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IMF Working Paper

The Great Lockdown: International Risk Sharing Through Trade and Policy Coordination

by Philipp Engler, Nathalie Pouokam, Diego Rodriguez Guzman, and Irina Yakadina

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APD, ICD, RES

The Great Lockdown: International Risk Sharing Through Trade and Policy Coordination¹

Prepared by Philipp Engler, Nathalie Pouokam, Diego Rodriguez Guzman , and Irina Yakadina

Authorized for distribution by Alison Stuart (APD), Norbert Funke (ICD), and Oya Celasun (RES)

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Abstract

Voluntary and government-mandated lockdowns in response to COVID-19 have caused causing drastic reductions in economic activity around the world. We present a parsimonious two-country-SIR model with some degree of substitutability between home and foreign goods, and show that trading partners' asynchronous entries into the global pandemic induce mutual welfare gains from trade. Those gains are realized through exchange rate adjustments that cause a temporary reallocation of production towards the economy with the lowest infection rate at any point in time. We show that international cooperation over containment policies that aim at optimizing global welfare further enhances the ability of countries to exploit trade opportunities to contain the spread of the pandemic. We characterize the Nash game of strategic choices of containment policies as a prisoners' dilemma.

JEL Classification: E1, F4, H0, I1

Keywords: Great Lockdown, epidemic, COVID-19, trade, optimal containment, cooperation, SIR macro model

Authors' E-Mail Addresses: PEngler@imf.org; NPouokam@imf.org; DRodriguezGuzman@imf.org; IYakadina@imf.org

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I. Introduction

Governments and individuals around the world reacted to the COVID-19 outbreak with massive lockdowns, causing the largest global recession since the Great Depression. The global and unprecedented nature of the COVID-19 pandemic which has been referred to as the "Great Lockdown" (see IMF2020a) is unarguable. It has affected almost all countries in the world and has led to an unparalleled economic fallout, with the largest fraction of world economies experiencing a decline in per capita output at one point in time since 1870.

In this paper, we devise a parsimonious epidemiological two-country macroeconomic model to study potential gains from international trade in the context of the Great Lockdown. Our model provides a stylized framework that illustrates two trade-offs at the heart of the policy making process underpinning governments' decisions in the face of a pandemic. Namely, a benevolent government that has to enforce containment policies to stop the virus spread is facing a choice between lives and livelihoods and, on top of this, a choice to cooperate or not to cooperate with trade partners to achieve the optimal timing and intensity of containment measures.

In our open-economy epidemiological model, governments' policies interplay with private agents' economic decisions to trace the course of the pandemic. Our model builds on the closed economy model of Eichenbaum, Rebelo and Trabandt (2020a), henceforth ERT (2020), to which we add a Nash game between a home government and a foreign government. Each government is committed to designing optimal containment responses to the pandemic that hits the foreign economy first and then spreads to the home country.

We describe a new mechanism in which terms of trade adjustments reflect differentials in infection rates and act as safety valves that allow to cushion the global impact of the pandemic. We demonstrate that when one country's infections are above those of the other country, the relative supply of its locally produced good plummets. This is driven by the decisions of individual agents to cut down on work hours in order to curb the risk of infection.

The safety valve channel works as follows: assuming that each country produces a single good and assuming a reasonable degree of substitutability between the home and the foreign goods, the rise in the relative price of the good of the most infected country leads to an expenditure switching effect towards the good of the least infected country. This results in a temporary production boost in the country that can afford to work more² without strongly increasing infections.

This new mechanism allows to cushion the pandemic-driven short-term drop in consumption in the two countries as they import more when their respective infection rates peak, which allows to save not only lives but also livelihoods. As our model is calibrated to a weekly frequency, it is best suited to understand the role of trade linkages which play through a temporary reduction of home production and an increase in imports during the most stringent containment phase, and through an increase in home production and exports during the recovery stage.

² For simplicity, we assume that each good is produced by a non-teleworkable sector.

In our model, the pandemic starts at different times across countries and spreads in each country through random encounters between susceptible and infected people while consuming domestic and imported goods, while working, and through contacts in the general community. Individuals try to reduce the risk of getting infected by cutting down on their work hours and consumption. Similar to ERT (2020), we assume that individuals do not fully internalize the impact of their consumption and labor supply decisions on the risk of infection for others, thus making the case for an optimal government containment policy to correct the infection externality. We model government policy responses to the pandemic as Pigouvian consumption taxes that are typically used to correct market failures.

We use our model to study cooperation vs. no cooperation between governments with respect to the optimal containment measure under the assumption of an asynchronous pandemic, and find that welfare gains from cooperation are sizeable relative to the laissez-faire outcome. Moreover, a new result emerges in our open-economy framework: relative to a no-policy scenario, global welfare-maximizing, cooperative containment policies increase welfare for both countries. In contrast, individual country level welfare-maximizing, non-cooperative containment policies reduce welfare both at home and abroad well below the no-policy scenario levels.

More specifically, we characterize the Nash game between the home and the foreign governments as a prisoners' dilemma in which each government has an incentive to improve its terms of trade in a beggar-thy-neighbor, or rather an implicit "infect-thy-neighbor" fashion. The underlying mechanism is that cooperation between governments enhances the market-driven terms of trade movements, which allows to shift production to the country with the lowest infection rate at any point in time.

We find that, in the absence of cooperation, when the most infected country envisages a containment policy that would drive its relative price up, the least infected country can optimally react with a much stronger containment policy than it would with cooperation. The absence of cooperation therefore prevents the relative price of the most infected country to move up as much as needed for global efficiency, resulting in suboptimally strong containment policies globally.

Finally, we test our model's predictions of a co-movement between exchange rates and infections against the data by providing cross-country evidence that the strongest declines in workplace mobility (we interpret those mobility declines as capturing infection peaks) during the COVID-19 pandemic on average were associated with a nominal exchange rate appreciation.

As with any model, our analysis abstracts from a number of potentially important features that might interfere with some of our findings. Among them are the absence of price and quantity rigidities and the role of global value chains. We also disregard any significant positive effect of strong containment policy in a foreign country and the associated lower infections from abroad, which could help the home country contain the outbreak more quickly, not least for the difficulty of the counterfactual in the real world of the pandemic.

The rest of the paper is organized as follows: section 2 provides a brief overview of the relevant strands of the literature; section 3 presents some stylized facts on the tendency of exchange

rates to appreciate around infection peaks. We then rationalize this finding in our two-country model in section 4, and then use the model to discuss the macroeconomic effects of a pandemic in section 5, and the normative implications of containment policies in section 6. Section 7 concludes.

II. Literature Review

Our paper extends the model of ERT (2020) to study optimal containment policies in the context of a Nash game between trading partners for whom international trade helps relax the resource constraints, thereby allowing to mitigate the fall in consumption needed to reduce fatalities.

We contribute to three strands of the nascent literature that merges epidemiological and macroeconomic models in the context of the COVID-19 pandemic: the literature on optimal containment policies; on the impact of trade responses to the pandemic; and on international cooperation to fight the pandemic.

In the first strand of the literature of optimal containment, the seminal ERT (2020) paper casts an epidemiological SIR model in the context of optimal macroeconomic choices of consumption and work hours. A large recession emerges from an explosive mix of infections and strict containment measures. Agents naturally cut down on their work hours and consumption to reduce the risk of becoming infected, but it takes a government acting as a benevolent social planner to fully internalize the impact of individual decisions on the risk of infection for others.

This mechanism of a voluntary reduction in consumption is illustrated by Baker et al., (2020) with US households' consumption responses by state, and by Haiqiang et al., (2020) with consumption responses across cities in China.

Several studies reinforce the recommendation of sizeable and early containment that we also find in our two-country setting. Alvarez et al. (2020) solve for a first-best-type of optimal lockdown policy in a SIR model when the planner minimizes fatalities by directly assigning which susceptible and infected agents have the right to participate in market production. Jones et al. (2020) study optimal containment policy in a shopper-worker setting with work-from-home. They find it optimal to front-load containment and enforce work from home early on when the number of infected households is relatively low.

While we focus on how heterogeneity between economic agents at home and abroad impacts optimal containment policies, several papers elaborate on various other dimensions of heterogeneity, namely the population's age distribution (Acemoglu et al. (2020); Glover et al. (2020); and Moll et al. (2020)) as well as the ability of individuals to shift consumption away from social and highly contagious sectors (Krueger et al. (2020)). Alon et al. (2020) study optimal containment policies in a framework in which households may respond to the shutdown of formal sector activities by switching to informality.

In the second strand of literature on trade responses to the COVID-19 outbreak, the papers most closely related to ours are Cakmakli et al. (2020) and Bonadio et al. (2020). Cakmakli et al. (2020) solve for optimal containment in a multi-sectoral small open economy SIR model with international input-output linkages. They find that domestic and external demand shocks from input-output linkages exacerbate the economic costs of the COVID-19 outbreak in an

open economy as compared to a closed economy. Bonadio et al. (2020) conduct a quantitative assessment of the role of global supply chains in the COVID-19 pandemic and find that most of the contractions in GDP could be attributed to domestic lockdown policies rather than global supply chains.

The third strand of recent literature relates to the role of international cooperation in curtailing the COVID-19 pandemic. Evenett (2020) assesses the resort to export curbs on medical supplies and concludes that exports curbs jeopardize international cooperation.

Zimmermann et al. (2020) empirically investigate the effect of globalization on the spread of the COVID-19 pandemic. They find that while measures of globalization are positively related to the spread of the virus, globalized countries are also better equipped to curb the spread of the pandemic. They conclude that the optimal policy is not to reduce globalization in the face of the pandemic but rather to monitor the human factor responsible for the global contagion spread while increasing collaboration to curtail the global impact of COVID-19.

To the best of our knowledge, our paper is the first to study the role of cooperation versus non-cooperation in a macroeconomic SIR model in which governments strategically choose containment policies to address infection externalities and decide whether to do so in the spirit of international cooperation or vice versa.

III. A Stylized Fact

In this section, we present evidence that countries with stronger containment at the height of the COVID-19 pandemic, on average, experienced a stronger appreciation (or a weaker depreciation) of the exchange rate. Our sample covers 36 OECD countries³ for which we use daily data of nominal effective exchange rates (NEER). The high-frequency analysis helps to track the exchange rate movements during the ascending phase of the pandemic. As it is customary, for each country, we start the sample on the day on which the 100th case was reported.

We compute the change in a country's NEER from the respective start date until the end of the sample (on July 17, 2020), as shown in Figure 1 on the vertical axis, with positive values for appreciations. On the horizontal axes, we show the largest drop in mobility (in percent) over the sample horizon, which we compute using the Google workplace mobility data that captures the decline in commuter activity to workplaces. We use it as a proxy for the intensity of containment.

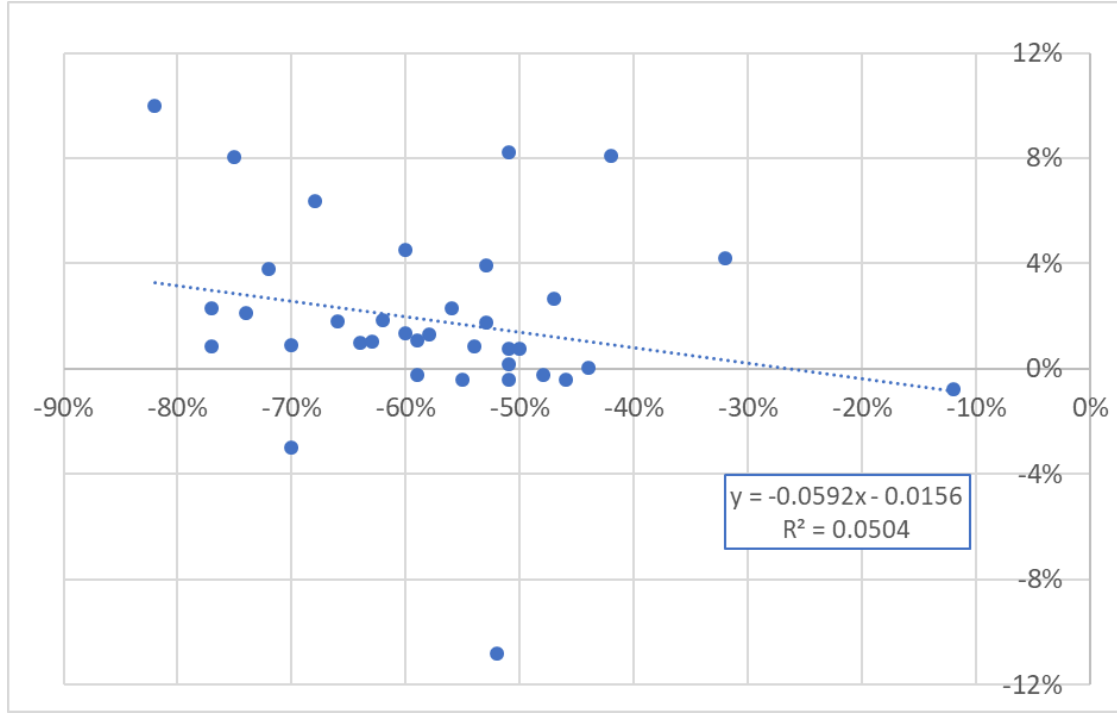
The regression line shows that, on average, a bigger decline in mobility is associated with a NEER appreciation.⁴ We interpret the latter as a proxy for a real effective exchange rate appreciation, which is plausible due to a short time period and a high-frequency nature of our data. That is, from the peak of infections to the data endpoint, we expect little change in relative aggregate goods prices. This is in line with other findings that in a little over a quarter, variations in the REER would be mainly driven by variations in the NEER.

In the next section we present a model that is able to rationalize this relationship between containment measures and relative price adjustment.

³ Iceland is the only missing OECD country due to a lack of data.

⁴ We also find this relationship when adding non-OECD countries from the European Union and the Group of Twenty nations.

Figure 1: Exchange rates and the depth of the recession in a pandemic



Note: The figure shows the appreciation of the NEER in percent on the vertical axis and the maximum workplace mobility decline on the horizontal axis after the 100th reported Covid-19 case. *Sources:* World Economic Outlook, Google and Johns Hopkins University

IV. An Open Economy SIR-Macro Model

To shed light on the international economic repercussions of the COVID-19 pandemic, we construct a two-country and two-good macro-epidemiological model based on the closed economy model of ERT (2020).

A. Preferences and Technologies

Prior to the onset of the pandemic, our two model economies are populated with ex-ante identical and infinitely living agents who value leisure and a composite consumption good according to the following preferences:

$$\sum_{t=0}^{\infty} \beta^t u(c_t, 1 - n_t)$$

with $u(c_t, n_t) = \ln(c_t) - \frac{\theta}{1+\psi}(n_t)^{1+\psi}$ for domestic agents and $u(c_t^*, n_t^*) = \ln(c_t^*) - \frac{\theta}{1+\psi}(n_t^*)^{1+\psi}$ for foreign agents. Quantities c_t and c_t^* are domestic and foreign composite consumption bundles given by

$$c_t = \left(\gamma \frac{1}{\omega} c_{h,t}^{\frac{\omega-1}{\omega}} + (1-\gamma) \frac{1}{\omega} c_{m,t}^{\frac{\omega-1}{\omega}} \right)^{\frac{\omega}{\omega-1}} \quad \text{and} \quad c_t^* = \left(\gamma \frac{1}{\omega} c_{m,t}^{*\frac{\omega-1}{\omega}} + (1-\gamma) \frac{1}{\omega} c_{h,t}^{*\frac{\omega-1}{\omega}} \right)^{\frac{\omega}{\omega-1}}$$

where $c_{h,t}$ and $c_{m,t}$ are the two goods produced in the home and the foreign economy respectively, with stars indicating consumption of those goods by the foreign consumers. ω is the elasticity of substitution between the domestic and the foreign goods, γ is the weight of the locally produced good. n_t and n_t^* are hours worked and θ and ψ are preference parameters capturing disutility from labor.

Domestic and foreign workers produce the local good using a linear technology given by $f(N_t) = AN_t$ in the home country and $f(N_t^*) = A^*N_t^*$ in the foreign country, where A and A^* are measures of productivity.

B. The Global Pandemic

The pandemic starts with two exogenous seeds representing positive measures ϵ and ϵ^* of infected agents in the home and foreign countries. From its onset in a given country, the pandemic spreads through three channels within a country: when susceptible agents shop for home and foreign-produced consumption goods and meet infected consumers, when susceptible agents work alongside infected workers, and via general community transmissions when susceptible agents randomly meet infected agents. In each country, infected agents either die with exogenous probability π_d or recover with exogenous probability π_r , while infected agents experience a drop in labor productivity by a factor of $\phi_i < 1$. We further assume that agents who have recovered from an infection become immune to the possibility of a future infection. A full description of the laws of motion governing the epidemiological (SIR) part of the model can be found in appendix A.

In the pandemic, susceptible, infected, and recovered households face distinctive objectives that we now describe. We denote by V_t^j the present value utility for an agent of type $j \in \{s, i, r\}$, where s , i , and r denote the susceptible, infected, and recovered types. Importantly, we assume agents have no technology at their disposal to transfer resources between periods, which implies that they are hand-to-mouth consumers. We therefore abstract from trade deficits and international borrowing.⁵

To construct proper consumption baskets in our two-country setting, we normalize the price of the composite consumption good to 1 in the home and the foreign countries.

Finally, because foreign agents solve problems that are perfectly analogous to the problems of the domestic agents, in the next section, we present the problems of the domestic agents only.

Susceptible agents

Susceptible agents choose consumption, c_t^s , and labor, n_t^s , understanding that these choices affect the probability that they will get infected and will become sick in the next period. This probability is described by τ_t which is a function of three terms:

⁵ Trade deficits and international borrowing in a pandemic are the object of forthcoming research.

$$\tau_t = \pi_1 c_t^s (I_t C_t^i) + \pi_2 n_t^s (I_t N_t^i) + \pi_3 I_t.$$

The first RHS term is the probability for a susceptible agent to get infected while consuming goods. This probability is proportional to the product of the agent's own consumption level, c_t^s , and a factor amounting to the total amount of consumption by infected agents, which itself is equal to the product of the measure of infected individuals, I_t , and their per capita consumption level, C_t^i . The second RHS term is the probability of an infection at the workplace which is proportional to the product of three terms: the susceptible agent's number of work hours, n_t^s , the measure of infected agents, and infected agents per capita work hours N_t^i . The third RHS term reflects the general community infections. Last, π_1 , π_2 and π_3 are scaling parameters.

The susceptible agents' optimization problem consists in choosing consumption and work hours, understanding that her/his individual choices for consumption and work hours today would determine the probability that she/he would be infected in the next period:

$$\begin{aligned} V_t^s &= \max_{c_t^s, c_{h,t}^s, c_{m,t}^s, n_t^s, \tau_t} V_t^s = u(c_t^s, n_t^s) + \beta((1 - \tau_t)V_{t+1}^s + \tau_t V_{t+1}^i) \\ \text{s. t. } p_{h,t} A n_t^s + \Gamma_t &= (1 + \mu_{c,t})(p_{h,t} c_{h,t}^s + p_{m,t} c_{m,t}^s) \\ c_t^s &= \left(\gamma^{\frac{1}{\omega}} c_{h,t}^{s \frac{\omega-1}{\omega}} + (1 - \gamma)^{\frac{1}{\omega}} c_{m,t}^{s \frac{\omega-1}{\omega}} \right)^{\frac{\omega}{\omega-1}} \\ \tau_t &= \pi_1 c_t^s (I_t C_t^i) + \pi_2 n_t^s (I_t N_t^i) + \pi_3 I_t \end{aligned}$$

The first constraint is the agent's budget constraint, given the Pigouvian consumption tax $\mu_{c,t}$, the domestic price of the home good, $p_{h,t}$, the domestic price of the foreign goods $p_{m,t}$, and the lump-sum transfer Γ_t from the government, all expressed in units of the local consumption goods bundle (in this case the domestic consumption goods bundle). The risk of infection crucially changes the susceptible agents' first order conditions, which can be written in compact form as follows⁶:

$$\theta n_t^s + \beta(V_{t+1}^s - V_{t+1}^i) \pi_2 (I_t N_t^i) = \frac{A}{(1 + \mu_{c,t})} \left(\frac{1}{c_t^s} - \beta(V_{t+1}^s - V_{t+1}^i) \pi_2 (I_t C_t^i) \right).$$

The first LHS term is the standard term for the marginal utility loss implied by an extra hour of work. The second term describes the expected utility loss in the following period, $(V_{t+1}^s - V_{t+1}^i)$, related to an infection that occurs with probability $\pi_2 (I_t N_t^i)$ due to working that additional hour. V_t^i is the utility of an infected individual that will be derived next. The right hand side describes the benefit of the additional hour of work that results in $\frac{A}{(1 + \mu_{c,t})}$ consumption units. Each unit of consumption raises utility by $\frac{1}{c_t^s}$, but reduces expected utility in the next period, as it increases the risk of an infection with probability $\pi_2 (I_t C_t^i)$.

⁶ See appendix A for the full set of first order conditions.

The domestic susceptible agent responds to these two risks in a pandemic by optimally reducing hours worked and consumption.

The aggregation of these individual downward adjustments to labor supply and consumption in the domestic economy produces a pandemic-induced recession which spills over to the foreign economy through two channels: (1) the reduction of the domestic labor supply leads to a fall in domestic exports, and (2) the downward adjustment to domestic consumption goes along with a fall in domestic imports. While we have not described the symmetric problem of a susceptible foreign agent for the sake of brevity, it is worth noting here that the aggregation of the individual behaviors of the susceptible foreign agents analogously creates spillovers to the home economy. We therefore have a model of pandemic-induced trade dynamics.

Infected agents

Infected agents solve the following problem:

$$\begin{aligned} V_t^i &= \max_{c_t^i, c_{h,t}^i, c_{m,t}^i, n_t^i} V_t^i = u(c_t^i, n_t^i) + \beta((1 - \pi_r - \pi_d)V_{t+1}^i + \pi_r V_{t+1}^r) \\ \text{s. t. } p_{h,t} \phi_i A n_t^i + \Gamma_t &= (1 + \mu_{c,t})(p_{h,t} c_{h,t}^i + p_{m,t} c_{m,t}^i) \\ c_t^i &= \left(\gamma^{\frac{1}{\omega}} c_{h,t}^{\frac{\omega-1}{\omega}} + (1 - \gamma)^{\frac{1}{\omega}} c_{m,t}^{\frac{\omega-1}{\omega}} \right)^{\frac{\omega}{\omega-1}} \end{aligned}$$

Recovered Agents

Recovered agents solve the following problem.

$$\begin{aligned} V_t^r &= \max_{c_t^r, c_{h,t}^r, c_{m,t}^r, n_t^r} V_t^r = u(c_t^r, n_t^r) + \beta V_{t+1}^r \\ \text{s. t. } p_{h,t} A n_t^r + \Gamma_t &= (1 + \mu_{c,t})(p_{h,t} c_{h,t}^r + p_{m,t} c_{m,t}^r) \\ c_t^r &= \left(\gamma^{\frac{1}{\omega}} c_{h,t}^{\frac{\omega-1}{\omega}} + (1 - \gamma)^{\frac{1}{\omega}} c_{m,t}^{\frac{\omega-1}{\omega}} \right)^{\frac{\omega}{\omega-1}} \end{aligned}$$

C. The Government

The government collects consumption taxes and rebates them to the three types of agents in a lump-sum manner. The government's budget constraint is:

$$\mu_{c,t}(S_t c_t^s + I_t c_t^i + R_t c_t^r) = \Gamma_t(S_t + I_t + R_t). \quad (1)$$

D. Closing the Model

As households cannot hold assets, trade must always be balanced:

$$\frac{p_{h,t}}{p_{m,t}} c_{h,t}^* - c_{m,t} = 0. \quad (2)$$

Appendix A presents the first order conditions, the household's and the government's budget constraints, and the SIR block for each economy.

V. Macroeconomic Effects of the Pandemic in a Two Country World

In this section, we describe the macroeconomic effects of an epidemic in our two-country world. In the first subsection, we describe the calibration, then turn to simulation results based on our baseline model, and finally discuss some sensitivity analyses.

A. Calibration

We employ the parameterization of ERT (2020) for parameters that are common to the closed-economy and the two-country frameworks. The mortality rate π_d is set equal to 0.5 percent for both economies, and we assume that after an infection, it takes 18 days until agents recover or die.⁷

The contagion probabilities π_1 , π_2 , and π_3 are calibrated such that consumption activities account for 16 percent of contagion, labor interactions for 17 percent, and random encounters between infected and susceptible for the remainder. We assume that both countries receive initial infections of $\epsilon^* = \epsilon = 0.001$.

Also, we chose the values for A and θ so that in the pre-epidemic steady-state, agents work 28 hours per week, and have a yearly income of \$58,000, which is the estimated average income for the US economy. We set $\beta = 0.96^{1/52}$ and $\phi = 0.8$ to reflect the lower productivity agents face when infected. The Frisch labor supply elasticity, $\frac{1}{\psi}$, is set to 1.

The open economy dimension of our model requires the calibration of two additional parameters: the share of the home and foreign consumption goods in the home and foreign consumption baskets, and the elasticity of substitution between these two goods. We assume home bias in consumption by setting $\alpha = 0.7$ for both countries, so that the consumption share of the local good is larger than consumption share of the good produced by the other country. Finally, we assume a unit elasticity of substitution between home and foreign goods.

Section 5.3 below shows that our results are robust to plausible variations of parameters that are consistent with the assumption of substitutability between the goods produced by the two countries. Substitutability is in line with literature bridging the gap between micro and macro estimates of the elasticity of substitution (Imbs and Mejean, 2015).

B. Baseline Model

As both economies are identical in their structure, a useful benchmark is a scenario of a simultaneous start of the pandemic at home and abroad, a scenario that mimics a closed-economy world. We refer to this scenario as our synchronous scenario (black dashed lines in Figure 2).

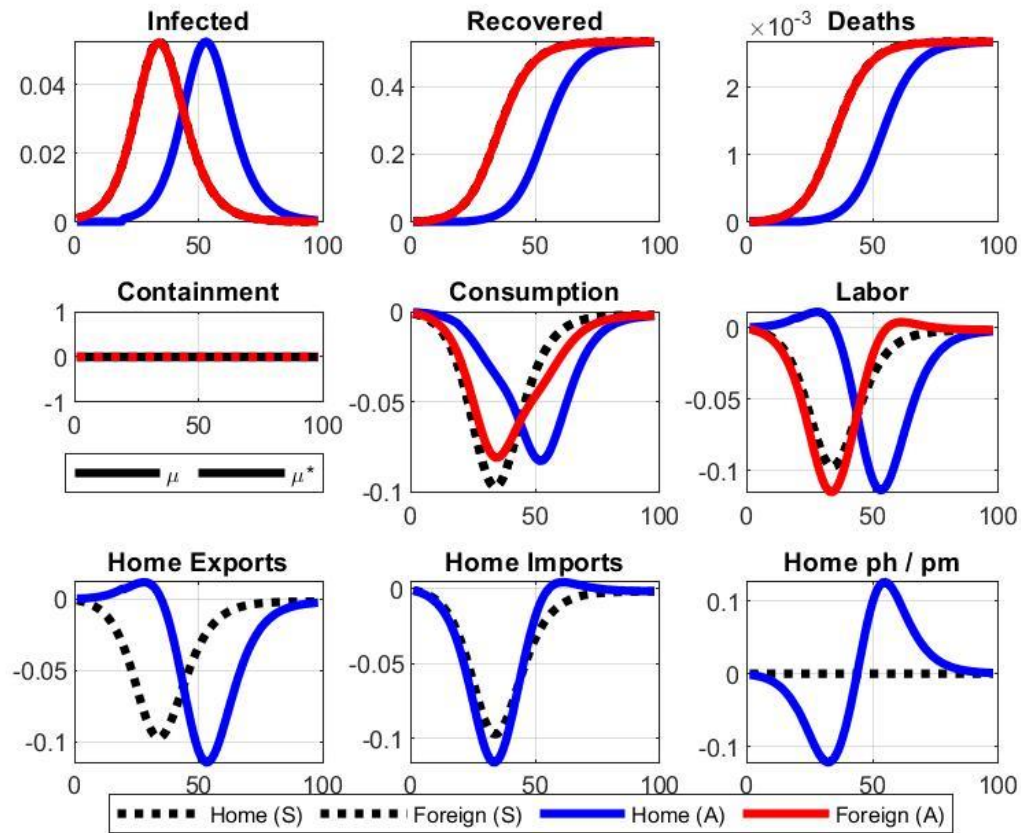
In the synchronous case, both economies are simultaneously hit by a virus of the same intensity. The virus then spreads among the population through contacts related to consumption, work-related interactions, and general community-type random encounters

⁷ We refer to Atkeson (2020) for a discussion of the fatality rate of COVID-19.

between susceptible and infected agents. Contagion rages until population immunity is acquired once some 60 percent of the surviving population has been infected. In response to the danger of the pandemic, susceptible agents slash their consumption and hours by about 10 percent relative to their pre-pandemic levels. This is because they try to minimize potential contagion and because of the productivity loss of the infected.

We compare the synchronous benchmark to the outcomes that arise from international spillovers when infections are not occurring simultaneously, which is our asynchronous scenario (red and blue lines in Figure 2 for the foreign and the home economies, respectively). Note that for the population dynamics, the dashed lines of the synchronous scenario coincide with the red lines of the asynchronous scenario.

Figure 2: Effects of the Pandemic in a Two-Country World



Under the synchronous scenario, perfect symmetry between the two countries leads to a symmetric decline in exports and imports while the relative price of the home and the foreign goods does not change. As infections converge to zero, the economy converges to its new long-run equilibrium levels.

Under the asynchronous scenario, each economy enters the pandemic at a different time, the foreign economy first and the home economy with a 20-period (20 weeks) delay. This implies that the time paths of infections, recoveries, and deaths for the foreign economy are similar to those observed in the synchronous case, while the home economy's dynamics follow with a delay.

The asynchronous scenario exhibits significant differences in the patterns of consumption and hours worked. At the core of what plays out differently in this scenario is the relative price of the domestic good. This price initially declines below and then rises above the pre-pandemic level.

The mechanism behind this price volatility is as follows: When the virus hits the foreign economy, the relative supply of foreign goods declines due to the reduction in hours worked and the decline in the productivity of infected workers. Later on, when the foreign economy starts to recover while the home economy is hardly hit by the virus, the home good's relative supply declines and this mechanism works in the opposite direction.

The pattern of relative price changes creates opportunities for gains from trade: the initially relatively ample and therefore cheaper supply of home goods allows foreign consumers to switch to the home good and contain both foreign production and foreign infections. In other words, when the pandemic peaks in the foreign country, foreign agents increase their imports of the home good, exploiting the home economy's initial competitive advantage of a relatively lower infection rate. This allows the foreign agents to contain the spread of the virus without cutting down on consumption as much as would be needed in a closed-economy, or in an open-economy world with synchronous infections.

Such a mechanism leads to three striking and contrasting patterns in our asynchronous scenario when compared to the synchronous case in the early phase of the pandemic: (1) foreign consumption falls less initially and foreign hours worked fall more; (2) home hours worked rise initially, and (3) as both home and foreign consumers switch away from the foreign good toward the home good in the early phase, home exports rise while home imports decline. When the home economy becomes the center of infections this mechanism moves into reverse.

The direction of change in the relative price between the home and the foreign good is in line with the stylized fact presented in section 3. In the model, the economy that is the most infected reduces the relative supply of its good vis-a-vis the other country in reaction to the pandemic, with its relative price increasing consequently, implying an improvement of the terms of trade.

This is consistent with our finding in the data that economies that experienced the sharpest contractions in workplace mobility due to adjustments to infections caused by the pandemic also saw their nominal effective exchange rates appreciate more. Our novel mechanism of global price adjustments has therefore allowed the world economies to transform pandemic-driven comparative advantages in terms of the relative risks of an infection into trade opportunities.

C. Sensitivity Analysis

In order to explore the sensitivity of the findings in the previous section to changes in parameters, we now assess the impact of alternative calibrations for selected variables. The first two lines in Table 1 show the results for the baseline calibration. The first column shows the peak of the infections per period with the period in which that peak occurs being shown in parentheses. The second and third columns show the maximum decline in consumption and hours worked in percent with the respective periods also being shown in parentheses. The fourth column shows the peak appreciations.

It turns out that all but one of the alternative calibrations presented in Table 1 confirm the qualitative results of the baseline scenario. This one parameterization that provides qualitatively different results is the case of complementarity between the home and the foreign goods that we also discuss in this section.

Table 1: Sensitivity Analysis

		Infected (period)	Consumption (period)	Hours (period)	Appreciation (period)
Baseline	H	5.3 (53)	-8.3 (52)	-11.4 (53)	11.2 (55)
	F	5.2 (34)	-8.1 (35)	-11.5 (34)	12.2 (32)
$\gamma = 0.5$	H	5.3 (53)	-6.4 (50)	-13.7 (53)	15.6 (55)
	F	5.2 (34)	-6.5 (50)	-14.0 (33)	16.9 (32)
$1/\psi = 0.5$	H	5.4 (53)	-6.2 (53)	-8.4 (54)	7.9 (55)
	F	5.5 (34)	-6.1 (35)	-8.5 (34)	8.5 (33)
$1/\psi = 2$	H	5.1 (52)	-10.2 (52)	-14.2 (53)	14.6 (55)
	F	5.0 (34)	-9.9 (34)	-14.4 (33)	16.1 (32)
$\varphi_i = 0.4$	H	3.7 (58)	-7.1 (57)	-9.3 (59)	8.3 (62)
	F	3.7 (40)	-6.9 (41)	-9.3 (39)	8.9 (36)
$AF > AH$	H	4.6 (55)	-7.1 (55)	-10.1 (55)	10.6 (57)
	F	5.9 (32)	-8.9 (32)	-13.1 (32)	14.5 (31)
$\omega = 5.00$	H	5.3 (53)	-9.6 (53)	-9.9 (53)	1.3 (55)
	F	5.3 (34)	-9.5 (34)	-9.9 (34)	1.4 (32)
$\omega = 0.10$	H	5.3 (53)	-11.5 (54)	-7.7 (52)	14.3 (32)
	F	5.3 (34)	-11.7 (34)	-7.5 (35)	13.2 (55)

Note: The table shows the largest deviations from the original steady state in percent. The period after the first shock in which this is achieved is shown in parenthesis.

No home bias in consumption: Eliminating the home bias in consumption by reducing the value of γ from 0.7 to 0.5 results in a stronger change in the relative price, a milder consumption decline, and a larger reduction of hours worked. This is because the trade-off between the cuts in hours worked and in consumption becomes milder in the no-home bias case: a given reduction in hours to reduce the likelihood of an infection reduces the agents' own consumption by less so that she will be willing to reduce those hours by more than under home bias. However, this larger supply contraction involves a stronger spillover to the other country and requires a larger change in relative prices to restore equilibrium. This larger price change, in turn, will induce a larger expenditure switching towards home goods.

Lower or higher Frisch elasticity: Reducing (increasing) the Frisch elasticity $1/\psi$ from 1 to 0.5 (2) decreases (increases) the sensitivity of hours worked to changes in the infection risk. Households thus reduce hours worked by less (more) than in the baseline calibration and thereby generate a smaller (larger) contraction in consumption and a smaller (larger) adjustment in relative prices.

Larger productivity drop for infected agents: Reducing the productivity of infected agents by half to $\phi_i = 0.4$ increases the costs of an infection, induces agents to flatten the infection curve more strongly by reducing consumption and hours more strongly early on. However, the troughs of consumption, hours, and relative prices are smaller than in the baseline setting as the recession is simply spread out more over time.

Asymmetric productivity level: In the baseline specification, we assume productivity and output levels to be the same across the two countries in the pre-crisis steady state. Here, instead, we reduce productivity in the home economy relative to the foreign economy. This shifts the burden of adjustment towards the richer economy: peak infections rise (fall) in the foreign country (the home country), consumption and labor decline by more (less), and the peak appreciations are stronger (milder) for the foreign good (the home good).

For a poorer country, the lower level of consumption reduces the willingness to sacrifice consumption and the sensitivity of hours and consumption to the risk of an infection and possible death decline. When home infections rise, there is thus a smaller supply contraction, requiring a smaller relative price adjustment. Similarly, when the (richer) foreign economy reduces its supply in response to rising infections, the terms of trade need to improve more to clear markets as the (poorer) home economy's supply reaction is weaker because the loss of utility from working more and consuming less is higher for poorer agents.

A lower (higher) elasticity of substitution: For an elasticity of substitution ω that is higher than the unitary value of the baseline scenario, the hours response and the appreciation become milder as the expenditure switching is more effective to restore equilibrium.

A figure with results for an elasticity of substitution close to zero (we show results for $\omega = 0.1$) is shown in Appendix B. With this parameterization, the home and foreign goods become complements: they are to be consumed in fixed proportions. This implies that there cannot be expenditure switching as this would change the proportion in which goods are consumed.

When the foreign country's infections rise and its goods supply is reduced, there is little room for foreign consumers to mitigate the decline in consumption by switching to foreign goods. Instead, the foreign agents will reduce the production of the foreign good by less.

Moreover, risk sharing works through a steeper consumption profile: the foreign country exports a greater share of its output for consumption to the home economy. The home economy, thus, instead of receiving a boost to output through increased export demand as in the substitutability case, sees an increase in the goods supplied by the foreign economy.

The relative price of the foreign, rather than the home good falls, and the home consumers increase their consumption level in the early phase of the pandemic.⁸ Declining hours and rising consumption imply a rise in utility in this phase for home agents while utility for foreign agents declines by more than in the substitutability case. Risk sharing through foreign trade with complementarity in consumption thus works through even lower utility during the phase of high infections and increased utility in the phase of lower infections.⁹

The bottom line of this section is that our model speaks to the data presented in section 3 when we assume that the home and the foreign goods are close substitutes, so that a rise in infections results in a terms of trade improvement.

VI. Optimal Containment Policies

Having highlighted the price adjustment mechanism which allows countries in our model to exploit trade opportunities to curb the impact of the pandemic, we next discuss how government interventions can internalize infection externalities. As it turns out, a government's containment policy also affects the other country, creating opportunities for cooperation.

Following ERT(2020) in the use of a Pigouvian consumption tax as containment policy, we assume that the governments of the home and the foreign economies have one instrument each at their disposal as containment policy: a consumption tax, denoted $\mu_{c,t}$ and $\mu_{c,t}^*$ for the home and the foreign economies respectively. The governments are free to vary their respective tax rate in every period, and they do so with the goal of optimizing their objective functions.

We further assume that the governments can implement their respective containment policies in a cooperative or a non-cooperative way. In the former case, both governments maximize global welfare $U^{world} = U^* + U$ while in the latter case, each government seeks to maximize its own agents' welfare only. When the consumption tax rate rises, agents reduce consumption and labor as the rewards to labor and consumption decline. The tax therefore contributes to reducing the local aggregate supply.¹⁰ In the open economy, as we have shown above, the adjustment to the pandemic occurs through the terms of trade, and the different approaches followed by governments will play out through the terms of trade as well.

The following subsections present a cooperative scenario (subsection 6.1), a non-cooperative scenario (subsection 6.2), and a partial cooperation scenario in which only one government cooperates (subsection 6.3). Subsection 6.4 concludes with a description of the equilibrium outcome in a Nash game featuring a prisoners' dilemma, quantifies the welfare gains from cooperation, and discusses the relevance of our analysis for actual policies in recent months.

⁸ We note that the foreign appreciation occurs in period 55 rather than 32 as in all other specifications so the sign of the terms of trade adjustment changes here.

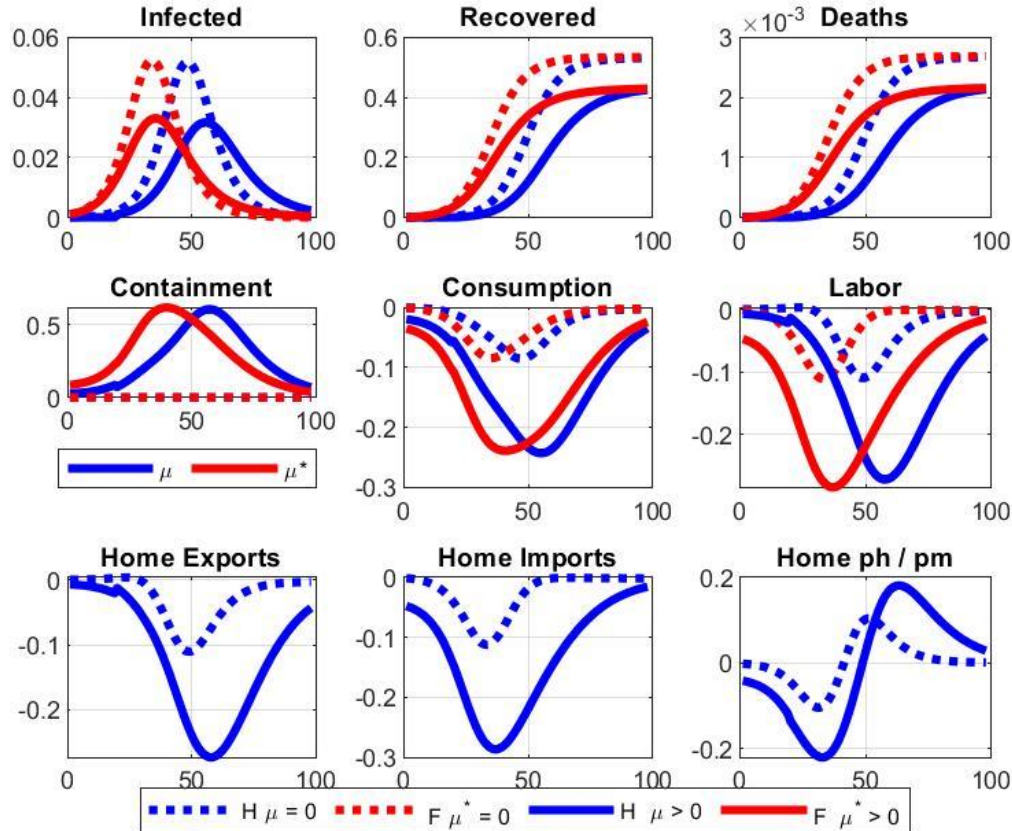
⁹ Appendix B also presents a scenario for complementary goods when infections only occur in the foreign economy. This setup serves to show that the results are driven by the macro part of our model rather than its pandemic part. Furthermore, Appendix B further presents results for a wide range of degrees of substitutability.

¹⁰ Please note that as we have only hand-to-mouth consumers, the time-varying consumption tax does not affect consumption patterns through the Euler equation.

A. Cooperation Scenario

Figure 3 presents a cooperative scenario. Similar to the closed economy case in open-economy cooperative case, containment policies reduce infections and deaths.

Figure 3: The cooperation scenario



The paths for the containment measures adapt to the infection dynamics in each country. This directly follows from the internalization of the infection risk by the government. Although containment measures increase global welfare and reduce the number of deaths, these policies come at the price of much deeper recessions that reduce employment, consumption and trade more strongly.

In an open-economy world, the movements in the terms of trade play a critical role in reducing the negative effect of containment measures on consumption relative to the closed-economy case. The optimal containment policies exploit the relative price adjustment and cause a larger increase in the relative price of the country facing more infections. It thereby induces a stronger substitution of consumption toward cheaper imported goods, strongly mitigating the drop in consumption.

Table 2 shows the welfare effects of the cooperative scenario for the top left field labeled with a "C" for both economies. Welfare rises by 0.18 and 0.29 percent above the no-policy baseline scenario, for the home and the foreign countries, respectively. The slight asymmetry with better outcomes for the foreign economy arises because in the initial 19 periods, the home economy

is not yet affected by the epidemic, so that the higher output that is induced by the expenditure switching mechanism allows for the provision of more risk-sharing for the foreign economy.

Table 2: Welfare effects of cooperation and non-cooperation

		Foreign	
		C	NC
Home	C	0.18, 0.29	-1.43, 0.66
	NC	0.49, -1.28	-1.01, -0.87

B. Non-Cooperation Scenario

Figure 4 presents optimal containment policies for each country in the non-cooperative case. In this simulation, each country chooses the path for the local Pigouvian consumption tax that maximizes its own welfare. It turns out that the non-cooperative scenario saves more lives, but at the cost of a much larger recession that follows from self-defeating beggar-thy-neighbor, or rather "infect-thy-neighbor" policies.

Computationally, we solve for the non-cooperative scenario by allowing the foreign economy to initially choose its optimal containment path. Later on, when infections have started to spread in the home economy, the home government responds conditional on the optimal path chosen by the foreign country. This process continues until a fixed point is reached.

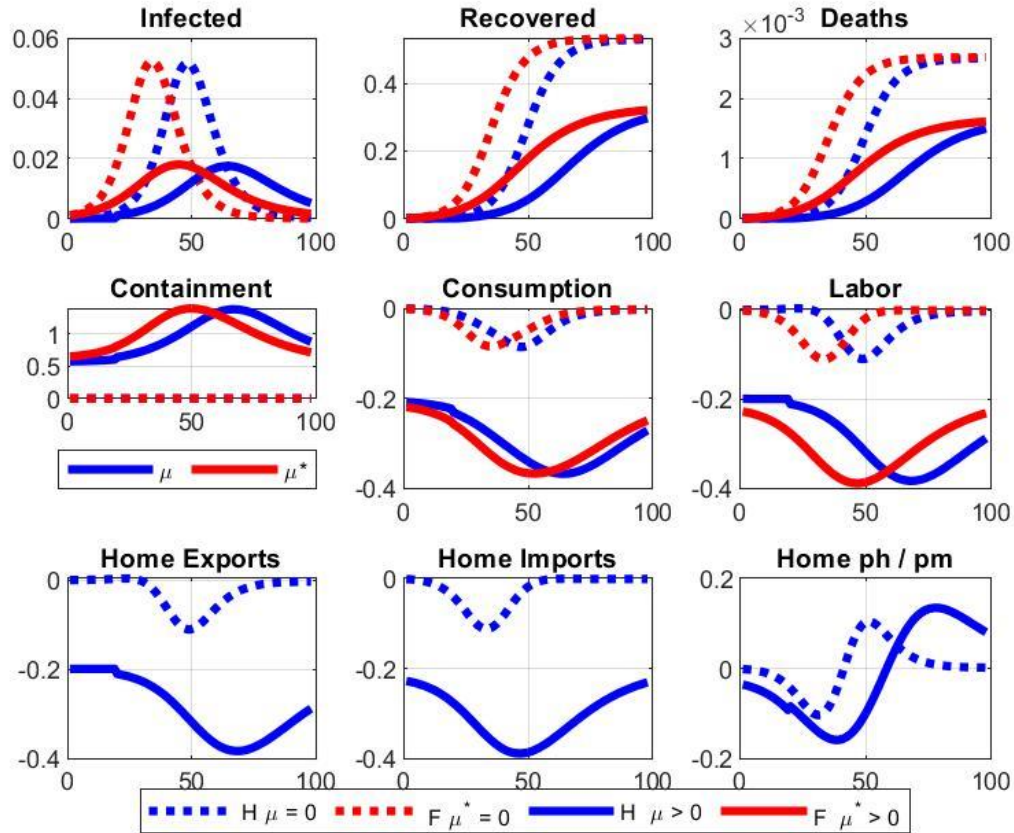
In the non-cooperative scenario, both economies aim to exploit the benefits from the adjustment to the terms of trade without taking into account the effects of their policy on the other country. In particular, they try to raise the relative price of their respective good in order to reduce the total number of hours worked and limit the fall in consumption by substituting toward cheaper imported goods.

In order to achieve this, each country raises the consumption tax by more than they would do under cooperation, thereby reinforcing the fall in the aggregate supply of the domestic goods. However, since neither country accounts for the impact of its consumption tax on the other country, both countries end up hiking the consumption tax as much as possible to create an appreciation of the price of the locally produced good, hence partially offsetting the change in the terms of trade induced by the other country's policy.

As a result, in the non-cooperative scenario, the overall volatility of the terms of trade declines compared to the cooperative scenario. The impacts of these policies on relative prices thus simply cancel out, preventing countries from benefiting from the additional policy-induced

movements in relative prices, causing a much larger recession and reducing welfare significantly in both countries.¹¹

Figure 4: Non-Cooperation Scenario



As pointed out earlier, in the non-cooperative scenario compared to the cooperation scenario, deaths are significantly lower. However, in the non-cooperative scenario, welfare levels are 1.01 and 0.87 percent below the no-policy baseline scenario, for the home and the foreign economies, respectively, as shown in the bottom right field in table 2 labeled with "NC". In other words, the absence of cooperation deteriorates the trade-off between lives and livelihoods.

C. Partial Cooperation Scenario

We now turn the analysis of a scenario of partial cooperation in which the home economy maximizes global welfare while the foreign economy maximizes own welfare.

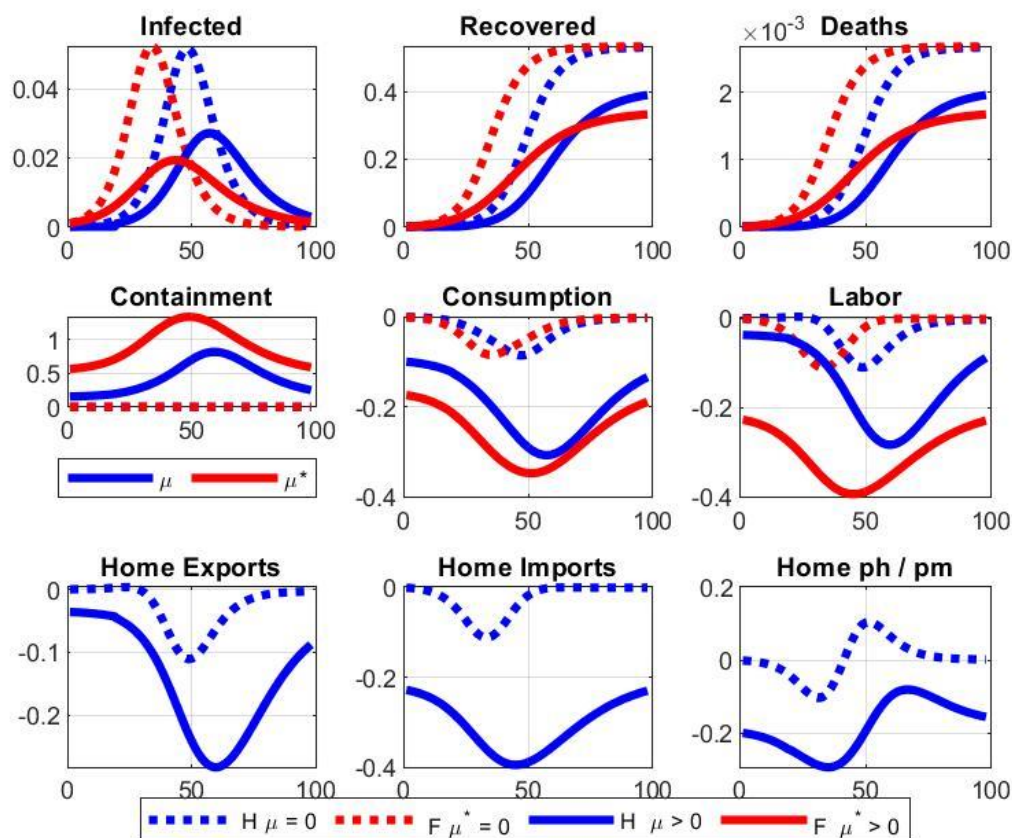
As shown in Figure 5, we find that the self-centered foreign government strongly raises its consumption tax to contain the pandemic by taking advantage of the benefits of an improvement of the terms of trade. In contrast to the scenario in which both countries behave non-cooperatively, in the scenario of partial cooperation, the home government enforces a milder containment, allowing the foreign government to induce a significant appreciation of

¹¹ To identify how much of this response is due to the pandemic or the open economy setup, appendix C presents the optimal tax policies under non-cooperation in the absence of an epidemic.

the relative price of the foreign good. Consequently, working hours in the foreign country fall by more than consumption, helping the foreign country reduce infections and deaths.

The top right panel of table 2 labeled with "C" for the home country and "NC" for the foreign country shows that welfare rises by 0.66 percent above the baseline level.

Figure 5: Partial Cooperation Scenario



Meanwhile, relative to the no-policy baseline, the benevolent government policy at home reduces welfare by 1.43 percent because it increases employment, reduces consumption, and increases the number of infections and deaths.

The opposite pattern arises when the home government maximizes its own welfare, while the foreign economy maximizes global welfare. Results for this scenario are shown in the bottom left panel of table 2.

D. Prisoners' Dilemma

Table 2 presents a summary of the welfare effects of the previous three subsections on cooperation, non-cooperation, and partial cooperation and shows that the international Nash game of strategic choices of containment policies by the home and the foreign governments is in fact a prisoners' dilemma. In this Nash game, each country would gain from improving its terms of trade in a non-cooperative way if and when the other country cooperates. However, if both countries embark on a non-cooperation strategy, they would neutralize the impact of their respective policies on the terms of trade. In this case, both countries would end up with too

high Pigouvian consumption taxes and suffer considerable losses: welfare would decline by 1.01 and 0.87 percent for the home and the foreign countries, respectively.

The cooperative solution is therefore not a Nash equilibrium. Yet, it is Pareto-superior to the game's unique Nash equilibrium, which is the non-cooperative outcome. In fact, the cooperative scenario raises welfare above the no-policy baseline scenario for both countries, while the non-cooperative scenario yields welfare well below the baseline levels for both countries. The cooperative scenario is thus an optimal outcome from the global perspective. Moreover, the gains from trade induced by containment policies are only feasible when the two economies abstain from selfish policies.

These findings and the description of the interaction between countries as a Nash game are reminiscent of the traditional and more recent optimal tariff literature. While our instrument is a Pigouvian consumption tax, desired changes in the terms of trade can also be achieved through import tariffs and export subsidies. The role of reciprocity of tariffs for a desired level of the terms of trade was already highlighted by Torrens (1844, p.50) who argued that while reciprocal free trade would be optimal, a unilateral removal of tariffs would be harmful as it would deteriorate a country's terms of trade.¹²

More closely related to our approach is Campolmi et al. (2014) who show in a trade model in the tradition of Krugman (1980) with various instruments at governments' disposal that a Nash equilibrium is characterized by countries choosing to subsidize imports and taxing exports in order to relocate production to the other economy. To the debate on the benefits of global cooperation that builds on this and other contributions, we add that it sets the right incentives to address a global pandemic.

While the use of the consumption tax should not be taken literally as a description of actual policies in recent months, it nevertheless serves as a useful shortcut. Using Global Trade Alert data, the IMF External Sector Report, IMF2020b, reports that as of May 2020, countries had imposed many new export restrictions and reduced import restrictions since the beginning of the pandemic. Overall, 120 new export restrictions were counted for 2020 on a net basis so far, a massive hike compared to all ten previous years. The most affected sectors comprise roughly 1.01 percent of global trade.

In our model, the reduction of exports and the increase of imports is at the heart of both the baseline and the optimal adjustment when infections are on the rise. Our normative analysis suggests that countries would have an incentive to overuse this channel while ignoring infections in other countries. Since the trade measures implemented so far are typically not adjusted to relative infections across countries, we interpret them to be of the infect-thy-neighbor type implying that countries are, in fact, caught in a prisoners' dilemma.

VII. Conclusion

Our analysis supports the following conclusions.

First, an asynchronous start of a global pandemic in different countries lends itself to the use of trade opportunities to curb infections by shifting production at a given point in time to the

¹² See Irwin (1991) for the debates on reciprocity and tariffs in the 19th century.

country that is the least affected by the pandemic. The gains from trade are channeled through changes in the terms of trade.

Our model predicts that the terms of trade appreciate when countries approach their infection peaks in relative terms. This mechanism allows countries to expand the consumption possibilities frontier when the pandemic hits, allowing to substitute the production of the local good with suitable imports so that hours worked and therefore infections can be reduced to save lives.

Second, a globally optimal containment policy internalizes the effects of individual countries' containment measures on aggregate infections, and is therefore welfare-improving. However, these gains are only available under cooperation between the trading partners: the country that is least affected by the pandemic needs to allow its trade balance to improve and its terms of trade to deteriorate in order to share the burden of the other country's infections.

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Appendix A

This appendix provides a full characterization of the model. We start with the SIR part and then describe the macroeconomic model part. The equations for the laws of motion of the distribution of the population (denoted by "*Pop*") among susceptible (*S*), newly infected (*T*), overall infected (*I*), recovered (*R*) and dead (*D*) agents, in the home and foreign countries (the latter denoted with an asterisk) are as follows:

$$\begin{aligned}
 T_t &= \pi_1(S_t C_t^S)(I_t C_t^I) + \pi_2(S_t N_t^S)(I_t N_t^I) + \pi_3 S_t I_t \\
 Pop_{t+1} &= Pop_t - \pi_d I_t \\
 S_{t+1} &= S_t - T_t \\
 I_{t+1} &= I_t + T_t - (\pi_r + \pi_d) I_t \\
 R_{t+1} &= R_t + \pi_r I_t \\
 D_{t+1} &= D_t + \pi_d I_t \\
 \\
 T_t^* &= \pi_1(S_t^* C_t^{S*})(I_t^* C_t^{I*}) + \pi_2(S_t^* N_t^{S*})(I_t^* N_t^{I*}) + \pi_3 S_t^* I_t^* \\
 Pop_{t+1}^* &= Pop_t^* - \pi_d I_t^* \\
 S_{t+1}^* &= S_t^* - T_t^* \\
 I_{t+1}^* &= I_t^* + T_t^* - (\pi_r^* + \pi_d) I_t^* \\
 R_{t+1}^* &= R_t^* + \pi_r I_t^* \\
 D_{t+1}^* &= D_t^* + \pi_d I_t^*
 \end{aligned}$$

Turning to the macroeconomic part of the model, we denote by $\lambda_{b,t}^j$ the Lagrange multiplier on the budget constraint of type *j* agent for $j \in \{r, s, i\}$ and $\lambda_{\tau,t}^S$ the Lagrange multiplier on the infection rate constraint in the problem of a susceptible individual for the home country. We are using similar notations for the Lagrange multipliers on the constraints faced by agents in the foreign country. The first order conditions for the choice of labor by the recovered, the infected, and the susceptible, in the home and foreign countries, are given by the following equations.

$$\begin{aligned}
 \theta n_t^r &= A \lambda_{b,t}^r \\
 \theta n_t^i &= \phi_i \lambda_{b,t}^i \\
 \theta n_t^s &= A \lambda_{b,t}^S + \lambda_{\tau,t}^S \pi_2(I_t N_t^I) \\
 \\
 \theta n_t^{r*} &= A \lambda_{b,t}^{r*} \\
 \theta n_t^{i*} &= \phi_i^* A \lambda_{b,t}^{i*} \\
 \theta n_t^{s*} &= A \lambda_{b,t}^{S*} + \lambda_{\tau,t}^{S*} \pi_2(I_t^* N_t^{I*})
 \end{aligned}$$

The first order conditions for the choice of the composite consumption good by the recovered, the infected, and the susceptible, in the home and foreign countries, are given by the following equations.

$$\begin{aligned}
\frac{1}{c_t^r} &= (1 + \mu_{c,t}) \lambda_{b,t}^r \\
\frac{1}{c_t^i} &= (1 + \mu_{c,t}) \lambda_{b,t}^i \\
\frac{1}{c_t^s} &= (1 + \mu_{c,t}) \lambda_{b,t}^s - \lambda_{\tau,t} \pi_1 (I_t C_t^i) \\
\\
\frac{1}{c_t^{*r}} &= (1 + \mu_{c,t}^*) \lambda_{b,t}^{*r} \\
\frac{1}{c_t^{*i}} &= (1 + \mu_{c,t}^*) \lambda_{b,t}^{*i} \\
\frac{1}{c_t^{*s}} &= (1 + \mu_{c,t}^*) \lambda_{b,t}^{*s} - \lambda_{\tau,t}^* \pi_1 (I_t^* C_t^{*i})
\end{aligned}$$

Critically, susceptible agents internalize the effects of their decisions on the probability of getting infected.

$$\begin{aligned}
\lambda_{\tau,t}^s &= \beta (V_{t+1}^i - V_{t+1}^s) \\
\lambda_{\tau,t}^{s*} &= \beta (V_{t+1}^{i*} - V_{t+1}^{s*})
\end{aligned}$$

Similarly, after normalizing the price of the composite consumption good in the home country to 1, the relevant equations for the choice of the composite basket in terms of quantities for the home and foreign goods by the recovered, the infected, and the susceptible, in the home country, are given by the following equations.

$$\begin{aligned}
c_t^s &= \left(\gamma^{\frac{1}{\omega}} c_{h,t}^{\frac{\omega-1}{\omega}} + (1 - \gamma)^{\frac{1}{\omega}} c_{m,t}^{\frac{\omega-1}{\omega}} \right)^{\frac{\omega}{\omega-1}} \\
c_{h,t}^s &= \gamma (p_{h,t})^{-\omega} c_t^s \\
c_{m,t}^s &= (1 - \gamma) (p_{m,t})^{-\omega} c_t^s \\
\\
c_t^r &= \left(\gamma^{\frac{1}{\omega}} c_{h,t}^{\frac{\omega-1}{\omega}} + (1 - \gamma)^{\frac{1}{\omega}} c_{m,t}^{\frac{\omega-1}{\omega}} \right)^{\frac{\omega}{\omega-1}} \\
c_{h,t}^r &= \gamma (p_{h,t})^{-\omega} c_t^r \\
c_{m,t}^r &= (1 - \gamma) (p_{m,t})^{-\omega} c_t^r \\
\\
c_t^i &= \left(\gamma^{\frac{1}{\omega}} c_{h,t}^{\frac{\omega-1}{\omega}} + (1 - \gamma)^{\frac{1}{\omega}} c_{m,t}^{\frac{\omega-1}{\omega}} \right)^{\frac{\omega}{\omega-1}} \\
c_{h,t}^i &= \gamma (p_{h,t})^{-\omega} c_t^i \\
c_{m,t}^i &= (1 - \gamma) (p_{h,t})^{-\omega} c_t^i
\end{aligned}$$

After normalizing the price of the composite consumption good in the foreign country to 1, the relevant equations for the choice of the composite basket in terms of quantities for the home and foreign goods by the recovered, the infected, and the susceptible, in the foreign country, are given by the following equations.

$$\begin{aligned}
c_t^{S^*} &= \left(\gamma^{\frac{1}{\omega}} c_{m,t}^{S^* \frac{\omega-1}{\omega}} + (1-\gamma)^{\frac{1}{\omega}} c_{h,t}^{S^* \frac{\omega-1}{\omega}} \right)^{\frac{\omega}{\omega-1}} \\
c_{m,t}^{S^*} &= \gamma (p_{m,t}^*)^{-\omega} c_t^{S^*} \\
c_{h,t}^{S^*} &= (1-\gamma) (p_{h,t}^*)^{-\omega} c_t^{S^*} \\
\\
c_t^{r^*} &= \left(\gamma^{\frac{1}{\omega}} c_{m,t}^{r^* \frac{\omega-1}{\omega}} + (1-\gamma)^{\frac{1}{\omega}} c_{h,t}^{r^* \frac{\omega-1}{\omega}} \right)^{\frac{\omega}{\omega-1}} \\
c_{m,t}^{r^*} &= \gamma (p_{m,t}^*)^{-\omega} c_t^{r^*} \\
c_{h,t}^{r^*} &= (1-\gamma) (p_{h,t}^*)^{-\omega} c_t^{r^*} \\
\\
c_t^{i^*} &= \left(\gamma^{\frac{1}{\omega}} c_{m,t}^{i^* \frac{\omega-1}{\omega}} + (1-\gamma)^{\frac{1}{\omega}} c_{h,t}^{i^* \frac{\omega-1}{\omega}} \right)^{\frac{\omega}{\omega-1}} \\
c_{m,t}^{i^*} &= \gamma (p_{m,t}^*)^{-\omega} c_t^{i^*} \\
c_{h,t}^{i^*} &= (1-\gamma) (p_{h,t}^*)^{-\omega} c_t^{i^*}
\end{aligned}$$

The budget constraints for the recovered, the infected, and the susceptible, in the home and foreign countries, are given by the following equations.

$$\begin{aligned}
p_{h,t} A n_t^r + \Gamma_t &= (1 + \mu_{c,t}) (p_{h,t} c_{h,t}^r + p_{m,t} c_{m,t}^r) \\
p_{h,t} A n_t^s + \Gamma_t &= (1 + \mu_{c,t}) (p_{h,t} c_{h,t}^s + p_{m,t} c_{m,t}^s) \\
p_{h,t} \phi_i A n_t^i + \Gamma_t &= (1 + \mu_{c,t}) (p_{h,t} c_{h,t}^i + p_{m,t} c_{m,t}^i) \\
\\
p_{m,t}^* A n_t^{r^*} + \Gamma_t^* &= (1 + \mu_{c,t}^*) (p_{h,t}^* c_{h,t}^{r^*} + p_{m,t}^* c_{m,t}^{r^*}) \\
p_{m,t}^* A n_t^{s^*} + \Gamma_t^* &= (1 + \mu_{c,t}^*) (p_{h,t}^* c_{h,t}^{s^*} + p_{m,t}^* c_{m,t}^{s^*}) \\
p_{m,t}^* \phi_i^* A n_t^{i^*} + \Gamma_t^* &= (1 + \mu_{c,t}^*) (p_{h,t}^* c_{h,t}^{i^*} + p_{m,t}^* c_{m,t}^{i^*})
\end{aligned}$$

The resource constraints for the home and foreign goods, are given by the following equations.

$$\begin{aligned}
S_t A n_t^s + I_t \phi_i A n_t^i + R_t A n_t^r &= S_t C_{h,t}^s + I_t C_{h,t}^i + R_t C_{h,t}^r \\
&\quad + S_t^* C_{h,t}^{s^*} + I_t^* C_{h,t}^{i^*} + R_t^* C_{h,t}^{r^*} \\
S_t^* A n_t^{s^*} + I_t^* \phi_i^* A n_t^{i^*} + R_t^* A n_t^{r^*} &= S_t^* C_{m,t}^{s^*} + I_t^* C_{m,t}^{i^*} + R_t^* C_{m,t}^{r^*} \\
&\quad + S_t C_{m,t}^s + I_t C_{m,t}^i + R_t C_{m,t}^r
\end{aligned}$$

The governments' budget constraints are

$$\begin{aligned}
\mu_{c,t} p_{h,t} (S_t c_{h,t}^s + I_t c_{h,t}^i + R_t c_{h,t}^r) &= \Gamma_t (S_t + I_t + R_t) \\
+ \mu_{c,t} p_{m,t} (S_t c_{m,t}^s + I_t c_{m,t}^i + R_t c_{m,t}^r) & \\
\\
\mu_{c,t}^* p_{m,t}^* (S_t^* c_{m,t}^{s^*} + I_t^* c_{m,t}^{i^*} + R_t^* c_{m,t}^{r^*}) &= \Gamma_t^* (S_t^* + I_t^* + R_t^*) \\
+ \mu_{c,t}^* p_{h,t}^* (S_t^* c_{h,t}^{s^*} + I_t^* c_{h,t}^{i^*} + R_t^* c_{h,t}^{r^*}) &
\end{aligned}$$

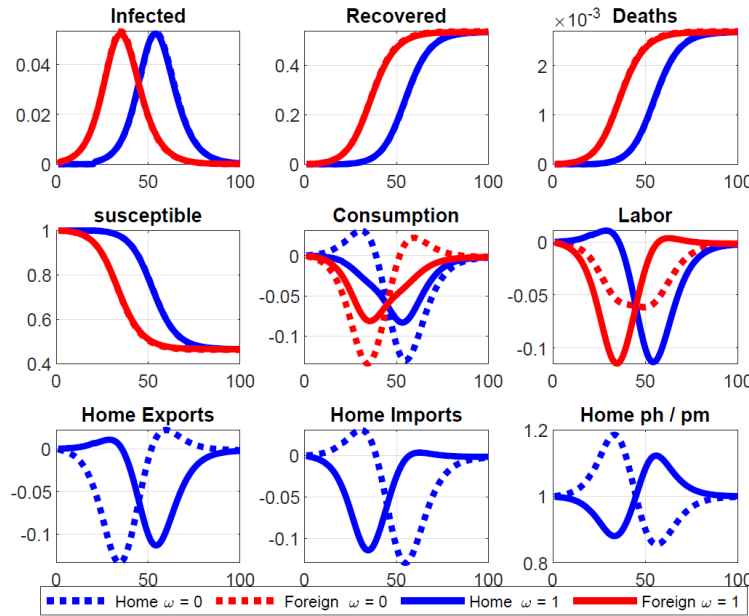
By Walras' law, combining the agents' budget constraints, the government's budget constraint, and the output restrictions (resource constraints) for the home and foreign countries respectively, we get the following two trade balance identities.

$$\begin{aligned} p_{m,t}c_{m,t} &= p_{h,t}c_{h,t}^* \\ p_{h,t}^*c_{h,t}^* &= p_{m,t}^*c_{m,t} \end{aligned}$$

Appendix B. The role of the elasticity of substitution

In this appendix we provide some more illustrations of the role of the elasticity of substitution for our model predictions. In the sensitivity analysis we explained the model mechanics when the elasticity of substitution between Home and Foreign goods, ω , is close to zero so that the two goods are complements. The dotted lines in figure 6 show this complementarity case while the solid lines show the baseline case with substitutes.

Figure 6: Complementarity between domestic and foreign goods



To illustrate the spillovers from trade for the Home economy separately from its own infections, figure 7 shows the case in which the home country is not affected by the pandemic so that only trade movements explain its business cycle. The figure confirms the negative correlation of aggregate consumption and the perfect correlation of hours worked. The absence of consumption risk sharing and the perfect alignment of output found above for complementary goods is thus driven by the trade block of the model rather than the dynamics of the epidemic in the home economy.

Figure 7: Complements without pandemic in Home country

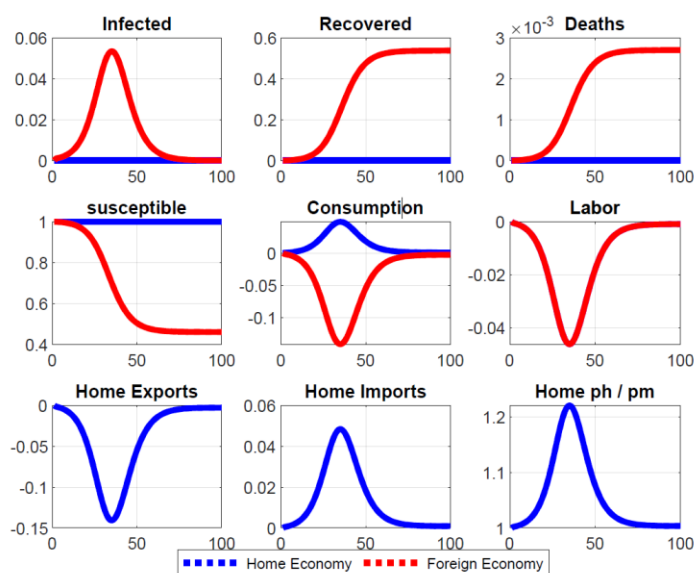
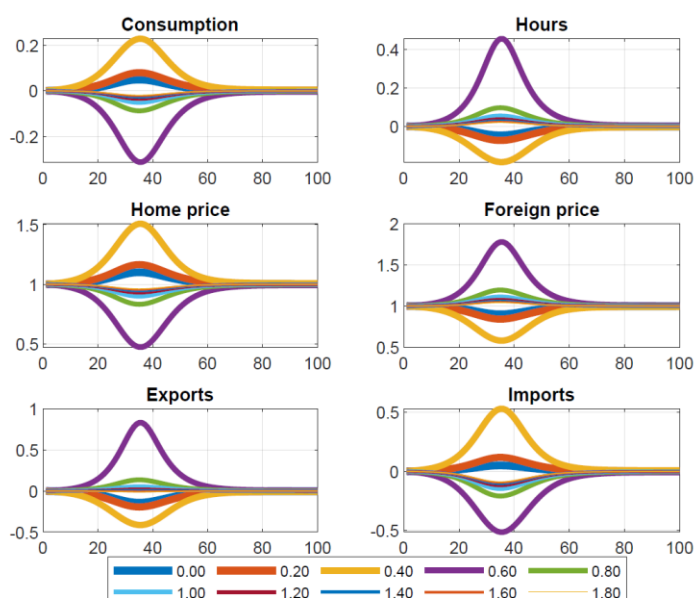


Figure 8 presents the dynamics of the home economy for a grid of different values for ω . As in figure 7, the pandemic only affects the foreign economy, and consequently, these dynamics only correspond to the trade channel. For an elasticity of substitution between Home and Foreign goods between 0 and 0.49, Home consumption rises, employment falls, and there is an increase in the Home economy's relative price. Meanwhile, for an elasticity between 0.51 and infinity, Home consumption falls, employment rises, and there is a reduction in the Home economy's relative price. Interestingly, the closer the values for this elasticity are to 0.5, the larger are the effects. For the particular case of 0.5, there is no solution.

Figure 8: Sensitivity Analysis Home Economy



Appendix C. Optimal policies without pandemic

Figure 9 compares the optimal policies in a non-cooperative environment with and without the pandemic. In the case without pandemic, each country aims to maximize their respective utility exploiting the relative price channel; that is, each country implements a policy that produces a fall in labor and consumption. The policy induces a more significant fall in employment that increases relative prices, incentivizing substitution toward cheaper imported goods. When both countries seek this policy simultaneously, the policies cancel out each other, and the relative price is unaffected. Nevertheless, there are permanent effects on the consumption and labor allocations that reduce global welfare.

Figure 9: Optimal policies with and without pandemic

