative wealth effect that further reduces agents' willingness to work.

Figure 2, which firstly reports the response of consumption and hours worked by I agents, illustrates the main market failure associated with SIR models: I agents do not internalize that their interactions with S agents exacerbate the health crisis. In sharp contrast with the case of S agents, contagion risk does not alter the optimality conditions of an I agent. As shown by the upper left panel of Figure 2, the health crisis generates an increase in the consumption of I agents.

The rise in consumption of I agents can be explained by the labor shortage induced by the epidemic. First, given that I agents work less than S agents, the reallocation of agents from the two groups reduces production. Second, S agents internalize the risk of contagion and react by reducing hours worked. The key, therefore, is that this labor shortage increases the marginal productivity of labor. This higher marginal productivity in turn implies higher wages and explains why I agents increase consumption, an effect which exacerbates the health crisis.

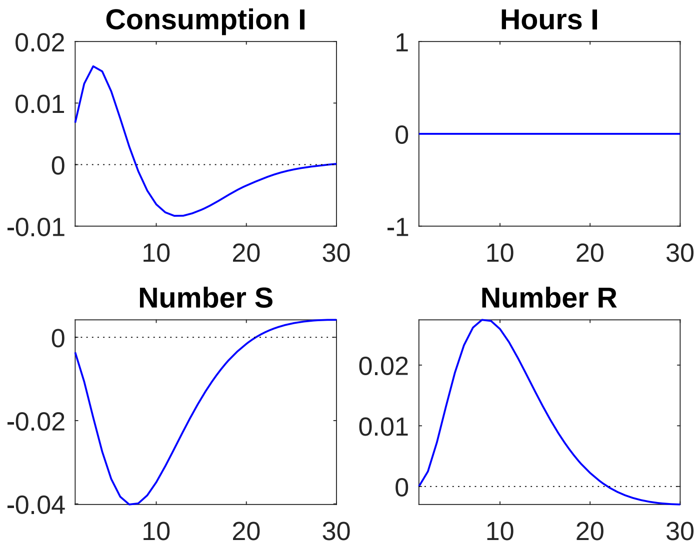

Figure 2. x axis: quarters after the shock. y axis: log deviation from steady state.

Given the log specification of utility, and since these agents are hand-to-mouth, the shock has no effect on the labor supply of an I agent. The number of hours worked by these agents remain constant. The effect of the shock on hours worked is therefore completely neutral, as can be seen on the upper right panel.

The two lower panels of Figure 2 report the evolution of the number of S and R agents, the dynamics of which is governed by equations (16) and (18). Given that I agents represent a small proportion of the total population, the shock only has a modest impact on the dynamics of n_S and n_R. Given the assumption of new entrants captured by the parameter b, the number of S agents eventually recovers. It nevertheless takes more than 5 years for the economy to recover the pre-epidemic population level. Similarly, as recovered agents are also subject to mortality risk, the number of R agents eventually returns to its long-term value.

4 The planner's equilibrium

This section derives the allocation that a social planner would choose. This equilibrium therefore corresponds to the first-best allocation that maximizes welfare. Relative to the problem described in the previous section, the planner perfectly internalizes the effect of each economic choice on contagion risk and hence fatalities.

The first key difference is that the planner takes contagion risk into account when choosing consumption and hours worked of I agents. Second, whereas individual agents take the evolution of all different types as given, the planner chooses trajectories for n_S, n_I, and n_R that are fully consistent with welfare maximization. Consequently, both the total number of agents as well as their repartition between the different types are taken into account by the planner. Finally, whereas markets are incomplete in the competitive equilibrium, the social planner equalizes marginal utility across types. The centralized equilibrium therefore implies that consumption risk is perfectly shared across agents.

The planner's problem

The social planner jointly maximizes the utility of all three agents. This maximization is subject to the aggregate budget constraint of the economy as well as the evolution of the three different types. The Lagrangian for this problem is given as follows:

$$\mathcal{L} = E_0 \Bigg\{ \sum_{t=0}^{\infty} \beta^t \left[\begin{array}{c} \varpi_S n_{St} \left(\log c_{St} + \psi_S \log(1 - h_{St})\right) + \varpi_I n_{It} \left(\log c_{It} + \psi_I \log(1 - h_{It})\right) \\ + \varpi_R n_{Rt} \left(\log c_{Rt} + \psi_R \log(1 - h_{Rt})\right) + \log c_{Et} \end{array} \right]$$

$$+ \sum_{t=0}^{\infty} \beta^t \lambda_t \left[\begin{array}{c} a k_{t-1}^{\alpha} (n_{It} h_{It} + n_{St} h_{St} + n_{Rt} h_{Rt})^{1-\alpha} \\ - n_{It} c_{It} - n_{St} c_{St} - n_{Rt} c_{Rt} - c_{Et} - k_t + (1 - \delta) k_{t-1} \end{array} \right]$$

$$+ \sum_{t=0}^{\infty} \beta^t \mu_{St} \left[n_{St-1} + b - \varkappa_h (n_{St} h_{St})(n_{It} h_{It}) - \varkappa_c (n_{St} c_{St})(n_{It} c_{It}) - \log \varsigma_t - n_{St} \right]$$

$$+ \sum_{t=0}^{\infty} \beta^t \mu_{It} \left[(1 - p_R - p_D)\, n_{It-1} + \varkappa_h (n_{St} h_{St})(n_{It} h_{It}) + \varkappa_c (n_{St} c_{St})(n_{It} c_{It}) + \log \varsigma_t - n_{It} \right]$$

$$+ \sum_{t=0}^{\infty} \beta^t \mu_{Rt} \left[(1 - \phi) n_{Rt-1} + p_R n_{It-1} - n_{Rt} \right] \Bigg\}$$

where the social planner chooses the optimal trajectory for $c_S, c_I, c_R, c_E, h_S, h_I, h_R, k, n_S, n_I$, and n_R. ϖ_S, ϖ_I, and ϖ_R are utility weight parameters, the calibration of which is discussed below. Marginal utility of consumption, which is common across agents under the first-best allocation, is denoted by λ. The three Lagrange multipliers associated with equations (16), (17), and (18) are denoted by μ_S, μ_I, and μ_R, respectively.

Optimality conditions

For an S agent, the optimality conditions with respect to consumption and hours are given as follows:

$$\varpi_S \frac{1}{c_{St}} = \lambda_t + (\mu_{St} - \mu_{It}) \varkappa_c (n_{It} c_{It})$$

$$\varpi_S \frac{\psi_S}{1 - h_{St}} = \lambda_t w_t - (\mu_{St} - \mu_{It}) \varkappa_h (n_{It} h_{It})$$

where:

$$w_t = (1 - \alpha) \frac{y_t}{n_{It} h_{It} + n_{St} h_{St} + n_{Rt} h_{Rt}}$$

Relative to equations (4) and (5), the main difference is that the effect of contagion risk is determined by the term $\mu_S - \mu_I$. As we explain below, the ratios μ_S/λ and μ_I/λ can be interpreted as the social value of S and I agents, respectively. In the laissez-faire equilibrium, the implicit tax on consumption and labor of an S agent was given by the ratio η/λ_S, where η is determined by the difference between the value function of S vs. I agents (see equation (6)). Therefore, the first key difference between the two equilibriums is that the implicit tax on consumption and labor decisions chosen by the planner differs from that obtained under laissez-faire.

The second key difference is that the planner internalizes the effect of consumption and hours worked by I agents on the dynamics of new infections. This can be firstly illustrated by comparing equations (9) and (10) with the corresponding optimality conditions obtained in the first-best equilibrium, that is:

$$\varpi_I \frac{1}{c_{It}} = \lambda_t + [\mu_{St} - \mu_{It}] \varkappa_c (n_{St} c_{St})$$

$$\varpi_I \frac{\psi_I}{1 - h_{It}} = \lambda_t w_t - [\mu_{St} - \mu_{It}] \varkappa_h (n_{St} h_{St})$$

A crucial difference across the two allocations is that the implicit tax also appears in the optimality conditions of I agents, whereas this term is absent under laissez-faire. For an I agent, the individual probability of transmitting the virus to an S agent when consuming and working depends on how much he or she interacts with S agents. In the case of consumption, the marginal increase in transmission firstly depends on the number of S agents that they meet, which is denoted by the term $\varkappa_c(n_S c_S)$. Then, the implicit tax chosen by the planner is the same across agents and is given by the term $(\mu_S - \mu_I)/\lambda$.

Since the implicit tax depends on the term $\mu_S - \mu_I$, it is useful to analyze the optimality conditions with respect to n_S and n_I to better understand how these two multipliers are determined in the first-best equilibrium. After rearranging terms, the dynamics of the Lagrange multiplier μ_S can be expressed as follows:

$$\frac{\mu_{St}}{\lambda_t} = \beta E_t \frac{\lambda_{t+1}}{\lambda_t}\frac{\mu_{St+1}}{\lambda_{t+1}} + \left[w_t h_{St} - c_{St} + \varpi_S \frac{\log c_{St} + \psi_S \log(1-h_{St})}{\lambda_t} - p_{It}\frac{\mu_{St}}{\lambda_t} + p_{It}\frac{\mu_{It}}{\lambda_t} \right] \quad (20)$$

where:

$$p_{It} = \varkappa_h(h_{St})(n_I h_I) + \varkappa_c(c_{St})(n_{It} c_{It})$$

denotes the probability that an S agent contracts the virus when interacting with I agents.

This condition states that the social value of an S agent, which can be expressed as μ_S/λ, depends on two terms. First, as any asset pricing formula, the value of an S agent today is given by its expected discounted value next period. Since S agents do not leave this group for reasons other than contagion, the discounted expected value is given by the term $\beta E_t \frac{\lambda_{t+1}}{\lambda_t}\frac{\mu_{St+1}}{\lambda_{t+1}}$, where $\beta\lambda_{t+1}/\lambda_t$ denotes the stochastic discount factor of the social planner. This term is akin to the capital gain component in asset pricing models.

The second component, which corresponds to the term in brackets in the right-hand side of equation (20), reflects the marginal gain for the social planner of a marginal increase in the number of S agents in the economy. This gain firstly depends on the difference between the marginal productivity of the agent and what he or she consumes, i.e. $w_t h_{St} - c_{St}$. If this agent consumes more than his or her contribution to production, the effect is negative. The second term inside the bracket is the utility derived by an S agent, which is expressed in euros by dividing by marginal utility. The higher the individual utility derived by an S agent, the higher the social value of a marginal increase in the number of S agents.

The third term, i.e. $p_I\mu_S/\lambda$, reflects the risk of contagion of an S agent on his or her social value. Indeed, with probability p_I, an S agent catches the virus during the period and becomes infected. This risk of contagion negatively affects the social benefit of a marginal increase in the number of S agents. Contagion risk therefore reduces the value of an S agent.

Finally, since an S agent becomes infected with probability p_I, his or her social value also depends on the social value of an I agent, which is denoted by μ_I/λ. The final term on the right-hand side of equation (20) therefore represents the contribution of an S agent who becomes infected in the current period, an event which occurs with probability p_I.

The social value of I agents, which we denote by μ_I/λ can be characterized by the optimality condition with respect to n_I :

$$\frac{\mu_{It}}{\lambda_t} = \beta E_t \frac{\lambda_{t+1}}{\lambda_t}\frac{\mu_{It+1}}{\lambda_{t+1}}(1-p_R-p_D) + \beta E_t \frac{\lambda_{t+1}}{\lambda_t}\frac{\mu_{Rt+1}}{\lambda_{t+1}} p_R + \frac{\mu_{It}}{\lambda_t} p_{Tt} - \frac{\mu_{St}}{\lambda_t} p_{Tt} \quad (21)$$
$$+ [w_t h_{It} - c_{It}] + \varpi_I \frac{(\log c_{It} + \psi_I \log(1-h_{It}))}{\lambda_t}$$

where:

$$p_{Tt} = \varkappa_h (n_{St} h_{St})(h_{It}) + \varkappa_c (n_{St} c_{St})(c_{It})$$

denotes the probability that an I agent transmits the disease to S agents.

Relative to the condition obtained for S agents, the first main difference is that the continuation value, which is the first term in the right-hand side of equation (21), depends on the fraction of agents that will leave this group next period. Indeed, each period, individuals belonging to the group of I agents recover from and succumb to the disease with probability p_R and p_D, respectively.

The next term reflects the contribution of agents that recovered in the previous period to the current value of I agents. The value of an R agent, which is denoted by μ_R/λ, is multiplied by the fraction of agents who recovered in period t. This term is discounted using the stochastic discount factor of the social planner.

From the perspective of an I agent, the individual probability of infecting an S agent is denoted by p_T. The term $p_T \mu_I/\lambda$ reflects the contribution of agents that are infected within the period. By interacting in shopping malls or at work with S agents, each I agent contributes to increase the total number of I agents. Hence, whereas p_R and p_D measure the effect of agents that leave group I on the valuation, p_T reflects the impact of new entrants.

Since new infections reduce the number of S agents, the social value of I agents also needs to reflect the negative effect on society of an increase in new infections. This is the last term in the first line of equation (21). With probability p_T an I agent transmits the virus to an S agent, which reduces the number of healthy individuals in the economy.

The last two terms on the second line of equation (21) have an interpretation similar to that discussed for equation (20). The value of an I agent is higher if his of her marginal contribution to production exceeds the resources that he or she consumes. Finally, the marginal benefit of increasing the number of I agents is determined by the utility of this agent in the current period, which is expressed in euros by dividing by marginal utility.

4.1 The COVID shock in the first-best allocation

To ensure comparability, we calibrate the first-best equilibrium to ensure that the steady state under the optimal allocation is the same as that in the decentralized equilibrium. Relative to the calibration discussed in Section 3, this is firstly achieved by keeping all parameter values unchanged. However, since the optimality conditions differ, the labor supply parameters ψ_S, ψ_I, and ψ_R will need to be adjusted to ensure that S, I, and R agents allocate 20%, 10%, and 20% of their time, respectively, to remunerated work-related activities. Given the log separable specification that we use, these parameters however only play a marginal role.[3]

Relative to the laissez-faire equilibrium, the fact that markets are complete in the efficient equilibrium also modifies the repartition of steady state consumption across types, an implication which greatly complicates comparisons. To address this issue, we add three weight parameters, which we denote by ϖ_S, ϖ_I, and ϖ_R. These parameters measure the relative importance assigned to each type of agent by the planner. We calibrate these parameters to ensure that steady state consumption of all three types of agents in the first-best and laissez-faire equilibriums are equal.[4]

Response to the COVID shock in the laissez-faire and first-best allocations

To facilitate comparisons with the laissez-faire case, Figure 3 firstly reports the impulse responses of output, consumption, and hours worked of S agents as well as investment that we obtained in the previous section, and which is depicted by the blue continuous line. In Figure 3, the green line with diamonds shows the response to the exact same shock but under the first-best allocation.

As shown in the upper left panel of Figure 3, it is striking to see that a social planner chooses an allocation that essentially eliminates all fluctuations in output. This contrasts with the sharp recession obtained under laissez-faire. Investment as well as hours worked of S agents also remain almost constant in the first-best allocation. This striking result demonstrates that the fluctuations induced by epidemics are highly inefficient. Indeed, once all the different externalities inherent to these types of models are eliminated, business cycle fluctuations essentially disappear.

Figure 4 illustrates that the inefficiency essentially stems from the contagion externality. Indeed, under laissez-faire, I agents do not take into account that they can transmit the

[3]For the calibration discussed in Section 3, these 3 parameters are always strictly positive.

[4]These 3 parameters are also strictly positive for the first-best allocation that reproduces this steady state distribution of consumption across agents.

disease to S agents when they work or consume, as noted earlier. In contrast, the social planner perfectly integrates this externality. Whereas consumption of I agents increases under laissez-faire, the planner finds it optimal to reduce it sharply when the shock hits. As shown by the right panel of Figure 4, the second major difference is that hours worked by I agents decline on impact while labor effort remains constant in the competitive equilibrium.

The consumption of I agents also declines by a much smaller magnitude than the number of hours that they work. This disconnect between hours and consumption illustrates that there is perfect insurance in the first-best allocation. Marginal utilities are equalized across agents and the planner can choose to allocate output between consumption of the different agents irrespective of individual labor efforts.

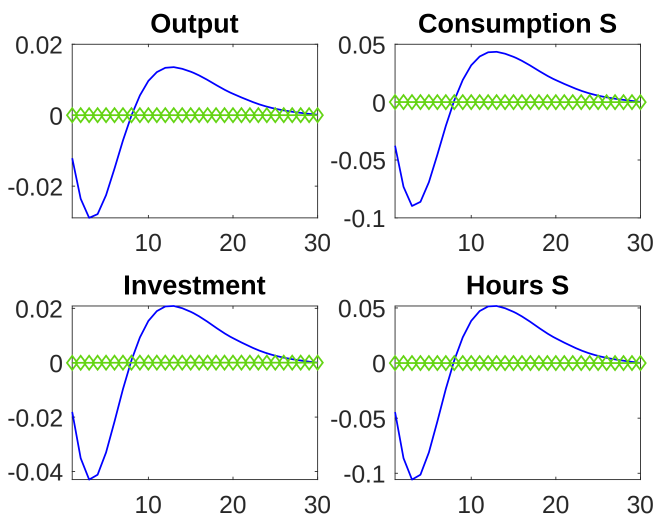

Figure 3. x axis: quarters after the shock. y axis: log deviation from steady state. Laissez-faire vs. social planner.

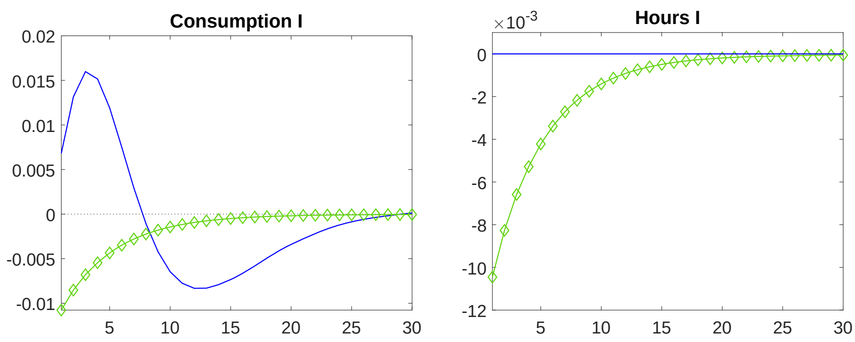

Figure 4. x axis: quarters after the shock. y axis: log deviation from steady state. Laissez-faire vs. social planner.

4.2 The case of technology shocks

In this subsection, we compare the allocation obtained in the laissez-faire equilibrium with the first-best allocation in the case of technology shocks. Relative to the calibration discussed in Section 3, the only difference is that we introduce shocks to total factor productivity and remove the COVID shock. The process for total factor productivity (TFP) is given as follows:

$$\log A_t = \rho_A \log A_{t-1} + \varepsilon_{At}$$

where ε_{At} is an iid innovation that is normally distributed with mean 0 and standard deviation $std(\varepsilon_{At})$. We set the standard deviation of the technology shock to 0.002 (e.g. King and Rebelo, 1999) and the persistence parameter ρ_A to 0.95, which are standard values in the real business cycle literature. To ensure comparability with the baseline representative agent real business cycle model, we define total consumption and total hours worked as follows:

$$c_{Tt} = n_{It}c_{It} + n_{St}c_{St} + n_{Rt}c_{Rt} + c_{Et}$$

$$h_{Tt} = n_{It}h_{It} + n_{St}h_{St} + n_{Rt}h_{Rt}$$

Figure 5 compares the impulse responses to a positive technology shock obtained in the laissez-faire and first-best economies. The competitive equilibrium corresponds to the continuous blue line, whereas the planner's problem is depicted by the green line with diamonds.

In contrast to what is observed in response to a COVID shock, the planner chooses to amplify the effect of technology shocks on output. Indeed, as can be seen in the upper left panel of Figure 5, under the first-best equilibrium, the increase in output is substantially higher than in the competitive equilibrium. Relative to the first-best case, the presence of contagion externalities therefore dampens the effects of technology shocks on output, and output is substantially more volatile when the planner is able to offset all market failures. This result illustrates that the first-best policy does not necessarily imply a decline in output volatility. From a welfare perspective, whether fluctuations are excessive critically depends on the source of shocks.

As illustrated in the upper right panel of Figure 5, under laissez-faire, consumption increases on impact and then declines. Under the optimal policy, by contrast, the response of consumption is hump-shaped and increases on impact before gradually declining as in a textbook real business cycle model.

The response of investment and aggregate hours worked are depicted in the lower panels of Figure 5. Under the optimal policy, investment is about 3 times as volatile as output. The response of aggregate hours worked is also very similar to that obtained in the textbook real business cycle model. Under laissez-faire, contagion risk acts as a tax on labor supply and hours worked fall in response to a positive technology shock.

The fluctuations of investment are also of a much lower amplitude under laissez-faire. This explains why consumption is so volatile in the competitive equilibrium. Indeed, without a strong contribution of the investment margin, consumption smoothing is more difficult to achieve.

A small trade-off between health and the economy emerges if technology shocks are the main driving force

Relative to the case of a COVID shock, a crucial difference is that the planner is willing to tolerate an increase in new infections in response to a positive technology shock. This point is illustrated in Figure 6, which compares the dynamics of infections n_I in the two scenarios. As depicted by the green line with diamonds, the positive technology shock leads to an increase in the number of infected agents under the first-best allocation.

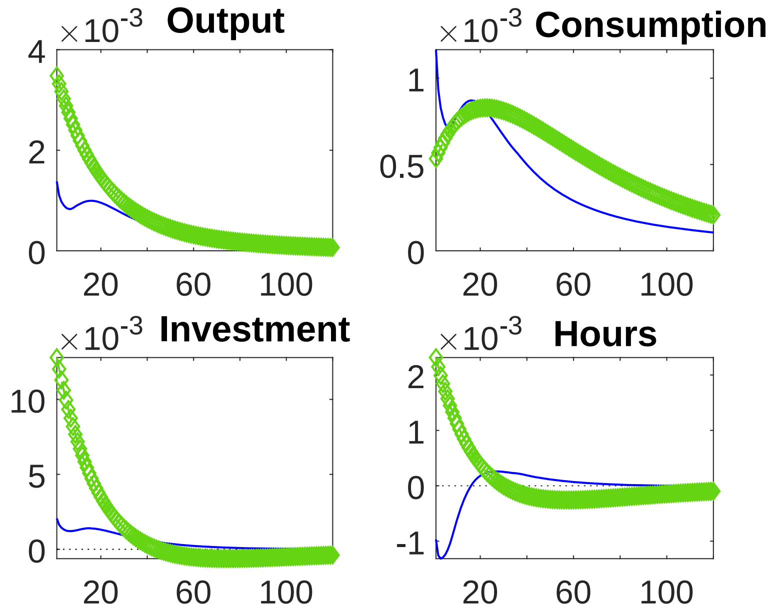

Figure 5. Impulse response of output, aggregate consumption, investment, and hours worked to a positive technology shock.

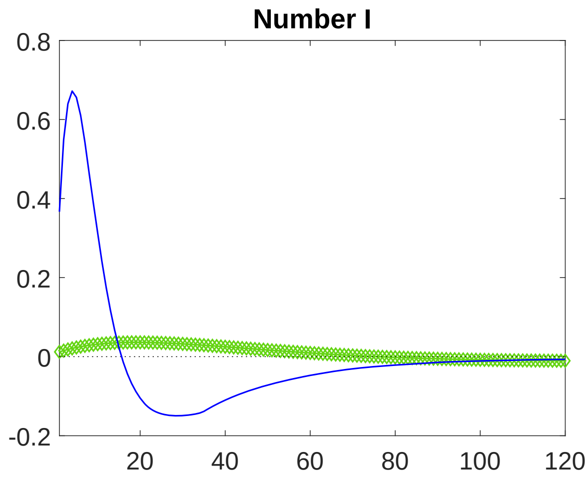

Figure 6. Impulse response of new infections n_I to a positive technology shock in the decentralized and first-best equilibriums.

Although the technology shock follows a standard autogressive dynamics, the infection peak is only reached after around 20 quarters. The hump-shaped dynamics of n_I also illustrates that the dynamics of new infections is strongly influenced by the model's endogenous propagation mechanism. Although in this case the shock has no direct effect on new infections, relative to steady state, the maximum increase in newly infected individuals exceeds 3%.

The main takeaway is therefore that it can be optimal in this environment to tolerate an increase in fatalities because of economic considerations. Indeed, despite the presence of contagion risk, the planner finds it optimal to increase the aggregate number of hours worked and consumption in response to a positive technology shock. At the same time, as can be seen by comparing the continuous blue line and the green line with diamonds in Figure 6, the increase in new cases is of several orders of magnitude smaller in the first-best allocation.

5 Second-best policies

One main issue with the first-best equilibrium discussed in Section 4 is that such an allocation is of course very difficult to implement in practice. Indeed, one implicit assumption is that the social planner is able to distinguish infected from healthy individuals. In reality, types are unobservable and individuals may carry and unintentionally transmit the disease. A more realistic assumption is to assume that the government needs to enlist agents into the same confinement policy implementation, without the possibility to distinguish infected from healthy individuals.

5.1 The zero COVID strategy

To address this concern, this subsection studies an economy in which the government can choose to confine workers at home by imposing a tax on labor supply. The objective is to evaluate the zero COVID strategy followed by some countries. We then calibrate our model to approximate the response of the Australian economy to the COVID shock.

Since types are unobservable, the tax is uniformly applied to all agents in the economy. Consequently, relative to the decentralized equilibrium discussed in Section 2, the difference is that workers are subject to a tax levied by the government. This tax, which we denote by τ^L, captures the effect of a lockdown that prevents agents from working. In the lockdown equilibrium, the budget constraint of S, I, and R agents is given as follows:

$$(1-\tau_t^L)w_t h_{jt} + tr_{jt} = c_{jt}$$

where the subscript j stands for S, I, and R. To best approximate the effect of a lockdown, we abstract from wealth effects by assuming that the government compensates workers by returning the tax at the end of the period in the form of a lump-sum transfer. Transfers are chosen to exactly offset the effect of the tax so that:

$$tr_{jt} = \tau_t^L w_t h_{jt}$$

Consequently, the policy reduces the incentive to work but without causing any direct income effect. The tax however does distort labor supply decisions by causing a negative substitution effect. In the laissez-faire equilibrium with lockdown policies, the optimality conditions with respect to labor for S, I, and R agents are therefore given as follows, respectively:

$$\psi_S \frac{1}{1-h_{St}} = \lambda_{St} w_t (1-\tau_t^L) - \eta_t \varkappa_h (n_{It} h_{It}) \tag{22}$$

$$\psi_I \frac{1}{1-h_{It}} = \lambda_{It} w_t (1-\tau_t^L) \tag{23}$$

$$\psi_R \frac{1}{1-h_{IR}} = \lambda_{Rt} w_t (1-\tau_t^L) \tag{24}$$

To approximate the zero COVID strategy, we assume that the government sets the tax rate τ^L such as to minimize the number of new infections. Given the dynamics of new infections, which is given by equation (17), it is possible to find a trajectory for the policy instrument that completely offsets the effect of an epidemic shock on new infections. Indeed, since an increase in τ^L reduces the incentive to work, the policy counteracts the effect of the exogenous increase in new infections by reducing hours worked and consumption.

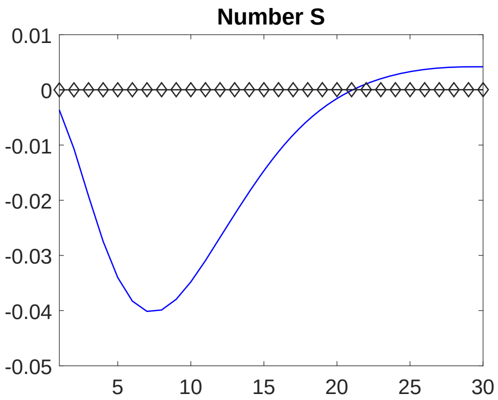

Figure 7. Impulse response of susceptible agents n_S in deviations from steady state.

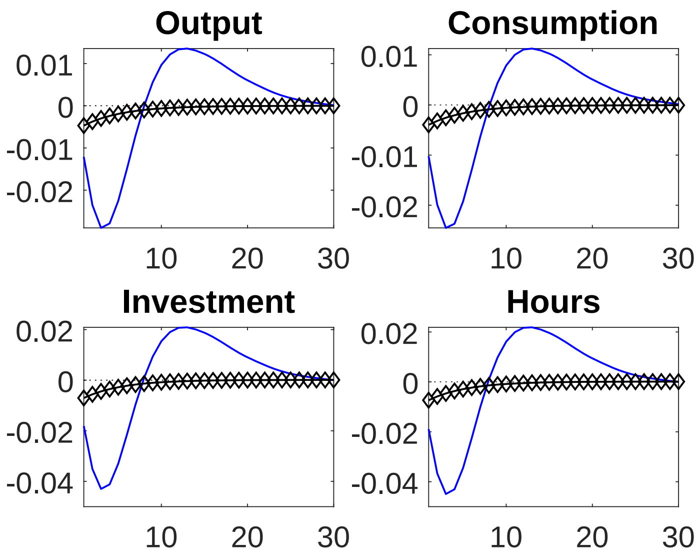

Figure 8. Impulse response of output, consumption, investment, and hours to a COVID shock.

The difference in the dynamics of infection is illustrated in Figure 7, which compares the number of susceptible agents in the laissez-faire equilibrium with the zero COVID strategy. Under laissez-faire, as depicted by the continuous blue line, since the number of infections increases, the number of susceptible agents declines by about 4% at the peak of the crisis. In contrast, under the zero COVID strategy, the government is able to engineer a reduction in activity that is sufficient to completely absorb the effect of the epidemic shock. Consequently, and as shown by the black diamonds in Figure 7, the number of newly infected agents as well as the number of healthy individuals remain constant under the zero COVID strategy.

Figure 8 compares the response of output, aggregate consumption, investment, and aggregate hours worked to the COVID shock under the two scenarios. Interestingly, our simulations suggest that the zero COVID strategy, which allows the authorities to avoid fatalities, only comes at the cost of a mild recession, at least compared to that obtained under laissez-faire. In the context of this model, there is therefore not a clear trade-off between saving lives and preserving the economy. Reacting quickly to an increase in new infections by imposing lockdowns not only eradicates the virus, it also leads to a much smaller recession than under laissez-faire.

The case of Australia

Next, we use our model to provide an estimate of the tax τ_L that the government would need to impose to implement the zero COVID strategy. This is achieved by selecting a sequence for the exogenous shock $\log \varsigma_t$ and a value for the persistence parameter ρ_ς that reproduce the dynamics of output observed in Australia from the second quarter of 2020 to the first quarter of 2021. We then assume that the government does "whatever it takes" to avoid fatalities by setting the tax τ_L to the level required to completely eliminate contagion.

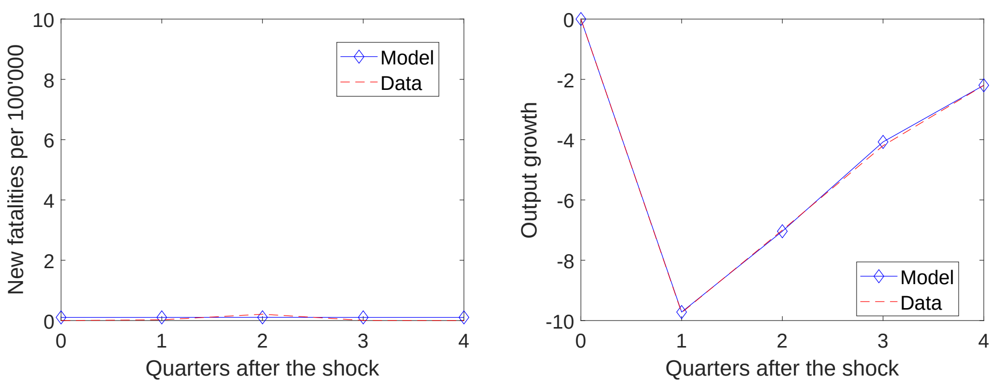

Figure 9. Left panel: New fatalities $p_D n_I$ per 100,000 inhabitants. Right panel: Year-over-year output growth in deviation from long-term mean

The outcome of this empirical exercise is shown in Figure 9. The left panel shows new fatalities per 100,000 inhabitants in both the model and in the data. As illustrated by the red dashed line, Australia managed to keep the number of new fatalities to a remarkably low number, especially in comparison to most other OECD economies (see Figure 1). In euro area countries such as France, for example, this number exceeded 30 at the height of the health crisis, whereas it hovered around zero in Australia. The difference between the model (see the continuous blue line with diamonds) and the data in the left panel of Figure 9 is also very small. This therefore suggests that the zero COVID rule, which implies a value for the instrument τ_L ensuring that n_I remains constant, is a reasonable approximation in the case of Australia.

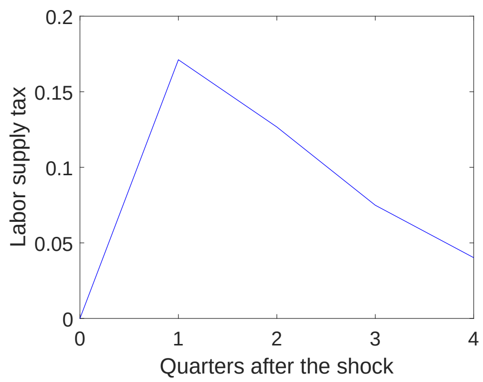

Figure 10. Level of the tax τ_L required to achieve zero infection.

The right panel of Figure 9 compares the dynamics of output growth both in the model and in the data, where output is expressed in deviation from its long-term value. It is possible to find a sequence of shocks that allows us to perfectly match the magnitude of the fall in output observed during this period.

The level of the policy instrument τ_L that implements the zero COVID strategy is shown in Figure 10. When the shock hits, the government needs to raise the tax on labor supply from 0 to 17%. This swift reaction completely offsets the effect of the shock on new infections. It is then possible to lower the tax from 17% down to 13% two periods after the shock hit and to 7% and 4%, respectively, in the subsequent periods, without causing any increase in new cases.

5.2 Compulsory testing

In the decentralized equilibrium, one main source of inefficiency is that the same wage rate is paid to both sick and healthy workers. Indeed, from the perspective of an entrepreneur, hours worked of S, I, and R agents are perfect substitutes. Entrepreneurs do not interact with I agents. Consequently, they have no incentive to undertake costly measures to reduce the risk of contagion in the workplace.

One possible solution to address this issue is to impose financial sanctions on firms that employ sick workers. This measure implicitly assumes that a testing technology able to detect the virus is sufficiently well developed and available. In Europe, the evidence suggests that such a solution is indeed feasible in practice. For example, in Germany, compulsory testing was introduced in schools in April 2021. Antigen tests are also required to check in at hotels since the Summer of 2021.

How could this strategy be implemented in practice? One possibility would be to organize random testing of a sample of workers in each firm. If the virus is detected, all workers are tested and a financial sanction proportional to the number of infected workers is imposed. Since the probability of being fined remains small, the sanction should be sufficiently dissuasive. For example, the fine f could take the following form:

$$f_t = \kappa \frac{1}{2} \left(n_{It} h_{It}\right)^2$$

where κ is a parameter that determines the severity of the penalty as well as the probability of being caught. To simplify matters, let us also assume that entrepreneurs receive a transfer tr from the government at the end of the period that offsets the effect of the penalty. Under this scenario, the budget constraint of entrepreneurs is as follows:

$$\begin{aligned} c_{Et} &= a k_{t-1}^{\alpha} (n_{It} h_{It} + n_{St} h_{St} + n_{Rt} h_{Rt})^{1-\alpha} + tr_t \\ &\quad - w_{It} n_{It} h_{It} - w_{St} n_{St} h_{St} - w_{Rt} n_{Rt} h_{Rt} - (k_t - (1-\delta) k_{t-1}) - \kappa \frac{1}{2} \left(n_{It} h_{It}\right)^2 \end{aligned}$$

Relative to the laissez-faire case, the key difference is that this measure introduces a difference in remuneration across agents. Indeed, under financial sanctions, the demand for I workers is given as follows:

$$w_{It} = (1-\alpha) \frac{y_t}{n_{It} h_{It} + n_{St} h_{St} + n_{Rt} h_{Rt}} - \kappa n_{It} h_{It}$$

whereas that for S agents is unchanged:

$$w_{St} = (1-\alpha) \frac{y_t}{n_{It} h_{It} + n_{St} h_{St} + n_{Rt} h_{Rt}}$$

To ensure that the measure is sufficiently dissuasive, we choose a value for κ implying a financial sanction that represents on average 1% of production. Figure 11 compares the response of output, consumption, investment, and hours worked obtained under financial sanctions with the laissez-faire case.

Clearly, imposing financial sanctions helps to alleviate the effects of a COVID shock on the economy. The key is that the penalty reduces the demand for hours worked of I agents. This lower demand puts downward pressure on wages, an effect which in turn reduces the consumption of I agents and hence contagion risk in the economy.

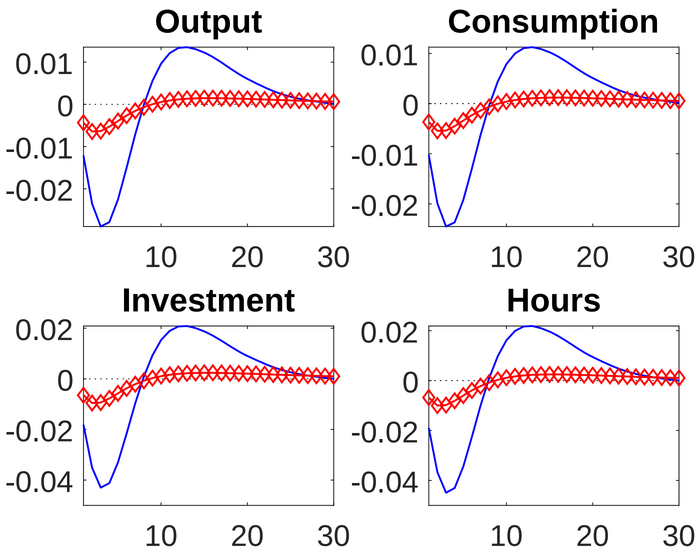

Figure 11. Impulse response of output, consumption, investment, and hours to a COVID shock.

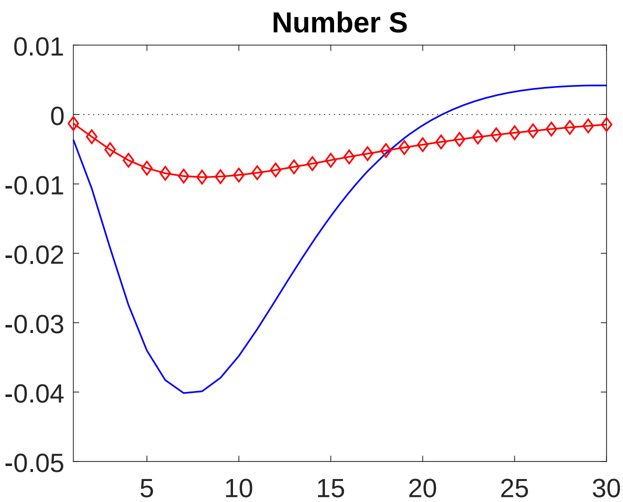

Figure 12. Impulse response of susceptibles n_S in deviations from steady state.

As illustrated in Figure 12, this measure also substantially reduces the death toll from the epidemic. The dotted red line shows the evolution of S agents under financial sanctions, whereas the continuous blue line is the response obtained under laissez-faire. If a testing technology is available, introducing financial sanctions forces firms to identify infected workers. This financial threat reduces the demand for I workers, which in turn lowers the wage received by these agents. This decline in wage also lowers the consumption of I agents, an effect which reduces contagion risk and hence fatalities.

6 Risk sharing

In the decentralized equilibrium, besides the contagion externality, another major distortion is the presence of market incompleteness. Indeed, whereas the social planner chooses to equalize marginal utilities across agents, risk is imperfectly shared under laissez-faire. To illustrate the quantitative importance of this distortion, we next study the case of redistributive policies. The objective of this experiment is to evaluate the merits of measures akin to health insurance on the transmission of an epidemic shock.

This is achieved by introducing a tax on S agents that is used to finance a transfer to I agents. Under risk sharing, the budget constraint of an S agent is therefore given as follows:

$$(1 - \tau_t^L) w_t h_{St} = c_{St}$$

The difference between a lockdown policy and health insurance is that the effect of the tax on agents' income is not offset by a transfer. In this case, the tax therefore induces both a substitution as well as an income effect. The revenue raised by the government is then redistributed to I agents, whose budget constraints become:

$$w_t h_{It} + tr_t = c_{It}$$

where:

$$tr_t = \tau_t^L w_t h_{St}$$

Since the objective of this experiment is to eliminate the distortion due to market incompleteness, the idea is to set the tax τ_t^L so as to equalize the marginal utilities of S and I agents. However, since eliminating this distortion would modify the steady state of the model, we assume that the tax is equal to zero on average. This is to ensure that the introduction of this redistributive policy does not modify the steady state of the model. Risk sharing is therefore only partial in the sense that the policy does not imply permanent transfers between agents. The tax only affects the transitional dynamics.

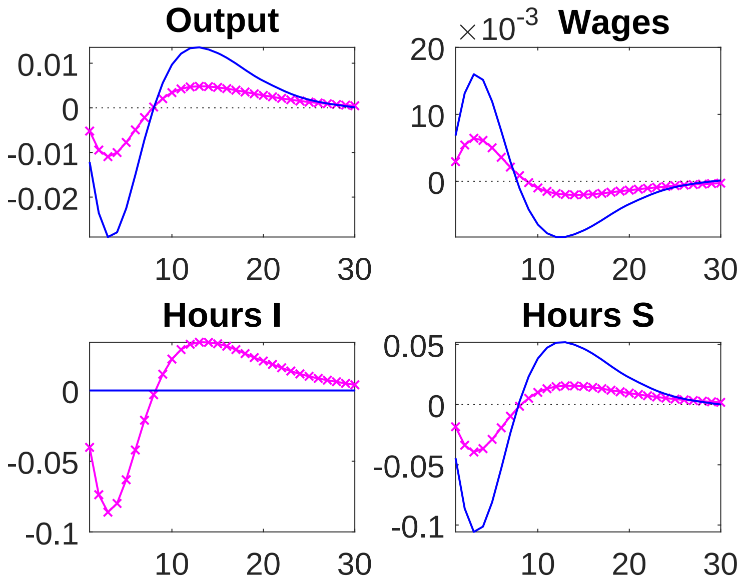

Figure 13. Impulse response of output, wages, hours worked of infected and susceptible agents to a COVID shock.

Under partial risk sharing, the marginal utility of an I agent is therefore proportional to that of an S, and we have that:

$$\lambda_{It} = \vartheta \lambda_{St}$$

where ϑ is the risk sharing parameter, which is calibrated so that the level of the tax τ^L is equal to zero in the steady state.

The difference between the laissez-faire and the partial risk sharing equilibriums in response to an epidemic shock is shown in Figure 13. As illustrated by the top left panel, providing insurance to I agents by taxing S agents substantially reduces the magnitude of the recession, where the adjustment under partial risk sharing is depicted by the crossed purple line. With insurance, the key is that infected agents can afford to reduce hours worked once contaminated. Indeed, as depicted by the lower left panel, hours worked by I agents decline substantially under partial risk sharing, while they remain constant under laissez-faire.

As the lower right panel demonstrates, the key is that the policy reduces the fall in hours worked by S agents. This effect is due to two reasons. First, since I agents cut hours worked, the insurance provided by the policy reduces the risk of catching the virus while working. Relative to the decentralized equilibrium, the insurance policy therefore reduces the implicit tax on labor supply induced by contagion risk.

Second, since the effect of the tax is not offset by a transfer, the measure reduces the revenue of S agents. The resulting negative wealth effect stimulates hours worked and therefore contributes to reduce the fall in hours worked that occurs under laissez-faire. Since the policy attenuates the aggregate fall in hours worked, and as shown by the top right panel, the increase in labor productivity is more muted under partial risk sharing.

7 Conclusion

The main takeaway from this article is that the trade-off between health and the economy critically depends on the extent to which the probability of contagion can be controlled by agents. If contagion is mainly related to economic choices, the type of mitigation policies discussed in this article can be very efficient. In this case, policies primarily aimed at saving lives also safeguard the economy. In contrast, in a model in which a significant fraction of new contagion occurs irrespectively of economic activity, as shown by ERT (2021), containment policies can substantially aggravate epidemic-induced recessions.

It is important to note that this paper focuses on the early stage of the COVID crisis and does not take into account the effect of vaccination. The reason is that in many euro area countries vaccines only became gradually available about one year after the outbreak of the pandemic. Moreover, once a vaccine is available and doses are in sufficient supply, vaccinating the entire population is a lengthy process. The emergence of new variants may also affect the calibration and hence the magnitude of the trade-off.

The analysis also remains stylized as our objective is to study this trade-off in the simplest possible business cycle model. Introducing nominal rigidities, financial frictions, or a realistic account of the health care system, for example, would be valuable extensions.

The degree of openness of an economy could also play a critical role. A stronger trade-off could for instance arise in economies that are particularly reliant on the travel and leisure industry. In highly integrated economies, such as the ones forming the euro area, the issue of coordination between countries could also play a critical role. Indeed, the trade-off between health and the economy could significantly deteriorate if lockdown policies across countries are not sufficiently well coordinated.

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8 Appendix A

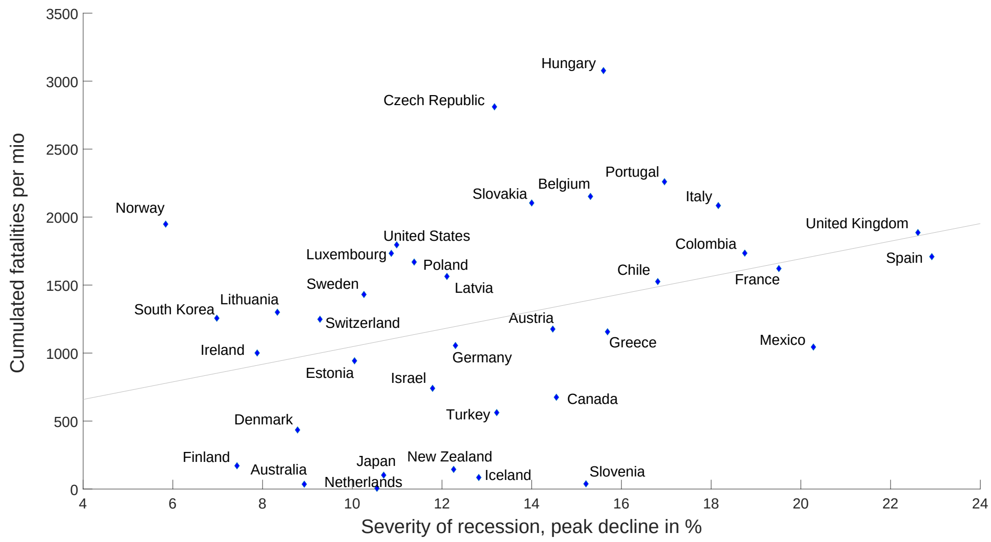

Chart A.1. x axis: Peak decline during COVID crisis relative to long-term trend. y axis: Cumulated fatalities per 1 mio inhabitants. Source: OECD and Oxford University.

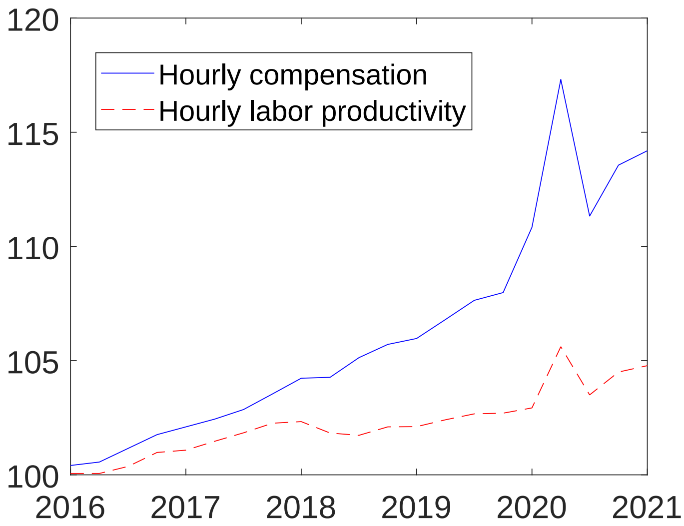

Chart A.2. Hourly compensation and hourly labor productivity during the COVID crisis in the euro area. Source: ECB Table 5.1.4.

9 Technical appendix (not for publication)

9.1 Decentralized equilibrium

Recovered agents

$$v_{Rt} = \log c_{Rt} + \psi_R \log(1 - h_{Rt}) + \beta E_t (1 - \phi) v_{Rt+1}$$

Budget constraint:

$$w_{Rt} h_{Rt} = c_{Rt}$$

Problem of recovered agent:

$$v_{Rt} = \max_{c_{Rt}, h_{Rt}} \left\{ \log c_{Rt} + \psi_R \log(1 - h_{Rt}) + \beta E_t v_{Rt+1} + \lambda_{Rt} \left[w_{Rt} h_{Rt} - c_{Rt} \right] \right\}$$

First-order conditions:

$$\frac{1}{c_{Rt}} = \lambda_{Rt}$$

$$\psi_R \frac{1}{1 - h_{Rt}} = \lambda_{Rt} w_{Rt}$$

$$w_{Rt} h_{Rt} = c_{Rt}$$

Susceptible agents

$$v_{St} = \log c_{St} + \psi_S \log(1 - h_{St}) + \beta E_t \left[p_{It} v_{It+1} + (1 - p_{It}) v_{St+1} \right]$$

Budget constraint:

$$w_{St} h_{St} = c_{St}$$

Probability of being infected:

$$p_{It} = \varkappa_h h_{St} (n_{It} h_{It}) + \varkappa_c c_{St} (n_{It} c_{It})$$

Problem of susceptible agent:

$$v_{St} = \max_{c_{St}, h_{St}, p_{It}} \left\{ \begin{array}{c} \log c_{St} + \psi_S \log(1 - h_{St}) + \beta E_t \left[p_{It} v_{It+1} + (1 - p_{It}) v_{St+1} \right] \\ + \lambda_{St} \left[w_{St} h_{St} - c_{St} \right] + \eta_t \left[p_{It} - \varkappa_h h_{St} (n_{It} h_{It}) - \varkappa_c c_{St} (n_{It} c_{It}) \right] \end{array} \right\}$$

First-order conditions:

$$\frac{1}{c_{St}} = \lambda_{St} + \eta_t \varkappa_c (n_{It} c_{It})$$

$$\psi_S \frac{1}{1 - h_{St}} = \lambda_{St} w_{St} - \varkappa_h \eta_t (n_{It} h_{It})$$

$$\eta_t = \beta E_t \upsilon_{St+1} - \beta E_t \upsilon_{It+1}$$

$$w_{St} h_{St} = c_{St}$$

$$p_{It} - \varkappa_h h_{St} (n_{It} h_{It}) - \varkappa_c c_{St} (n_{It} c_{It}) = 0$$

Infected agent

$$\upsilon_{It} = \log c_{It} + \psi_I \log(1 - h_{It}) + \beta E_t \left[(1 - p_R - p_D) \upsilon_{It+1} + p_R \upsilon_{Rt+1} \right]$$

Problem of infected agent:

$$\upsilon_{It} = \max_{c_{It}, h_{It}} \left\{ \begin{array}{c} \log c_{It} + \psi_I \log(1 - h_{It}) + \beta E_t \left[(1 - p_R - p_D) \upsilon_{It+1} + p_R \upsilon_{Rt+1} \right] \\ + \lambda_{It} \left[w_{It} h_{It} - c_{It} \right] \end{array} \right\}$$

Budget constraint:

$$w_t h_{It} = c_{It}$$

First-order conditions:

$$\frac{1}{c_{It}} = \lambda_{It}$$

$$\frac{\psi_I}{1 - h_{It}} = \lambda_{It} w_{It}$$

$$w_{It} h_{It} = c_{It}$$

Entrepreneurs

$$\upsilon_{Et} = \log c_{Et} + \beta E_t \upsilon_{Et+1}$$

$$c_{Et} = ak_{t-1}^{\alpha}(n_{It}h_{It} + n_{St}h_{St} + n_{Rt}h_{Rt})^{1-\alpha} - n_{It}w_{It}h_{It}$$
$$-n_{St}w_{St}h_{St} - n_{Rt}w_{Rt}h_{Rt} - (k_t - (1-\delta)k_{t-1})$$

The problem:

$$\upsilon_{Et} = \max_{\substack{c_{Et},k_t,h_{It},\\ h_{Rt},h_{St}}} \left\{ \begin{array}{c} \log c_{Et} + \beta E_t \upsilon_{Et+1} \\ +\lambda_{Et} \left[\begin{array}{c} ak_{t-1}^{\alpha}(n_{It}h_{It} + n_{St}h_{St} + n_{Rt}h_{Rt})^{1-\alpha} \\ -n_{It}w_{It}h_{It} - n_{St}w_{St}h_{St} \\ -n_{Rt}w_{Rt}h_{Rt} - (k_t - (1-\delta)k_{t-1}) - c_{Et} \end{array} \right] \end{array} \right\}$$

First-order conditions:

$$\frac{\partial \upsilon_{Et}}{\partial k_{t-1}} = \lambda_{Et}\left[\alpha \frac{y_t}{k_{t-1}} + (1-\delta)\right]$$

$$w_{It} = (1-\alpha)\frac{y_t}{n_{It}h_{It} + n_{St}h_{St} + n_{Rt}h_{Rt}}$$

$$w_{Ht} = (1-\alpha)\frac{y_t}{n_{It}h_{It} + n_{St}h_{St} + n_{Rt}h_{Rt}}$$

$$w_{Rt} = (1-\alpha)\frac{y_t}{n_{It}h_{It} + n_{St}h_{St} + n_{Rt}h_{Rt}}$$

$$c_{Et} = a_t k_{t-1}^{\alpha}(n_{It}h_{It} + n_{St}h_{St} + n_{Rt}h_{Rt})^{1-\alpha} - n_{It}w_{It}h_{It}$$
$$-n_{St}w_{St}h_{St} - n_{Rt}w_{Rt}h_{Rt} - (k_t - (1-\delta)k_{t-1})$$

$$\frac{1}{c_{Et}} = \lambda_{Et}$$

Envelope condition:

$$\lambda_{Et} = \beta E_t \frac{\partial \upsilon_{Et+1}}{\partial k_t}$$

Law of motion types

$$n_{It} = (1 - p_R - p_D)\, n_{It-1} + p_{It} n_{St} + \log \varsigma_t$$

$$n_{St} = n_{St-1} + b - p_{It} n_{St} - \log \varsigma_t$$

$$n_{Rt} = (1-\phi) n_{Rt-1} + p_R n_{It-1}$$

Market clearing

$$y_t = n_{It} c_{It} + n_{St} c_{St} + n_{Rt} c_{Rt} + c_{Et} + k_t - (1-\delta) k_{t-1}$$

9.2 Centralized equilibrium

$$\mathcal{L} = E_0 \left\{ \sum_{t=0}^{\infty} \beta^t \left[\begin{array}{c} \varpi_S n_{St} \left(\log c_{St} + \psi_S \log(1-h_{St})\right) + \varpi_I n_{It} \left(\log c_{It} + \psi_I \log(1-h_{It})\right) \\ +\varpi_R n_{Rt} \left(\log c_{Rt} + \psi_R \log(1-h_{Rt})\right) + \log c_{Et} \end{array} \right] \right.$$

$$+ \sum_{t=0}^{\infty} \beta^t \lambda_t \left[\begin{array}{c} a k_{t-1}^{\alpha} (n_{It} h_{It} + n_{St} h_{St} + n_{Rt} h_{Rt})^{1-\alpha} \\ -n_{It} c_{It} - n_{St} c_{St} - n_{Rt} c_{Rt} - c_{Et} - k_t + (1-\delta) k_{t-1} \end{array} \right]$$

$$+ \sum_{t=0}^{\infty} \beta^t \mu_{St} \left[n_{St-1} + b - \varkappa_h (n_{St} h_{St})(n_{It} h_{It}) - \varkappa_c (n_{St} c_{St})(n_{It} c_{It}) - \log \varsigma_t - n_{St} \right]$$

$$+ \sum_{t=0}^{\infty} \beta^t \mu_{It} \left[(1 - p_R - p_D) n_{It-1} + \varkappa_h (n_{St} h_{St})(n_{It} h_{It}) + \varkappa_c (n_{St} c_{St})(n_{It} c_{It}) + \log \varsigma_t - n_{It} \right]$$

$$\left. + \sum_{t=0}^{\infty} \beta^t \mu_{Rt} \left[(1-\phi) n_{Rt-1} + p_R n_{It-1} - n_{Rt} \right] \right\}$$

First-order conditions

$$\varpi_S n_{St} \frac{1}{c_{St}} = \lambda_t n_{St} + \left[\mu_{St} - \mu_{It}\right] \varkappa_c (n_{St})(n_{It} c_{It})$$

$$\varpi_I n_{It} \frac{1}{c_{It}} = \lambda_t n_{It} + \left[\mu_{St} - \mu_{It}\right] \varkappa_c (n_{St} c_{St})(n_{It})$$

$$\varpi_R n_{Rt} \frac{1}{c_{Rt}} = n_{Rt} \lambda_t$$

$$\frac{1}{c_{Et}} = \lambda_t$$

$$\varpi_S n_{St}\frac{\psi_S}{1-h_{St}} = \lambda_t(1-\alpha)n_{St}\frac{y_t}{n_{It}h_{It}+n_{St}h_{St}+n_{Rt}h_{Rt}} - [\mu_{St}-\mu_{It}]\,\varkappa_h(n_{St})(n_{It}h_{It})$$

$$\varpi_I n_{It}\frac{\psi_I}{1-h_{It}} = \lambda_t(1-\alpha)n_{It}\frac{y_t}{n_{It}h_{It}+n_{St}h_{St}+n_{Rt}h_{Rt}} - [\mu_{St}-\mu_{It}]\,\varkappa_h(n_{St}h_{St})(n_{It})$$

$$\varpi_R n_{Rt}\frac{\psi_R}{1-h_{Rt}} = \lambda_t(1-\alpha)n_{Rt}\frac{y_t}{n_{It}h_{It}+n_{St}h_{St}+n_{Rt}h_{Rt}}$$

$$\lambda_t = \beta E_t\lambda_{t+1}(1-\delta) + \beta E_t\lambda_{t+1}\alpha\frac{y_{t+1}}{k_t}$$

$$\begin{aligned}
\mu_{St} &= \beta E_t\mu_{St+1} - \mu_{St}\left[\varkappa_h(h_{St})(n_I h_I) + \varkappa_c(c_{St})(n_{It}c_{It})\right] \\
&\quad +\mu_{It}\left[\varkappa_h(h_{St})(n_{It}h_{It}) + \varkappa_c(c_{St})(n_{It}c_{It})\right] \\
&\quad +\lambda_t\left[(1-\alpha)\frac{y_t}{n_{It}h_{It}+n_{St}h_{St}+n_{Rt}h_{Rt}}h_{St} - c_{St}\right] \\
&\quad +\varpi_S\left(\log c_{St} + \psi_S\log(1-h_{St})\right)
\end{aligned}$$

$$\begin{aligned}
\mu_{It} &= \beta E_t\mu_{It+1}\left(1-p_R-p_D\right) + \mu_{It}\left[\varkappa_h(n_{St}h_{St})(h_{It}) + \varkappa_c(n_{St}c_{St})(c_{It})\right] \\
&\quad -\mu_{St}\left[\varkappa_h(n_{St}h_{St})(h_{It}) + \varkappa_c(n_{St}c_{St})(c_{It})\right] \\
&\quad +\lambda_t\left[(1-\alpha)\frac{y_t}{n_{It}h_{It}+n_{St}h_{St}+n_{Rt}h_{Rt}}h_{It} - c_{It}\right] \\
&\quad +\beta E_t\mu_{Rt+1}p_R \\
&\quad +\varpi_I\left(\log c_{It} + \psi_I\log(1-h_{It})\right)
\end{aligned}$$

$$\begin{aligned}
\mu_{Rt} &= \beta E_t\mu_{Rt+1}(1-\phi) \\
&\quad +\lambda_t\left[(1-\alpha)\frac{y_t}{n_{It}h_{It}+n_{St}h_{St}+n_{Rt}h_{Rt}}h_{Rt} - c_{Rt}\right] \\
&\quad +\varpi_R\left(\log c_{Rt} + \psi_R\log(1-h_{Rt})\right)
\end{aligned}$$

$$ak_{t-1}^{\alpha}(n_{It}h_{It}+n_{St}h_{St}+n_{Rt}h_{Rt})^{1-\alpha} - n_{It}c_{It} - n_{St}c_{St} - n_{Rt}c_{Rt} - c_{Et} - k_t + (1-\delta)k_{t-1} = 0$$

$$n_{St-1} + b - \varkappa_h(n_{St}h_{St})(n_{It}h_{It}) - \varkappa_c(n_{St}c_{St})(n_{It}c_{It}) - \log\varsigma_t - n_{St} = 0$$

$$(1 - p_R - p_D)\, n_{It-1} + \varkappa_h (n_{St} h_{St})(n_{It} h_{It}) + \varkappa_c (n_{St} c_{St})(n_{It} c_{It}) + \log \varsigma_t - n_{It} = 0$$

$$(1 - \phi) n_{Rt-1} + p_R n_{It-1} - n_{Rt} = 0$$

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