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Abstract

This paper studies the aggregate effects of supply chain disruptions in the post-pandemic period in a heterogeneous-firm, general equilibrium model with input-output linkages and a rich set of supply chain frictions: uncertain shipping delays, fixed order costs, and storage costs. Firms optimally hold inventories that depend on the source of sup- ply, domestic or imported. Increases in shipping times are contractionary, raise prices, and increase stockouts, particularly for goods intensive in delayed inputs. These effects are larger when inventories are already at low levels. The paper fits the model to the United States and global economies over 2020|2022 and estimates large aggregate effects of supply disruptions. The model predicts that the boost in output from reducing delays will be smaller than the contraction from the waning effects of stimulus.

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The Aggregate Effects of Global and Local Supply Chain Disruptions: 2020–2022*

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1 Introduction

Since the onset of COVID, the reopening of the global economy has been hampered by large and unprecedented supply-chain disruptions that have substantially increased both the costs and time involved in moving goods within and across borders. For example, from the start of the pandemic to the beginning of 2022, the costs of shipping goods from Asia to the United States by air nearly doubled while the costs of long-distance trucking in the United States rose by almost 60 percent (Figure 1). These cost increases were accompanied by a large increase in lead times on production inputs. While the focus has been largely on delays at ports, which are processing record trade volumes, delays are also present in purely domestic transactions. The Institute for Supply Management (ISM) delivery times index shows that the average lead time for materials and inputs has risen by about 35 days in the United States. The IHS Markit survey of global purchasing managers shows a similar increase in delays for the Euro area (Figure 2) and a general increase in delays worldwide. The higher costs and longer lead times come at a time in which inventories, relative to sales, in some sectors in the United States are at historically low levels, making it hard for firms to adjust to changes in demand and leading to a worldwide increase in retail stockouts, particularly for imported goods (Cavallo and Kryvtsov, 2021).

In this paper, we quantify the aggregate effects of supply-chain delays experienced in the United States and the rest of the world (ROW) in the post-COVID period.[1] A key challenge to our analysis is that the unique features of the current environment—increased delivery times and depleted inventories—are absent in the standard macroeconomic and trade models used in policy or business-cycle analysis. For our purposes, we apply the heterogeneous firm model developed by Alessandria et al. (2022)—used to study supply disruptions in an earlier, less globally integrated, era—to current events. In this model, firms pay fixed costs to order imported and domestically-produced goods that may be delayed in shipping. This delay is costly and uncertain. Firms also face idiosyncratic demand shocks, so they optimally hold costly inventories to guard against stocking out and missing sales.

In this model, we consider an increase in international delivery times from 55 days to

[1]By "post COVID," we mean "following the onset of COVID"—March 2020.

90 days, mirroring the recent U.S. experience. The shock is transitory but persistent. As firms wait longer to restock and run down inventories, they optimally raise prices. Consumer prices deflated by wages rise by 7 percent from their steady-state value.[2] The increase in shipping time is contractionary, lowering output in the traded goods sector by 8.7 percent on impact. The large impact of this shock arises for two reasons. First, there is the standard cost channel as the longer time to restock increases the cost of inputs and thus reduces the incentive to produce. Second, the shipping delays have a differential effect across firms, constraining the sales of the firms for whom restocking is most valuable—those with relatively low inventories or relatively high demand. Although the shock dissipates quickly, it takes time for the economy to recover as the reduction in inventories is an important constraint on production.

Our model suggests that the effects of the shipping delays are magnified if the shock arrives when inventories are low or consumer demand is high, two conditions that have certainly been true for the U.S. economy in the post COVID period. Inventories in the United States fell to historically low levels in early 2021, reflecting manufacturing shutdowns and border closures that were meant to mitigate the impact of COVID, along with the shift in consumer expenditures toward goods. The drawdown of inventory was a key margin used to smooth out the shock initially. The easing of COVID restrictions, changing patterns of spending, and significant government stimulus raised consumer expenditures as shipping delays increased. With low inventories and high consumer demand, prices increase more, and inventories are driven to lower levels, suggesting that continued stimulus in the face of supply constraints will likely push prices higher.

In Section 6, we use the model to recover a set of domestic and foreign shocks that can match the salient features of the global economy in the COVID collapse and recovery period in terms of the usual macroeconomic time series—production, consumption, and the trade balance—plus our delivery time series. By shutting down the delivery delay shocks, we can estimate the aggregate impact of these supply frictions. Generally, we find that the delays were a substantial drag on economic activity in the United States and the ROW, particularly in 2021. As the delays continue to be high into 2022, they represent a continued drag on

[2]Our model is a real model and, thus, our focus is on the relative price of goods to wages, our numeraire.

economic activity through 2022 and into 2023 and a key source of elevated prices. We show that the quantitative effects on the aggregate economy depend on expectations about the nature of the delay shock. Delay shocks that are expected to get worse before they get better (an AR(2) shock process) lead to effects that are about one-third smaller than shocks that monotonically decay (an AR(1) shock process).

We undertake an analysis of the increase in global and local supply chain frictions on the global economy in a two-country version of the heterogeneous firm model of Alessandria et al. (2022) which extends the two-country sS inventory model of Alessandria et al. (2010b) to include an input-output structure and sectoral heterogeneity in the use and consumption of domestic intermediates. Models with inventory frictions have been shown to capture the cyclical behavior of trade, inventories, prices, and aggregate economic activity in the Great Recession and, more generally, over the business cycle. A key feature of the approach is that it explicitly models the differential costs in time, resources, and risk for domestic and international transactions. These risks are reflected in the different inventory management approaches used for imported and domestic transactions: global and local supply chains. For example, goods involved in international trade are held in inventory about twice as long as goods in domestic transactions (Alessandria et al., 2010; Nadais, 2017; Khan and Khederlarian, 2020), and inventory accumulation and depletion in international transactions are particularly sensitive to business cycles and policy shocks (Khan and Khederlarian, 2021; Alessandria et al., 2019). The differences between international and domestic transactions allow us to discipline the parameters of our model with firm-level data on inventories and ordering behavior.

Our study builds on a recent, largely micro-oriented literature that studies the effects of supply disruptions on firms, to consider the aggregate implications. Barrot and Sauvagnat (2016) show that natural disasters that constrain the production of upstream suppliers can have large and persistent effects on downstream firms' values and production. They find these effects are partly mitigated for firms with relatively large stocks of inventories. Several papers use the Tōhoku earthquake and tsunami to identify and quantify firm-level disruptions. Boehm et al. (2019) show that firms that use inputs from Japan reduced output one-for-one with imports. Carvalho et al. (2020) study the firm-level impact of the Tōhoku shock and quantify its aggregate effects in a closed economy, general equilibrium model with production linkages. Our related work, Alessandria et al. (2022), studies the aggregate effects of these types of shocks on the U.S. economy since 1950.

Several recent papers have studied the effect of COVID in the presence of global production networks (Cakmakli et al., 2021; Bonadio et al., 2021) but do not consider the supply constraints related to the time to restock that we emphasize. Another literature considers, empirically, how cross-industry delays or backlogs affect industry prices or production (Alessandria et al., 2022; Santacreu and LaBelle, 2022). Recently, Cavallo and Kryvtsov (2021) has shown that COVID has substantially and persistently increased the retail stock out rate in the U.S. and around the world. Motivated by our research, and consistent with our model, they also show that goods with a larger import content are taking longer to restock and that prices have risen by more for these goods. Our paper is also related to general equilibrium models of inventory management and business cycles (Khan and Thomas, 2007; Iacoviello et al., 2011; Ortiz, 2021) that explore how inventories propagate aggregate shocks. Unlike this earlier work, we consider the aggregate effects of transitory changes in lead times for a specific episode.

Our paper is also related to work that estimates the long-run effects of timeliness on trade flows. Djankov et al. (2010) introduce a measure of "time to trade" into a gravity analysis and find that an extra shipping day lowers trade by more than one percent—more so for time-sensitive products. Hummels and Schaur (2013) use variations in shipping times to different ports and transport modes in the United States and estimate a tariff-equivalent time cost of 0.6–2.1 percent per day in transit. Clark et al. (2014) use variation in arrival rates to the same port to estimate that 10 percent more delivery uncertainty (about a half of one day) lowers trade by 1–2 percent. Feyrer (2019) uses the change in geography from the introduction of faster air transport to estimate a relatively large effect of trade on income.

The paper is organized as follows. In Section 2, we summarize the evidence on input lead times and inventory levels. We also summarize the dynamics of the aggregate economy. Section 3 lays out the model. In Section 4, we use data, such as inventory holding and order frequency, to parameterize our model. In Section 5, we study the output and price effects of a persistent increase in shipping times in our baseline model and some variants.

We also consider the effects of these shocks in conjunction with consumption stimulus and initial conditions with low inventories. In Section 6, we consider a combination of home and foreign shocks to shipping times, labor supply, and stimulus that best account for the salient features of the U.S. and global economies in the COVID collapse and recovery. Section 7 concludes.

2 Data

We summarize some salient features of the U.S. and global economy in a three-year window around COVID. These features are related to increases in input lead times, substantially depleted inventories, large swings in economic activity, and an increase in the price of goods. For many of these series, the changes are unprecedented in recent memory. Of course, the shock and policy actions were unprecedented, too.

Lead times. It is taking much longer than usual to get inputs for production or sale. These delays vary across industries and by direction of trade. They reflect delays in the time between order and shipment and the time from shipment to delivery.

We have already noted that global measures of lead times, measured by the IHS Markit diffusion indices, increased substantially with COVID, fell back, and worsened in 2021 before returning to normal by late 2022 (Figure 2). Figure 3 plots measures from the ISM lead times index, which is a survey of U.S. purchasing managers on the time from order to delivery for various important inputs. An advantage of this series, compared to a diffusion index, is that it yields a time series of the level of delays that we can use to discipline our model parameters and shocks. Figures 3(a)–3(c) show average lead times, in days, for production materials, capital expenditures, and maintenance, repair, and operating (MRO) supplies.[3] Figure 3(d) is a diffusion index that summarizes the direction of delivery times, with numbers above (below) 50 reflecting an increase (decrease) in delivery times. All four panels display levels in 2021 and 2022 that have not been experienced in the last 25 years. Production material delivery times were stable in the 2000s at about 45–50 days, drifted up to about 60 days following the Great Recession, and have risen to almost 100 days since the start of 2021. It is uncertain how persistent these recent changes in lead times may be. For instance, following

[3] Firms report lead times by windows, e.g., 0–45 days. The reported times are converted to an average.

the Great Recession, the rise in lead times was quite persistent.[4] It is worth noting that, while lead times remain elevated, the diffusion index has returned to constant lead times by the end of 2022.

An alternative measure of the time to restock is the ratio of unfilled orders to shipments (measured in days), which has also risen substantially. Figure 4 plots the unfilled orders of capital equipment, excluding defense and aircraft, from the Census against the ISM series on lead times on capital expenditures. Both series show a large and persistent increase in the days to delivery, although the unfilled order series shows an earlier, but smaller, increase than the ISM series.

Both international and domestic transactions have been affected by supplier delays. In Figure 5, we plot a measure of delivery challenges, by type of transaction, from a survey of U.S. firms conducted by the Census Bureau that began at the onset of COVID. Firms are surveyed about delivery delays on supplies by source (domestic and foreign) as well as their own delays. Firms reporting delays by foreign suppliers have more than doubled from the beginning to end of 2021 while domestic and own delays have risen by about 50 percent. These delays are concentrated in the tradable sectors (measured by inputs): construction, manufacturing, retail, and wholesale. Figure 6 shows that these delays are especially large in international shipping, as the time to ship, measured by ocean shipment transit time from China to the United States by two logistics companies, rose from 40–50 days to 80–110 days from the end of 2019 to the end of 2021.[5]

Inventories. The current level and distribution of inventories across sectors are quite unusual. Figure 7 plots U.S. inventory-sales ratios for three major sectors: manufacturing, retail trade, and wholesale trade. Two things are apparent. First, inventory-sales ratios have fallen in all sectors since the start of the crisis, but the decline has been largest in the retail sector, as retailers have moved from about 1.5 months of inventory to about 1.1 months (a record low). Second, the traditional structure of inventory holdings across sectors

[4]Carreras-Valle (2021) attributes this secular rise in delivery times to a shift to more distant trade partners, particularly China, while Alessandria et al. (2022) attribute variation in lead times over a longer period to changes in local and global sourcing along with new modes of transport.

[5]The measure from Flexport measures the time from when a container leaves the factory to when it is picked up from the destination port by the importer. It is retrospective in that it measures products picked up at that date. The second measure, from Freightos.com, is door to door and is prospective.

has been upended, with retail—normally the most inventory-intensive industry—becoming the least inventory-intensive.[6] The low levels of retail inventories have greatly reduced the availability of goods, especially for imported goods. Using online data from retailers, Cavallo and Kryvtsov (2021) show that the onset of COVID led to a substantial and persistent rise in retail stockouts globally. These stockouts were more common in the United States and remain at elevated levels through May 2022, even as aggregate measures of inventory-sales ratios are recovering. Importantly, they also show that these stockouts are more common and last longer for imported goods, consistent with our findings that delivery challenges have risen by more for international transactions.

The persistently high stockouts point to a challenge in interpreting the inventory data during this period. Inventories can be held at various stages of the supply chain and by various owners. For instance, longer shipping times between ports or dwell times for containers at the ports may lead those goods to be included in retail, wholesale, or manufacturing inventories but will not be available for production or consumption. Moreover, inventories that are ultimately used in one country may be on the books of its trading partner.

Production, sales, and trade. Finally, we summarize the response of the aggregate economy to the pandemic and the supply disruptions that followed. Figure 8 plots some key variables of interest. These variables, along with our measures of delays and inventories, are the key moments we seek to interpret through the lens of the model. The first three panels are relative to their levels in the fourth quarter of 2019. From the first panel, we see that industrial production in manufacturing fell sharply in the United States and the rest of the world, by about 20 percent. The recovery was relatively fast however, especially in the rest of the world, which by the fall of 2020 was producing more than it had pre-crisis. Most of the movements in industrial production in the United States reflect the dynamics of employment and not productivity, particularly the decline and rebound.

Turning to the second panel, sales of goods (manufacturing plus wholesale and retail trade) in the United States also fell sharply but by considerably less than production. Sales

[6] The inventory-sales ratio for motor vehicles held by retailers fell by almost half of its level prior to COVID, reaching a record low in 2021Q2. By the end of 2022, it had recovered to two-thirds of its pre-COVID level. There are important challenges to rebuilding the stock of motor vehicles as lead times for parts have risen sharply due to several factors and this has been a large constraint on production.

rebounded faster than production and have remained about five percent above pre-crisis levels. Real consumption of goods fell even less and rebounded even more strongly. These expenditures accelerated at the end of 2020, and remain 15–20 percent above the level prior to the crisis. To fill the gap between production and sales, firms ran down inventories and the United States ran larger trade deficits.

In the third panel, we see that international trade (exports plus imports) fell about as sharply as production but rebounded faster and lagged overall sales and real consumption of goods. The trade balance, measured as the export-import ratio, is plotted in the fourth panel. The United States was exporting less than it imported before the pandemic and the drop in exports in 2020 was larger than the drop in imports. The drop in overall trade suggests that the shocks have had a relatively large effect on trade and the drop in the export-import ratio speaks to the relative size of shocks in the United States and the rest of the world.

Price. Movements in the price of goods relative to wages have been relatively large. In the fifth panel we plot the personal consumption expenditures price index on goods and the producer price index for consumer goods. Both series are deflated by the hourly wage of manufacturing workers. Additionally, we remove a trend from the consumer price index. Both series show similar dynamics: a drop in the price of goods in early 2020 followed by a substantial increase in prices that peaked in June 2022. The rise in producer prices is about twice that of consumer prices.

Caveats. The data are not generally informative on the source of the delays. Delays may reflect capacity constraints owing to restrictions on input availability or high demand. These delays may be related to transportation infrastructure, public health restrictions, or production constraints. For example, Boehm and Pandalai-Nayar (2022) show how capacity constraints lead to convex supply curves. If firms synchronize their orders, prices will rise more strongly, inducing firms to restock more slowly and exacerbating delays. Knowing the source of delay is primarily important for determining the optimal policy response, but not the aggregate effects of these delays. Thus, in our modeling, we do not take a stand on the source of the increase in lead times.

3 Model

In this section, we describe a two-country dynamic general equilibrium model with heterogeneous firms facing domestic and international transaction frictions that lead them to hold inventories. It extends the closed-economy model developed by Alessandria et al. (2022). There are three sectors: 1) a *manufacturing sector* that combines labor and intermediate goods to produce, 2) a *consumption sector* that uses intermediate goods to produce, and 3) a wholesale/retail sector (for brevity, the *retail sector*) that purchases goods from manufacturers, differentiates them, and sells the differentiated goods to the consumption and manufacturing sectors. The retail-sector firms order domestic and imported inputs to sell domestically, subject to source-specific delay shocks, and face idiosyncratic demand shocks. These two sources of uncertainty, demand and supply, affect the timing of a firm's orders and the prices they set. In general, firms want to avoid stocking out of their products to maximize profits. Unsold goods can be saved in inventory to be sold in future periods, but they incur a holding cost that depends on the interest rate and a product's depreciation rate.

The aggregate state in the model is the realization of exogenous aggregate shocks and distributions over firm inventory levels and idiosyncratic demand. We denote the aggregate state η_t, a history is $\eta^t = (\eta_0, \eta_1, ..., \eta_t)$, and the probability of a history is $\pi(\eta^t)$. We consider a single aggregate shock (shipping delays) in the baseline model and extend the model to include more shocks in Section 6.

3.1 Shipping delays

Retail firms place orders after observing their idiosyncratic demand shocks but before setting prices. Goods ordered at the beginning of the period arrive within the same period with probability $1 - \mu_i(\eta^t)$, where $i \in \{D, I\}$ denotes an order from a domestic supplier or an international supplier. With probability $\mu_i(\eta^t)$ the goods are delayed and arrive in the next period. We assume that the share of current orders that are delayed, $\mu_i(\eta^t)$, follows a stochastic process defined by

$$\mu_i(\eta^t) = \rho_\mu \, \mu_i(\eta^{t-1}) + (1 - \rho_\mu)\bar{\mu}_i + \varepsilon_{\mu_i}(\eta^t), \tag{1}$$

where ρ_μ is the persistence of the shock and $\bar{\mu}_i$ is the steady-state probability that goods from source i are delayed and arrive in the next period. Thus, a positive $\varepsilon_{\mu i}(\eta^t)$ increases the average shipping delay faced by firms.

3.2 Households

There are two symmetric countries, Home and Foreign, populated by a unit mass of identical agents that are modeled as representative households. Foreign-country variables are denoted with an asterisk. Households in Home and Foreign supply labor, consume, and trade state-contingent bonds. The representative household's maximization problem is

$$\max_{C,L,B} \sum_t \sum_{\eta^t} \beta^t \pi\left(\eta^t\right) u\left(C\left(\eta^t\right), L\left(\eta^t\right)\right) \tag{2}$$

$$\text{s.t. } P_c(\eta^t)C(\eta^t) + \sum_{\eta^{t+1}} Q(\eta^{t+1}|\eta^t)B(\eta^{t+1}) = B(\eta^t) + W(\eta^t)L(\eta^t) + \Pi(\eta^t), \tag{3}$$

where $B(\eta^{t+1})$ denotes the quantity of bonds that pay one unit of consumption in state η^{t+1} (and zero otherwise) and are priced at $Q(\eta^{t+1})$. The consumption price and wage level are denoted by $P_c(\eta^t)$ and $W(\eta^t)$, respectively. The Home wage is the numeraire. Thus, when we discuss prices, we are always considering a price relative to the wage. Retail firms are owned by the household and their aggregate profits are denoted by $\Pi(\eta^t)$.

3.3 Consumption producers

The aggregate consumption good is a constant elasticity of substitution (CES) bundle of domestic, D, and imported, I, varieties,

$$\begin{aligned} Y_C(\eta^t) = \Bigg[&(1-\tau_c)^{\frac{1}{\gamma}} \left(\int_0^1 \nu_D(j,\eta^t)^{\frac{1}{\theta}} c_D(j,\eta^t)^{\frac{\theta-1}{\theta}} dj \right)^{\frac{\theta}{\theta-1}\frac{\gamma-1}{\gamma}} \\ &+ \tau_c^{\frac{1}{\gamma}} \left(\int_0^1 \nu_I(j,\eta^t)^{\frac{1}{\theta}} c_I(j,\eta^t)^{\frac{\theta-1}{\theta}} dj \right)^{\frac{\theta}{\theta-1}\frac{\gamma-1}{\gamma}} \Bigg]^{\frac{\gamma}{\gamma-1}}, \end{aligned} \tag{4}$$

where $\nu_i(j,\eta^t)$ denotes the demand shock to variety j from source $i \in \{D, I\}$ and $c_i(j,\eta^t)$ denotes the corresponding quantity demanded by the firm. Home bias in the consumption bundle is governed by τ_c. The elasticity parameters θ and γ denote the degree of substitutability within and across domestic and foreign goods, respectively.

The firm chooses quantities of domestic and imported consumption goods, $c_D(j,\eta^t)$ and $c_I(j,\eta^t)$, to maximize profits,

$$P_C Y_C(\eta^t) - \int_0^1 p_D(j,\eta^t) c_D(j,\eta^t)\, dj - \int_0^1 p_I(j,\eta^t) c_I(j,\eta^t)\, dj, \tag{5}$$

subject to (4). The associated demand functions are

$$c_D(j,\eta^t) = \left(\frac{p_D(j,\eta^t)}{P_D(\eta^t)}\right)^{-\theta} \left(\frac{P_D(\eta^t)}{P_C(\eta^t)}\right)^{-\gamma} \nu_D(j,\eta^t)(1-\tau_C) Y_C(\eta^t) \tag{6}$$

$$c_I(j,\eta^t) = \left(\frac{p_I(j,\eta^t)}{P_I(\eta^t)}\right)^{-\theta} \left(\frac{P_I(\eta^t)}{P_C(\eta^t)}\right)^{-\gamma} \nu_I(j,\eta^t)\tau_C Y_C(\eta^t), \tag{7}$$

where $P_D(\eta^t)$ is the price of the bundle of domestic varieties and $P_I(\eta^t)$ is the price of the bundle of imported varieties, defined by

$$P_D(\eta^t)^{1-\theta} = \int_0^1 \nu_D(j,\eta^t) p_D(j,\eta^t)^{1-\theta} dj \tag{8}$$

$$P_I(\eta^t)^{1-\theta} = \int_0^1 \nu_I(j,\eta^t) p_I(j,\eta^t)^{1-\theta} dj. \tag{9}$$

The aggregate price $P_C(\eta^t)$ is a function of the prices of domestic and imported bundles,

$$P_C(\eta^t)^{1-\gamma} = (1-\tau_C) P_D(\eta^t)^{1-\gamma} + \tau_C P_I(\eta^t)^{1-\gamma}. \tag{10}$$

3.4 Manufacturing producers

In each country, there are a continuum of manufacturers that produce a homogeneous good and operate in a perfectly competitive market. These manufacturers are modeled as representative firms. They combine local labor and intermediate goods to produce,

$$M(\eta^t) = \left((1-\alpha) L_p(\eta^t)^{\frac{\omega-1}{\omega}} + \alpha Y_M(\eta^t)^{\frac{\omega-1}{\omega}}\right)^{\frac{\omega}{\omega-1}} \tag{11}$$

where $L_p(\eta^t)$ denotes labor used production, α measures the material share in production, and ω measures the elasticity of substitution between labor and materials. The bundle of intermediate goods used in manufacturing production, $Y_M(\eta^t)$, is a CES bundle of domestic and imported varieties,

$$Y_M(\eta^t) = \Bigg[(1-\tau_m)^{\frac{1}{\gamma}} \left(\int_0^1 \nu_D(j,\eta^t)^{\frac{1}{\theta}} m_D(j,\eta^t)^{\frac{\theta-1}{\theta}} dj\right)^{\frac{\theta}{\theta-1}\frac{\gamma-1}{\gamma}} + \tau_m^{\frac{1}{\gamma}} \left(\int_0^1 \nu_I(j,\eta^t)^{\frac{1}{\theta}} m_I(j,\eta^t)^{\frac{\theta-1}{\theta}} dj\right)^{\frac{\theta}{\theta-1}\frac{\gamma-1}{\gamma}}\Bigg]^{\frac{\gamma}{\gamma-1}}, \tag{12}$$

where $\nu_i(j,\eta^t)$ is the same firm-specific demand shock in (4). The quantity of variety j used to produce manufactured goods is denoted by $m_i(j,\eta^t)$. The home bias in intermediate good use is captured by τ_m. The differential home bias in consumption and manufacturing allows us to make trade less intensive in consumption goods, as observed in the data (Boileau, 1999; Miroudot et al., 2009). Note that the home bias is the only difference in the consumption and manufacturing production technologies.

Manufacturers take the wage, the price of intermediates, $P_M(\eta^t)$, and the price of output, $p^m(\eta^t)$, as given and choose quantities of imported and domestic goods and labor to maximize profits

$$p^m(\eta^t)M(\eta^t) - \int_0^1 p_D(j,\eta^t)m_D(j,\eta^t)\,dj - \int_0^1 p_I(j,\eta^t)m_I(j,\eta^t)\,dj - W(\eta^t)Lp(\eta^t), \tag{13}$$

subject to (11). Optimization yields demand functions for each intermediate variety,

$$m_D(j,\eta^t) = \left(\frac{p_D(j,\eta^t)}{P_D(\eta^t)}\right)^{-\theta} \left(\frac{P_D(\eta^t)}{P_M(\eta^t)}\right)^{-\gamma} \nu_D(j,\eta^t)(1-\tau_M)Y_M(\eta^t) \tag{14}$$

$$m_I(j,\eta^t) = \left(\frac{p_I(j,\eta^t)}{P_I(\eta^t)}\right)^{-\theta} \left(\frac{P_I(\eta^t)}{P_M(\eta^t)}\right)^{-\gamma} \nu_I(j,\eta^t)\tau_M Y_M(\eta^t). \tag{15}$$

The price index for the intermediate input used in manufacturing, $Y_M(\eta^t)$, is

$$P_M(\eta^t)^{1-\gamma} = (1-\tau_M)P_D(\eta^t)^{1-\gamma} + \tau_M P_I(\eta^t)^{1-\gamma}. \tag{16}$$

3.5 Retailers

Each country has two retail sectors, one for domestic goods and another for imported goods. Each sector consists of a unit mass of firms that sell differentiated products. The firms face stochastic, idiosyncratic demand, $\nu(j, \eta^t)$, and hold inventories, $s(j, \eta^t)$. In each period, firms decide how much input, $z(j, \eta^t)$, to order and what price, $p(j, \eta^t)$, to charge for their differentiated variety.

Input orders are subject to delay, as defined in (1). The timing is as follows: firms observe their demand and place their input orders, then they observe whether the inputs arrive in the current period, and finally, they set prices. Firms pay a fixed cost ϕ_D or ϕ_I if they order a positive quantity of inputs. Thus, firms have an incentive to order less frequently and save inputs in inventories to meet demand. Inventories of firms selling domestically-sourced goods $s_D(j, \eta^t)$ (and for imported-good firms, $s_I(j, \eta^t)$) depreciate at rate δ. Goods that were ordered but not delivered in the current period also depreciate at the same rate—they depreciate in transit.

A firm's sales are limited by the stock of goods on hand, so total sales are restricted to sales of inventories and any goods that arrive in the current period. If demand exceeds this value, the firm sells all of its goods on hand and carries zero inventories into the next period. Ending-period inventories are carried over to the next period net of depreciation.

In the following, we present the recursive problem of the home country's domestic-good retailers. The problems for the home country's imported-good retailers and the foreign country's retailers are analogous. For simplicity, we suppress the notation for the aggregate state unless needed for clarity.

Given the firm's beginning of period inventory and demand, s and ν, the firm's value is

$$V_D(s, \nu) = \max \left\{ V_D^N(s, \nu), J_D(s, \nu) - W\phi_D \right\}, \qquad (17)$$

where V_D^N is the value of the firm if it does not place an order for inputs and $J_D(s, \nu)$ is the gross value of the firm if it places an order for inputs. If the firm places an order, it pays the fixed cost ϕ_D, which is denominated in units of labor.

If the firm does not place an order, it chooses its price and quantities to sell to the manufacturing and consumption-good firms. These quantities are constrained by the inventories on hand,

$$V_D^N(s,\nu) = \max_{p,c,m} p\left[c\left(p,\nu\right) + m\left(p,\nu\right)\right] + \mathop{\mathbb{E}}_{\nu'} QV_D(s',\nu') \tag{18}$$

$$\text{s.t.} \;\; s \geq c\left(p,\nu\right) + m\left(p,\nu\right) \tag{19}$$

$$s' = (1-\delta)\left[s - c\left(p,\nu\right) - m\left(p,\nu\right)\right]. \tag{20}$$

If the firm places an order, either the inputs arrive in the current period or the next. If the inputs did not arrive in the current period, the value of the firm is

$$V_D^O(s,\nu,z) = \max_{p,c,m} p\left[c\left(p,\nu\right), m\left(p,\nu\right)\right] + \mathop{\mathbb{E}}_{\nu'} QV_D(s',\nu') \tag{21}$$

$$\text{s.t.} \;\; s \geq c\left(p,\nu\right) + m\left(p,\nu\right) \tag{22}$$

$$s' = (1-\delta)\left[s + z - c\left(p,\nu\right) - m\left(p,\nu\right)\right]. \tag{23}$$

Notice that the inputs, z, do not appear in the stockout constraint (22) and deterministically arrive in the next period. If the inputs arrive in the current period, the firm's value is the same as that defined in (18) except its inventories are $s+z$. The value of the firm when it places an order is

$$J_D(s,\nu) = \max_z \; -p^m z + (1-\mu_D)V_D^N(s+z,\nu) + \mu_D V_D^O(s,\nu,z). \tag{24}$$

The solution to these problems takes the form of an "sS rule," where firms place orders when inventories have fallen to low enough levels. Conditional on reordering, the firm places an order to equate the expected marginal value of a unit of inventory in the next period to the marginal price of the input today

$$\mathop{\mathbb{E}}_{\nu',\eta',\mu_D} Q(\eta'|\eta)(1-\delta)V_{D1}\left(s',\nu';\eta'\right) = p^m(\eta), \tag{25}$$

where V_{D1} is the derivative of the value function with respect to the inventory level and the expectation is over next period's aggregate and idiosyncratic shocks and this period's delivery shock.

The firm's pricing rule depends on the level of current inventories and demand. When firms are constrained by their stock of inventories, they set a price to sell everything on hand. When they are unconstrained, the pricing function has the usual constant markup specification common to CES-monopolistic-competition formulations,

$$p(s,\nu) = \frac{\theta}{\theta-1}(1-\delta) \mathop{\mathbb{E}}_{\nu',\eta'} Q(\eta'|\eta) V_{D1}\left(s',\nu';\eta'\right). \tag{26}$$

Notice that the markup is over the discounted marginal value of inventories tomorrow and is adjusted by the depreciation rate of inventories. If the firm makes a sale today, it begins the next period with fewer inventories.

3.6 Equilibrium

An equilibrium is a set of quantities: $C(\eta^t)$, $B(\eta^t)$, $L(\eta^t)$, $M(\eta^t)$, $\Pi(\eta^t)$, $L_p(\eta^t)$, $m_D(j,\eta^t)$, $m_I(j,\eta^t)$, $c_D(j,\eta^t)$, $c_I(j,\eta^t)$, $s_I(j,\eta^t)$, $s_D(j,\eta^t)$, $z_I(j,\eta^t)$, $z_D(j,\eta^t)$, prices: $p^m(\eta^t)$, $W(\eta^t)$, $Q(\eta^{t+1}|\eta^t)$, $p_I(j,\eta^t)$, $p_D(j,\eta^t)$, for $t = 0,\ldots,\infty$ and $j \in [0,1]$ and value functions for Home and Foreign, such that

1. Given prices, allocations are the solutions to the households', consumption-good firm, manufacturing-good firm, and the retail firms' optimization problems in each country.
2. The consumption- and retail-good markets clear in each country.
3. The manufacturing-good markets clear in each country. The supply of the manufactured good produced in each country is sold domestically and exported,

$$M(\eta^t) = \int_0^1 z_D(j,\eta^t)dj + \int_0^1 z_I^*(j,\eta^t)dj \tag{27}$$

$$M^*(\eta^t) = \int_0^1 z_D^*(j,\eta^t)dj + \int_0^1 z_I(j,\eta^t)dj. \tag{28}$$

   where $z_i(j,\eta^t)$ denotes the intermediate good orders by retailer j of type $i \in \{D,I\}$.

4. Inventories are equal to

$$S(\eta^t) = \int_0^1 s_D(j,\eta^t)dj + \int_0^1 s_I(j,\eta^t)dj \tag{29}$$

$$S^*(\eta^t) = \int_0^1 s_D^*(j,\eta^t)dj + \int_0^1 s_I^*(j,\eta^t)dj. \tag{30}$$

5. Labor markets clear in each country. Labor-market clearing in the home country equates labor supply with labor demand from production labor and labor used for order costs,

$$L(\eta^t) = L_p(\eta^t) + \int_j \phi_D \mathbf{1}_{z_D(j,\eta^t)}dj + \int_j \phi_I \mathbf{1}_{z_I(j,\eta^t)}dj, \tag{31}$$

   where $\mathbf{1}_{z_D(j,\eta^t)}$ is equal to one when firm j places an order and zero otherwise. Labor market clearing in the foreign country is analogous.

6. Bonds are in zero net supply, i.e. $B(\eta^t) + B^*(\eta^t) = 0$ for all η^t.

3.7 Decisions rules in and out of steady state

In Figure 9(a), we plot the ordering rules for domestic and importing retailers that receive the median demand shock as a function of their inventory level. Fixed ordering costs imply that firms only order when inventories fall below a threshold. The importing firm, which faces a higher fixed cost, orders at a lower threshold and places a larger order than the domestic retailer. Notice that, below the order threshold, the amount ordered falls with the level of inventory as firms can meet some of the current demand out of its current order if it is delivered. Owing to the different delivery times, this option is more valuable for domestic than importing firms and leads to a steeper drop in purchases with inventories.

In Figures 9(b) and 9(d) we plot the steady-state distribution of inventories and the ordering hazard that integrates over the demand shocks. The domestic retailers order more frequently and face shorter lead times, so the inventory distribution for domestic firms has a lower mean and less variance than the importing retailers.

In Figure 9(c) we plot the same retailers' pricing decisions as a function of inventory level in the steady state. Two functions are plotted. The first is the price when the firm's shipment arrives in the period. The second is the price when the firm's order is delayed. When the firm does not order (to the right of the order threshold) the two are identical and falling with the level of inventories. If the firm orders and the goods arrive in the period, the firm's price falls slightly with the inventory level but is very close to a constant markup over p_m. If the order does not arrive, the firm sets its price to stockout and the price function follows the inverse demand function. Notice that in the delayed delivery case, the price of imported goods is identical to the domestic price but otherwise it is higher owing to the larger logistic costs increasing the marginal value of imported inventories relative to domestic inventories.

In Figure 9(a), we plot the change in the importing retailer's ordering rule following a persistent aggregate shock to global import delivery times that raise the delivery time from 55 to 90 days (dashed line). There are two main changes along the intensive and extensive margins. First, low-inventory firms reduce their orders as there is no chance of them selling to current customers with inputs purchased in the current period. Furthermore, the longer delivery time incurs higher holding costs. Second, higher inventory firms start ordering sooner (i.e., the threshold shifts to the right) as firms expect to be unable to meet future demand with a contemporaneous shipment. To avoid being constrained in the future, they stock up on inputs today.

4 Quantification

In this section, we describe how we choose parameters for our quantitative analysis. The calibration largely follows the approach in Alessandria et al. (2022), which is primarily focused on understanding the effect of domestic delays in an earlier period (1950–1987) when trade was less important and logistic frictions were larger. Here, we calibrate the steady state of a two-country symmetric model to capture key features of the U.S. and ROW economies in the period 2010–2019, as measured in real terms. We abstract from differences in the composition of trade across countries and steady state-trade imbalances. As we aim to capture the dynamics of production, inventory investment, input usage, and consumption of goods, we focus on the goods-producing sector. A period in the model is one quarter. The parameter values are summarized in Table 1.

Assigned Parameters. The aggregate effects of transitory shocks are largely determined by the different substitution elasticities. In particular, the three substitution elasticities in production (θ, γ, ω) and two substitution elasticities in preferences (σ, ψ) are important for the quantitative results. We follow the literature on international business cycles in setting these parameters. As our focus is on delays, we emphasize that the elasticity of substitution across varieties, θ, is particularly important. In Alessandria et al. (2022) we show that the contractionary effect of shipping delays is falling in the elasticity of substitution across varieties since agents become more willing to substitute between in-stock and delayed goods.

The utility function is

$$u(C, L) = \frac{C^{1-\sigma}}{1-\sigma} - \chi \frac{L^{1+\frac{1}{\psi}}}{1+\frac{1}{\psi}}. \tag{32}$$

The intertemporal elasticity of substitution, $1/\sigma$, is set to two. We set the Frisch elasticity to one-half and the discount factor, β, is $0.96^{1/4}$.

The elasticity of substitution across varieties in the manufacturing (12) and consumption-good (4) technologies, θ, governs how consumers and producers substitute between inputs that are constrained by inventories or not. We set θ to six to generate a 20 percent gross markup absent an inventory constraint. After accounting for the fixed order costs and inventory holding costs, the net markups are 14 percent. The elasticity of substitution between intermediate goods and labor in (11), ω, is one. We set the intermediate-good share, α, of manufacturers to 64 percent, to match the intermediates' share of gross output in manufacturing. Goods depreciate at rate δ. We set the annual depreciation rate to 20 percent, similar to the value found in Richardson (1995).

The Armington elasticity, γ, is a key parameter for the transmission of shocks across countries. Estimates of this parameter vary widely between work in international macro and international trade (Ruhl, 2008) and our model includes elements from both of these literatures. These differences stem in large part from the identification scheme and horizon considered. Following Backus et al. (1994), most authors choose an elasticity of 1.5, yet there are good reasons to go with a lower value. Alessandria and Choi (2021) estimates both short-run and long-run Armington elasticities for the United States, accounting for inventory adjustments, and find a quarterly elasticity of 0.2 and a long-run elasticity of 1.1, with about 7 percent of the gap closed per quarter. Heathcote and Perri (2014) show that international business cycles are best explained with an Armington elasticity of about 0.6. Given this range of values, we set the Armington elasticity to 1.1. Note that, at the product level, each wholesale/retail firm is specialized in the distribution of a single input distinguished by source and has no substitution possibilities.[7]

Jointly determined parameters. The remaining eight parameters are jointly determined by matching eight moments from the data.[8] The weight on leisure, χ, largely determines the household's work effort. We match a steady-state labor share of total time to be one-third. The taste for foreign goods in consumption, τ_c, and manufacturing production, τ_m, are set so that the exports-to-manufacturing sales ratio is 30 percent and the share of manufacturing in total imports is 75 percent.[9]

The ordering fixed costs, ϕ_D and ϕ_I, average order delays, $\bar{\mu}_D$ and $\bar{\mu}_I$, and the variance of the idiosyncratic demand-shock process, σ_ν^2, shape the ordering and inventory behavior in the model. These parameters help us match moments from domestic and global supply chains related to frequency, size, and speed of shipments.

We target an aggregate inventory-to-sales ratio of 1.22 quarters, as it is in the U.S. data.[10] The inventory-sales ratio of imported goods is twice that of domestic goods, as documented in firm-level data for a range of countries (Alessandria et al., 2010b; Nadais, 2017; Khan and Khederlarian, 2020). From the ordering frequency data, we target that 32 percent of importers order per quarter and domestic buyers order twice as often (63 percent), in line with the evidence in Alessandria et al. (2010b) and Alessandria and Ruhl (2021). We target a lead time of 41 days as measured in the ISM data.

The fixed cost of ordering the domestic good relative to the imported good is critical in determining the differences in ordering frequencies. Higher fixed costs lead to less frequent orders but, as is well-known from the Economic Order Quantity model, the log difference in the ordering frequency rises at half the difference in the log ordering costs, thus we need

[7]Boehm et al. (2019) estimate a firm-level substitution elasticity following the Tōkhu earthquake and find foreign inputs are Leontief with domestic inputs.

[8]The eight parameters are: $\chi, \tau_c, \tau_m, \phi_D, \phi_I, \mu_D, \mu_I$, and σ_ν^2.

[9]This division is based on end-use. We follow the convention of Caliendo and Parro (2015) and allocate capital to material input trade.

[10]In our model, all inventories are held by the retail/wholesale sector, while in reality, inventories are distributed across manufacturers, wholesalers, and retailers. Thus, we use the aggregate inventory-sales ratio in the data.

much larger fixed costs for international transactions.

The demand shocks are log-normally distributed and are identically and independently distributed across varieties and time. We find the variance of the demand shocks to be 1.5. The fixed order costs are 1 percent and 13 percent of the average quarterly revenues for domestic and imported goods buyers, respectively.

Measuring lead times is challenging, more so when trying to measure them separately for domestic and international transactions. We follow the ISM data on production inputs and target a steady state expenditure-weighted delay of 41 days. This is about two-thirds of the average lead time for production materials in the period 2010–2019. With our other target moments we recover a domestic lead time of 35 days and import lead time of 55 days. The additional 20 days for international trade is on the low side compared to the time to ship by boat from China, but perhaps captures a reasonable average once one considers the alternative trading relationships and some faster modes of transport that are possible internationally.

5 Aggregate effects of transitory delays

In this section, we illustrate how the aggregate economy responds to an unanticipated, exogenous, and temporary increase in the delivery time for international goods. We also explore how increases in delivery time affect the economy when inventories are low, consumption is subsidized, or employment is discouraged (e.g., for public health reasons). All the shocks we consider follow an AR(1) process with a quarterly persistence of 0.75. We continue to study a symmetric model. The shocks are global and hit each country identically. We study the transition following these shocks from the non-stochastic steady state.

5.1 Import delays

Our baseline analysis considers a shock, ε_{μ_I}, to (1), that, on impact, increases international shipping times from 55 days to 90 days. Recall, shipping times from China to the U.S. West Coast rose by about 40 days from pre-COVID to the start of 2022. Given the share of international trade in total expenditures, this is equivalent to increasing the average shipping delay by about 5.5 days. We assume that firms observe the shock *before* deciding to order goods during that period. Figure 10 plots the aggregate implications of this shock relative to the steady state.

The direct effect of the international delay is to reduce international trade, although the effects are non-monotonic and depend on where trade flows are measured. In Figure 10(b), we report the path of imports relative to the steady state for two different measures of imports. The first measure (the solid blue line) counts goods as home imports only when they arrive at the importer and, therefore, excludes any goods that are delayed until they are delivered in the next period. With this measure of imports, the only imports at $t = 0$ are those goods that were ordered in the previous period and were delayed, so trade falls sharply. The second measure (the dashed red line) counts as imports all of a given period's orders whether they arrive or not. In this measure, orders (and imports) increase on impact as firms realize that, over the next few periods, it will take longer than usual to receive goods so they buy goods earlier than they otherwise would. This can also be seen in Figure 10(e), in which the labor devoted to ordering costs increases substantially on impact, reflecting the increase in the number of firms that order at $t = 0$. This ordering behavior was common in mid-2021 and mid-2022, as many firms, expecting shipping delays, rushed to obtain goods for the holiday shopping season months earlier than normal. The model predicts that, after the first period, orders fall because many firms that want to restock already ordered in $t = 0$ and will get those shipments at $t = 1$ with probability one. In addition to a large number of past orders, a small fraction of goods ordered in $t = 1$ also arrive in $t = 1$ as the shock to delays is transitory. Thus, ordered goods fall below the steady state, and "arrived" goods rise above the steady state, yielding the non-monotonic response of the model. In actual trade data, imports are counted when they reach the port, even if they have not yet reached the manufacturer. Thus, we would expect the response of actual imports to the shock to lie somewhere between our two import measures in Figure 10(b).

The delays in importing foreign goods lead to a substantial contraction in economic activity, with production, consumption (panel a), and employment (panel e) falling sharply on impact. The largest effect is on production, which drops 8.7 percent on impact. Production stays low for two quarters before rebounding sharply in the third quarter, but remains 4.8 percent below the initial steady state. The economy gradually converges to the steady state, although one year after the shock, production remains 2.7 percent below its steady-state value. The effect of the shock is smaller for employment than for production because firms can substitute between material inputs and labor and there is a sharp increase in logistic costs (ordering labor) related to restocking inventories.

For production, the increase in import lead times is qualitatively similar to a negative productivity shock. There are three key forces at work. First, there is the standard cost channel as the longer time to restock increases the cost of inputs and thus reduces the incentive to produce. Second, the shipping delays have different effects across firms, constraining the sales of the firms for whom restocking is most valuable—those with relatively low inventories or relatively high demand. Third, even though the shock dissipates quickly, it takes time for the economy to recover as the reduction in inventories is an important constraint on production.

The weaker effect of the international shipping delay shock on consumption compared with production is a function of imports being less important for consumption than for production and the usual consumption smoothing motive. Inventory decumulation cushions the fall in consumption compared to production. Although the effect on consumption is weaker on impact, it is as persistent as the effect on production, as consumers are limited in the goods they can buy until manufacturers have finished replenishing their inventories.

Given the inability to restock imported goods within the period, more importing firms stockout, which we measure as being constrained by their inventory on hand, as seen in panel (d). By contrast, firms that use domestic goods are little affected, as they face two largely offsetting forces: the lack of imported goods causes substitution in consumption and manufacturing toward domestic goods, but the increase in the price of final goods relative to wages decreases demand for all goods. As importers stock out, they raise the prices that they charge manufacturers, as shown in the line for P_I in panel (f). The increase in the input price increases the prices for consumption and manufacturing producers. The consumption price (P_c) increases by 6.9 percent on impact and remains 1.8 percent above steady state two years later.

The total stock of inventories falls gradually with a delay. The effect on impact reflects two offsetting forces. On the one hand, the import delays substantially reduce the products being held at retailers of imported goods. On the other hand, more goods are being held in transit. We assign goods in transit to manufacturers and goods available for sale to retailers. Using this division, retail inventories fall over 15 percent on impact while manufacturing inventories rise by nearly 20 percent.

5.2 Shipping delays when inventories are low

We now discuss how the stock of inventories affects the aggregate economy and the propagation of shocks. A key feature of the aggregate economy since the onset of the pandemic is a very low level of inventories. The initial decline in spending on goods early in the pandemic was small compared to the decline in production and thus was met by a draw from the stock of goods. When inventories are low, the scarcity of goods will increase prices even though the rebuilding of stocks is expansionary. With low stocks, the increase in shipping delays can lead to larger aggregate effects.

Specifically, we allow the economy to experience two shocks at $t = 0$. The first shock destroys one-third of the retail sector's inventories and the second shock is the import delay shock we studied in the previous section. Both shocks are surprises at $t = 0$ but agents have perfect foresight thereafter.[11] To clarify the role of the natural recovery from the low inventories, we plot the path of the economy with only the low inventory shock (black line with marker) and the economy with low inventories and our import delay shock (dashed red line).

We first describe the effects of having low inventories holding delivery times constant. As Figure 11 shows, with low inventories, on impact, manufacturing production increase 2.2 percent above the steady state as workers increase hours by 9.5 percent to meet the demand from retailers to rebuild their stocks. Production rises and then falls back gradually to its steady-state level. A similar, but larger, pattern occurs in imports as importing retailers have a stronger restocking motive. Rebuilding inventories is an investment, so, despite the production and import boom, consumption falls 7.4 percent below the steady state and recovers slowly. The low stock of inventories leads to a persistent rise in stockouts and a rise in the price of consumption. The increase in prices is about one-third as large as the fall in

[11] This implies that only two-thirds of the shipments that were expected to arrive in the next period arrive and that these orders were based on expectations of larger inventories.

inventories and reflects the high marginal value of inventories and not an unusual spike in stockouts (which only rise by 4.4 percentage points).

The effects of an increase in delivery times are magnified when the economy starts out with lower inventories (Figure 11). In this case, production drops by 8.8 percent on impact and largely follows the path from our baseline case. This is the result of a decrease in production from the delay shock, but an increase in production from the inventory destruction shock. We can net out the dynamics of the inventory shock by taking the difference between a variable in the model with both the inventory and delay shock (red dashed line) and the same variable in the model with only the inventory shock (black line with marker). In manufacturing production, for example, the delay shock leads to a larger decrease on impact when inventories are low, compared with the case when the delay shock is the only shock to the economy (11 percent compared with 8.7 percent).

Consumption falls by 13.1 percent on impact, four times more than in the baseline case, and recovers more slowly as rebuilding inventories takes time.[12] Many more firms stock out, the shock has a much larger effect on firm inventory levels, and the consumption price increase is three times larger than in the case with only the delay shock. The magnified response arises because more firms find themselves constrained by a lack of inputs, making it harder to rebuild inventory. Adding the import delay results in more firms charging higher prices to stock out.

5.3 Shipping delays when demand is high

In response to the COVID-induced recession, governments in the United States and the rest of the world increased unemployment benefits, sent checks to households, and made low-interest loans to businesses. These programs, coupled with increased savings during lockdowns and a shift in demand away from services, led to strong consumption growth for goods starting in the summer of 2020. In our model, an increase in delays decreases consumption. In this experiment, we consider a demand shock that increases consumption concurrently with the import delay shock.

To capture these features, we modify the household's budget constraint to include a

[12]Compared to the consumption path with only low inventories, the consumption drop in this case is 77 percent larger.

proportional consumption subsidy, $\tau(\eta^t)$, that is financed by a lump-sum tax, $T(\eta^t)$. In the steady state, the consumption subsidy is zero. The new home-country budget constraint is

$$\tau(\eta^t)P_c(\eta^t)C(\eta^t) + \sum_{\eta^{t+1}} Q(\eta^{t+1}|\eta^t)B(\eta^{t+1}) = B(\eta^t) + W(\eta^t)L(\eta^t) + \Pi(\eta^t) + T(\eta^t), \quad (33)$$

with an analogous budget constraint in the foreign country.

This experiment considers a transitory shock to τ that lowers the cost of consumption goods by five percent and then mean reverts. The shock occurs at $t = 0$, along with the import delay shock, and agents have perfect foresight thereafter. The consumption subsidy cushions the fall in consumption, as seen in Figure 12. Compared with the baseline economy, the extra consumption is primarily accomplished through a larger drawdown of inventories and slightly more production. The price increase is larger as more firms' sales are constrained by their current stock of inventory. Owing to the larger draw on inventories and longer restocking period, prices are persistently elevated.

5.4 Shipping delays when labor supply is low

To capture the lockdowns and the reduction in labor supply during COVID, we introduce a shock to the disutility of working. Specifically, we introduce a transitory shock to the weight on leisure, χ_t. We let the taste for leisure rise by 5 percent, leading workers to work less. In this case, manufacturers struggle not only to get physical inputs because of the delay but also lose workers and cannot substitute toward labor to make up for the lack of goods. In Figure 13, we see that manufacturing production falls more relative to the baseline case. Consumption falls both because fewer manufactured goods are available and because households value it less than leisure. Because of the decreased demand for goods, stockouts and consumption prices are relatively unaffected by the added shortage in labor.

6 A fitting exercise

In this section, we introduce several contemporaneous shocks into the model to account for key features of the U.S. and global economies from the end of 2019 to the middle of 2022. We allow these shocks to differ in the United States and the ROW and fit them to the data.

We then eliminate the delivery delay shocks to decompose the contribution of the different types of supply chain disruptions (domestic, international) to the dynamics of the aggregate economy. We find that shipping delays were a drag on production in 2021 and 2022 and, owing to their elevated levels, will continue to be a drag on economic activity and a source of elevated prices through 2023.

We fit the model to the data with the three types of shocks described earlier: delivery delays, labor supply, and consumption subsidies.[13] Save for the import and domestic delay shocks, we allow these shocks to be asymmetric to capture differences in economic activity between the United States and the rest of the world. These six shocks each follow an AR(1) process with persistence of 0.75.

We assume the economy is in a steady state in 2019Q4 and then recover a sequence of unanticipated shocks that can account for the dynamics of several key macroeconomic variables from 2020Q1 to 2022Q2.[14] We choose these shocks to match the changes in industrial production in the United States and the ROW, the U.S. trade balance as a share of trade, and U.S. consumption of goods. The trade balance is key to identifying foreign stimulus shocks. Given the global resource constraint, matching both foreign output and the trade balance implicitly determines the foreign consumption level. We do not target trade owing to the measurement issues outlined earlier. The supply-chain delay shocks are chosen to match evidence of delays at home and abroad. Specifically, we use the ISM production material delay series to measure delays on domestic deliveries and the change in shipping times between the U.S. and China to measure import delays. There is some uncertainty about the size of these delay shocks and smaller (larger) shocks will scale the effects down (up). Figure 14 plots the path of delays (targeted), stimulus, and disutility of labor. Owing to the different production and public health responses, we recover larger and more persistent stimulus and labor supply shocks in the United States than in the ROW.

In Figure 15, we plot our targeted series (panels a–d) and several additional untargeted

[13] Including productivity shocks would allow us to match labor and industrial production separately, and likely be a force for smaller increase in prices, but as these changes are relatively small, we focus on the other shocks.

[14] Given the complexity of such a fitting exercise with our non-linear model, we follow Boppart et al. (2018) and take a linear approximation of the model around the steady state. We then use these linear decision rules to recover the combination of shocks that fits the model to the data.

series on sales, trade, inventory, and consumer prices (panels e–h) in the United States for our target period and the following year. The model hits the six series exactly and captures some aspects of the untargeted series. Business sales of goods rebound a bit slower than in the data. International trade recovers more slowly than in the data initially but exceeds actual trade flows by the end of 2021. The model predicts a larger inventory drawdown in 2020 and a more robust restocking through 2022. And finally, the price of consumption goods in the United States rises considerably more than the data, with the model predicting prices that are up nearly 50 percent by the end of 2021 compared to about 2.8 percent in the data. All series mean revert as the shocks dissipate, but remain away from the steady state through the end of 2023Q4.

We next consider the aggregate effects of eliminating each of the supply delays: local delays in the U.S., local delays in the ROW, and international delays. Figure 16 plots the change in each variable from the path in our benchmark model when we eliminate the specific delay. For the United States, domestic delays generally have the biggest effects since they are large and hit a larger part of the economy. By 2022Q2, we estimate that domestic delays reduced U.S. industrial production by 12.4 percent. These delays have decreased inventory holdings by as much as 9.4 percent and increased consumption prices by as much as 35.8 percent over the period. Given home bias in production and consumption, delays in the ROW on local transactions have smaller effects in the United States. Delays on international trade are slightly less of a drag on U.S. industrial production in 2021 and 2022 but were a larger drag on output in the early stages of COVID. Reducing the delays in international trade was a big boost to economic growth in 2020Q3. While delays in international inputs have been slightly less important than delays in domestic transactions for economic activity, they are considerably less important for the rise in consumption prices owing to trade being more intensive in intermediate inputs for production than consumption.

6.1 Measurement

There are two main challenges in lining the model up with the data. The first is related to how delays affect measured trade flows and, to a lesser extent, shipments and inventories. As discussed earlier, the impact on trade flows depends on whether the delays occur before or after the border. Likewise, it is not clear when goods in transit show up in measures of inventories at the retail and manufacturing levels. For domestic shipments, delays will have different effects when the delay occurs in shipping from the factory compared with delays in delivery.

The second challenge is related to prices, which increase substantially with our delay shocks. Recall that, in the model, firms set prices contingent on deliveries. This leads firms that have their orders delayed to raise their prices to sell all the goods they have on hand, which substantially increases measured prices. This price captures the marginal value of the constrained goods to our representative consumer or producer.

We now show that alternative measures of prices lead to much smaller increases in prices in the model. First, we construct a price index that uses only goods that are not constrained by current inventories. Figure 17(a) plots the impulse response of the ideal price index alongside the impulse response for the average price of in-stock goods for the baseline international delay-shock economy. The average price increase of in-stock goods rises by about 40 percent of that in the (welfare-relevant) ideal price index. There are reasons to prefer this alternative measure when compared to the data, as national price statistics use only the price of in-stock goods to construct price indices.[15] To get some sense of the effect on aggregate prices from this measurement issue, in Figure 17(b), we construct the consumer price index using the in-stock prices for our fitting exercise. This alternative price index reduces measured prices by about one-third, but still leads to a large gap between the model and the data.[16]

Finally, our model abstracts from labor inputs in the retail/wholesale and consumption sectors. In this respect, it may be more appropriate to compare consumer prices in the model with the producer price index for consumption goods (Figure 17(b)). Since the start of COVID, the producer price index of finished consumer goods deflated by production wages peaked at 16 percentage points above the starting point and had grown twice as much as the CPI-based price index.

[15] The BLS imputes the change in the price of goods that are temporarily unavailable using the change in the price of continuously available goods.

[16] Alternatively, we could allow firms to set prices prior to delivery, which would lower prices of stocked-out goods considerably but not change allocations in the delayed delivery state since firms would still be constrained by their stock on hand. Preliminary work with this alternative model has minimal effects on real quantities but brings the model closer in line with the movements in retail prices.

6.2 Expectations

Here, we explore how the effects of an increase in restocking delays depend on the process for the delay. We show that, when there is an anticipated component to delays, the delays have smaller effects on the economy, as firms prepare by stockpiling. Previous work has shown that this type of anticipatory stockpiling is common when there is a certain or uncertain future shock to trade costs, trade policy, or taxes (Alessandria et al., 2010; Alessandria et al., 2019; Khan and Khederlarian, 2021; Baker et al., 2021). We show how our estimates of the contribution of international delays on aggregate outcomes are influenced by the process of the shock.

We consider a smaller, but hump-shaped, shock with the same discounted change (at the steady-state interest rate) as our baseline case,

$$\mu_I(\eta^{t+1}) = (1 - \rho_{1,I} - \rho_{2,I})\bar{\mu}_I + \rho_{1,I}\mu_I(\eta^t) + \rho_{2,I}\mu_I(\eta^{t-1}) + \epsilon_I(\eta^{t+1}) \tag{34}$$

where $\rho_{1,I} = 1.4$ and $\rho_{2,I} = -0.475$.[17] On impact, the shock increases delays by about 10 days and rises another 5 days by the third quarter before gradually reverting to the mean. Given that delays are smaller on impact and will get worse before they get better, agents have an opportunity to prepare for the future. As shown in Figure 18, this leads to a minor boost in production on impact as firms stockpile inputs in advance. Production falls gradually and bottoms out three percent below the steady state in the fourth quarter. The path after the fourth quarter is similar to the case with an AR(1) shock. Early in the transition, consumption falls by less while prices and stockouts rise by less. The swings in trade are moderated.

We now show how our assumption about the process for the path of delays has modest effects on our estimated contribution of international shipping delay shocks. Specifically, we redo our fitting exercise using the AR(2) international delay rather than an AR(1) international delay. Figure 19 compares the effects on key variables of shutting down the international delay shock. With delays that get worse before getting better, we find smaller

[17] In Alessandria et al. (2022), VAR analysis recovers hump-shaped delay shocks for the United States from 1950–1987.

and smoother effects on output and consumption. The peak effect of delays is about five-percent smaller than our baseline case and comes one period later (in 2022Q2). The effects on consumption are also smaller and peak earlier than in our baseline. There are more substantial differences in the path of trade and inventory. The effects on prices are also about one-third smaller along the path as firms have more time to prepare for worsening delays. The path of stockouts is largely unchanged, however, as it is mostly affected by the shock that constrains ordering firms rather than expectations.

7 Final thoughts

A key feature of the post-COVID economy has been an increase in the time to restock retail and manufacturing inputs. In 2021, owing to a confluence of factors, lead times in the United States rose to levels unseen in 50 years. These restocking delays manifested in a high rate of retail stockouts. We show how changes in lead times, both domestic and international, can influence the aggregate economy. In particular, we show that an increase in lead times similar to those from 2020–2022 can be quite contractionary, more so when inventories are already low, and cause a substantial, but transitory, increase in prices. The restocking cycle increases the persistence of the responses of prices and production to delay shocks.

Our model allows us to decompose the source of fluctuations in aggregate economic activity in the United States and the world economy in the 10 quarters from 2020Q1 to 2022Q2. Delays in restocking goods locally and globally appear to have been a substantial drag on economic activity and a source of rising prices. Given the challenges in bringing these delays down, our model suggests delays will continue to be important factors in aggregate economic activity. However, going forward, our model predicts that the unwinding of restocking delays will be a source of expansion in output and reduction in prices, but that the positive effects on output may not offset the waning influence of the stimulus from 2021.

Our model captures the major forces at work in supply chains: uncertainty in supply and demand, time to ship, and costly inventories. We have abstracted from other factors which could provide additional insights, such as asymmetric industries and countries or shock structures that depart from those we have considered. The dynamics of prices in our framework suggest that incorporating pricing frictions may better account for the data than our model with flexible prices. In this period, we observed firms using faster transport methods, at a higher cost, to speed up the arrival of delayed goods. It would be interesting to study this margin of adjustment in the model.

Finally, we are agnostic about the sources of rising supply-chain delays. Our aim is to understand how these delays propagate through the economy and their influence in the post-COVID world. Gaining a deeper understanding of the source of these delays is important for developing policy responses to address these delays or prevent them in the future. The framework here can be a useful foundation for such an analysis.

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8 Data Sources

- Figure 1: U.S. Bureau of Labor Statistics
  - Inbound Price Index (International Services): Air Freight for Asia (IC1312)
  - Outbound Price Index (International Services): Air Freight (IS231)
  - Producer Price Index by Industry: Truck Transportation (PCU484484)
- Figure 2: IHS Markit Ltd., Markit Purchasing Manager's Index (PMI)
  - Delivery Times (United States, Euro Area, Rest of the World)
- Figure 3: Institute for Supply Management: Report on Business
  - Buying policy: (a) Production Materials (b) Capital Expenditures and (c) Maintenance Repair and Operating (d) Supplier Deliveries Diffusion Index (50+ Slower)
- Figure 4: U.S. Census Bureau M3 Survey
  - Manufacturers' Value of Shipments: Nondefense Capital Goods Excluding Aircraft (ANXAVS)
  - Manufacturers' Unfilled Orders: Nondefense Capital Goods Excluding Aircraft (ANXAUO)
- Figure 5: U.S Census Bureau's Pulse Surveys
- Figure 6: Shipping Times
  - Door to Door shipping from China to U.S. (Freightos.com).
  - Ocean Timeliness Indicators for shipments from China to West Coast: Factory Cargo Ready to Destination Port pickup, measured at pickup date (Flexport.com).
- Figure 7: U.S Census Bureau's Manufacturing and Trade Inventories and Sales Report
  - Inventories to Sales Ratio (a) Wholesalers (WHLSLRIRSA); (b) Manufacturers (MNFCTRIRSA); (c) Retailers (RETAILIRSA)
- Figure 8
  - U.S. industrial production (Board of Governors of the Federal Reserve System) (IPMAN)
  - Rest of World industrial production from the Dallas Federal Reserve Bank;
  - Real Personal Consumption Expenditures: Goods U.S. Bureau of Economic Analysis: Personal Income and Outlays (DGDSRX)
  - Real Manufacturing and Trade Industries Sales: FRB St. Louis based on BEA Supplemental Estimates, Underlying Detail Tables. (CMRMTSPL)
  - Real Exports and Imports: U.S. Census Bureau Monthly Trade Report
- Figures 8e, 16, & 17
  - Real Price of Goods = Price of Goods (PCE)/Average Hourly Earnings and then detrended with HP filter with 10^8.

- Real PPI = PPI/Average Hourly Earnings.
- Personal consumption expenditures: Goods (chain-type price index) U.S. Bureau of Economic Analysis: Personal Income and Outlays (DGDSRG3M086SBEA)
- Average Hourly Earnings of Production and Nonsupervisory Employees, Manufacturing: U.S. Bureau of Labor Statistics (CES3000000008)
- Real Manufacturing and Trade Inventories U.S. Bureau of Economic Analysis, Supplemental Estimates, Underlying Detail Tables (INVCMRMT)
- Importer Stockouts from Cavallo and Kryvtsov (2021). US stockout rate multiplied by 1.1 to capture higher stockout rate of imports.
- Producer Price Index by Commodity: Final Demand: Personal Consumption Goods (Finished Consumer Goods) (WPSFD49502)

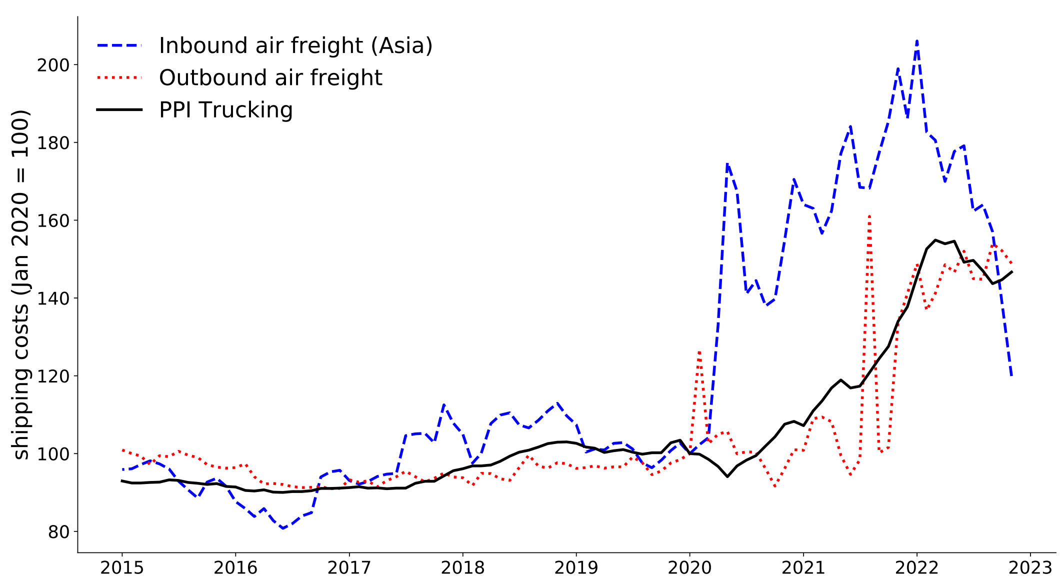
9 Figures and Tables

Table 1: Parameter values and moments (2010–2019)

Assigned parameters: $\beta = 0.96^{1/4}$, $\theta = 6$, $\sigma = 0.5$, $\psi = 0.5$, $\gamma = 1.1$, δ=0.055, α=0.64				
Moments		**Parameters**		
Share of time devoted to work	33%	Disutility of work	χ	65.9
Exports to manufacturing sales	30%	Import weight consumption	τ_c	0.165
Manufacturing share of imports	75%	Import weight manufactures	τ_m	0.425
Inventory-sales ratio (agg)	1.22	Demand variance	σ_ν^2	1.5
Inventory-sales: importer/domestic	2	Domestic delay	$\bar{\mu}_D$	35 days
Average lead time (days)	41	Import delay	$\bar{\mu}_I$	55 days
Order freq (dom)	63%	Fixed order cost† (dom)	ϕ_D	1.02
Order freq (imp)	32%	Fixed order cost† (imp)	ϕ_I	13.05

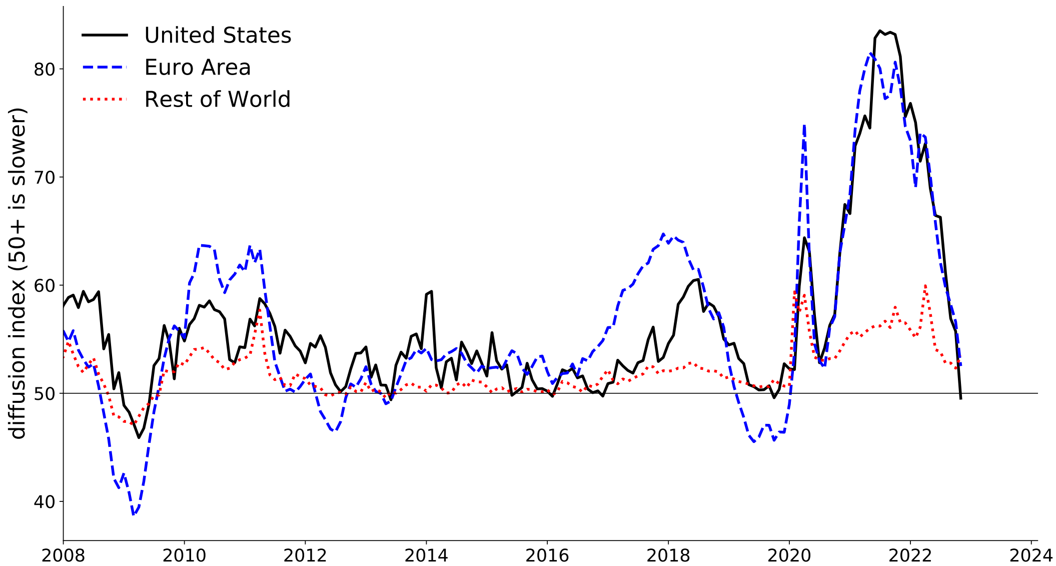
†Expressed as share of average revenue.

Figure 1: Domestic and international shipping costs



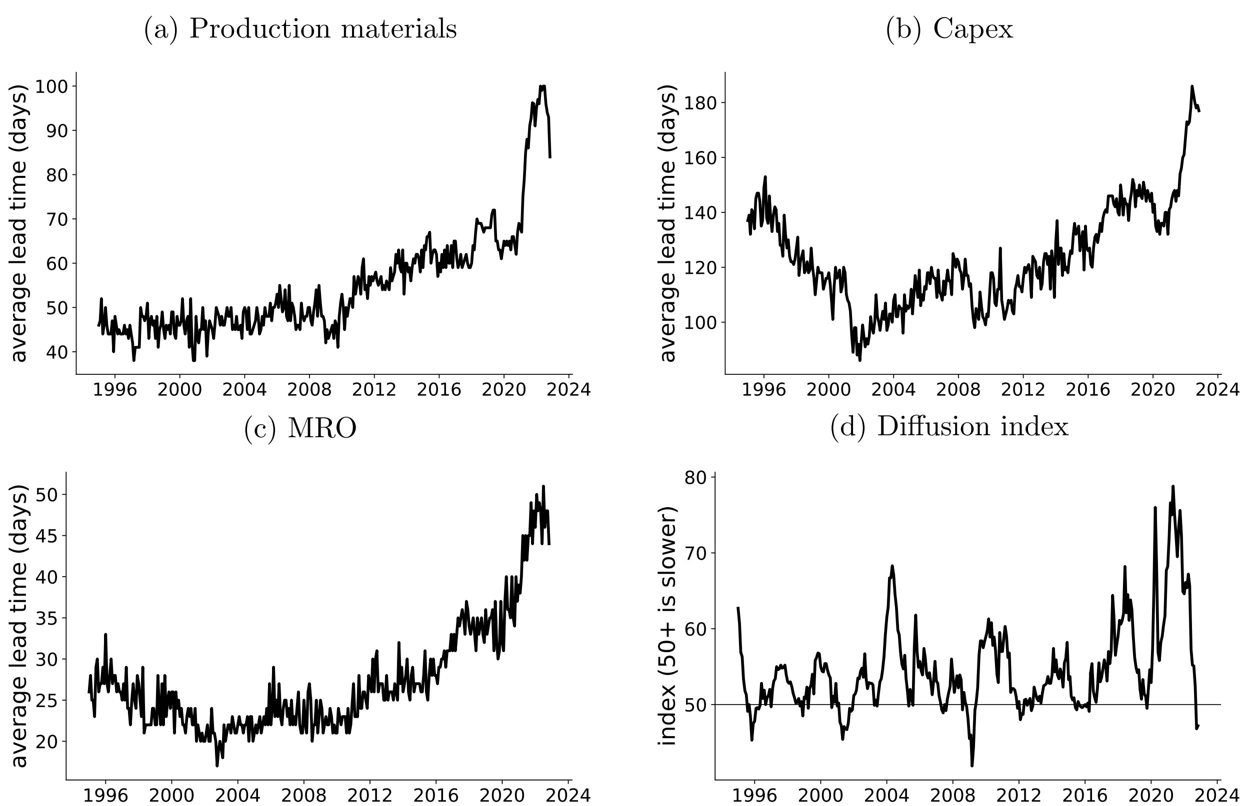
Source: U.S. Bureau of Labor Statistics (last obs. 11/2022).

Figure 2: Manufacturing supplier delivery times



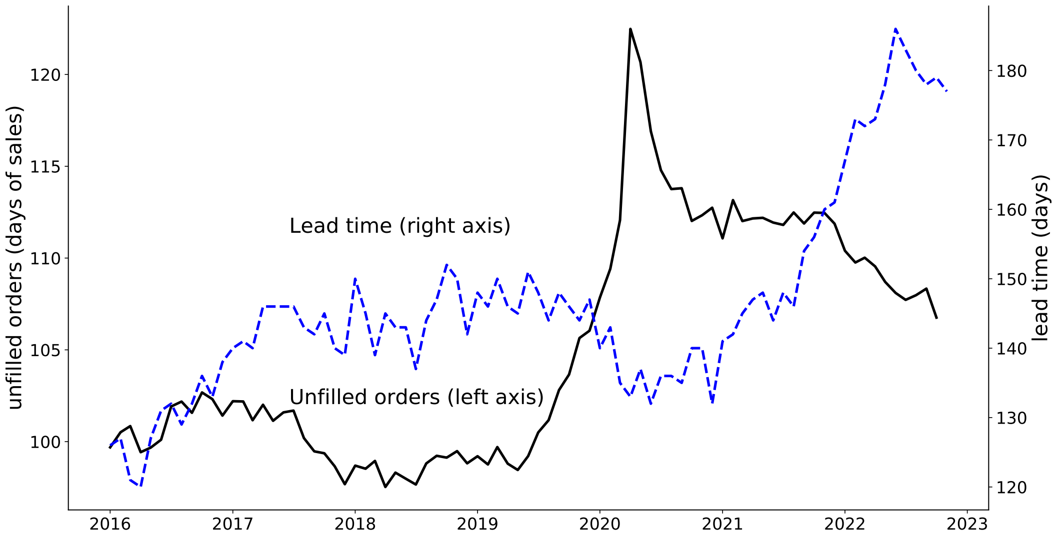
Source: IHS Markit Ltd. (last obs. 11/2022). A diffusion index below 50 implies that delivery times are decreasing. A diffusion index above 50 implies that delivery times are increasing.

Figure 3: Delivery times



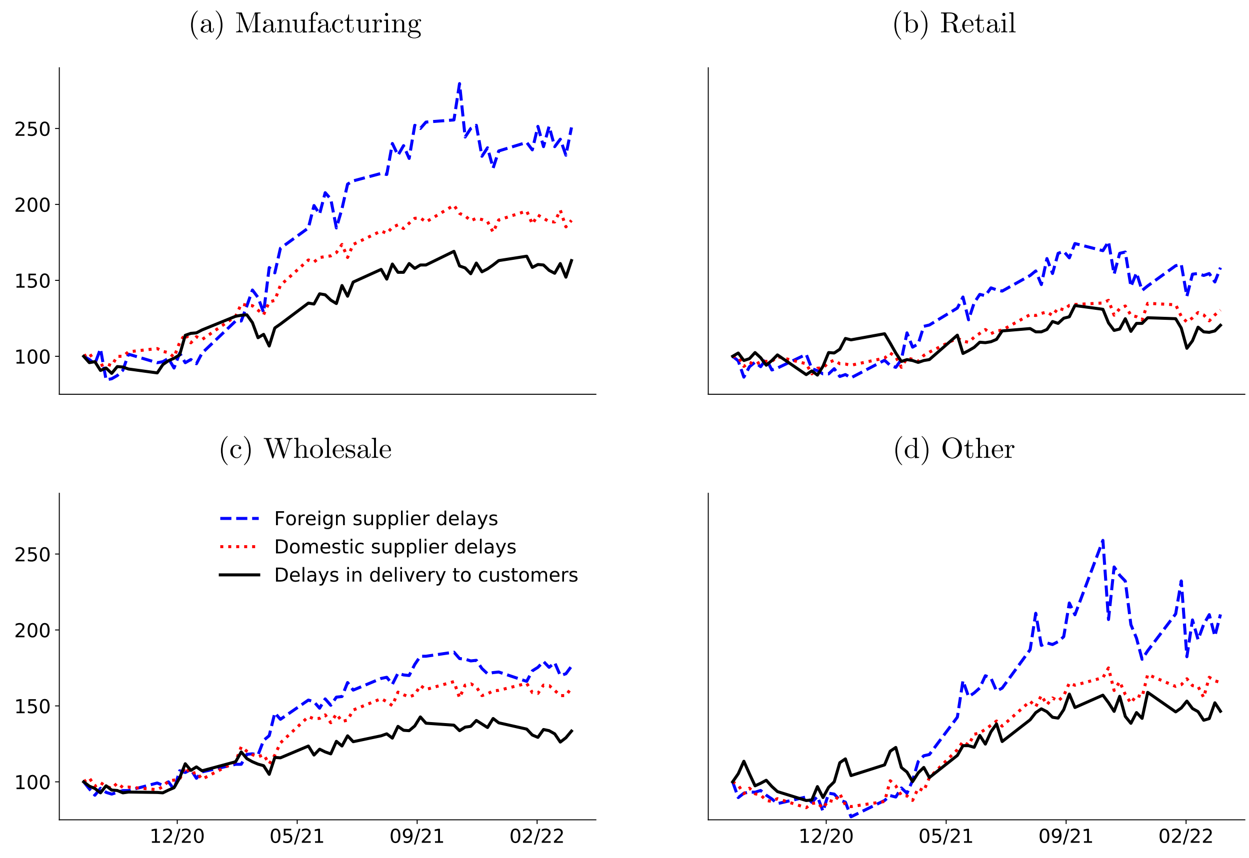
Source: Institute for Supply Management (last obs. 11/2022). Panel d: A diffusion index below 50 implies that delivery times are decreasing. A diffusion index above 50 implies that delivery times are increasing.

Figure 4: U.S. unfilled orders (nondenfense capital goods, ex. aircraft)



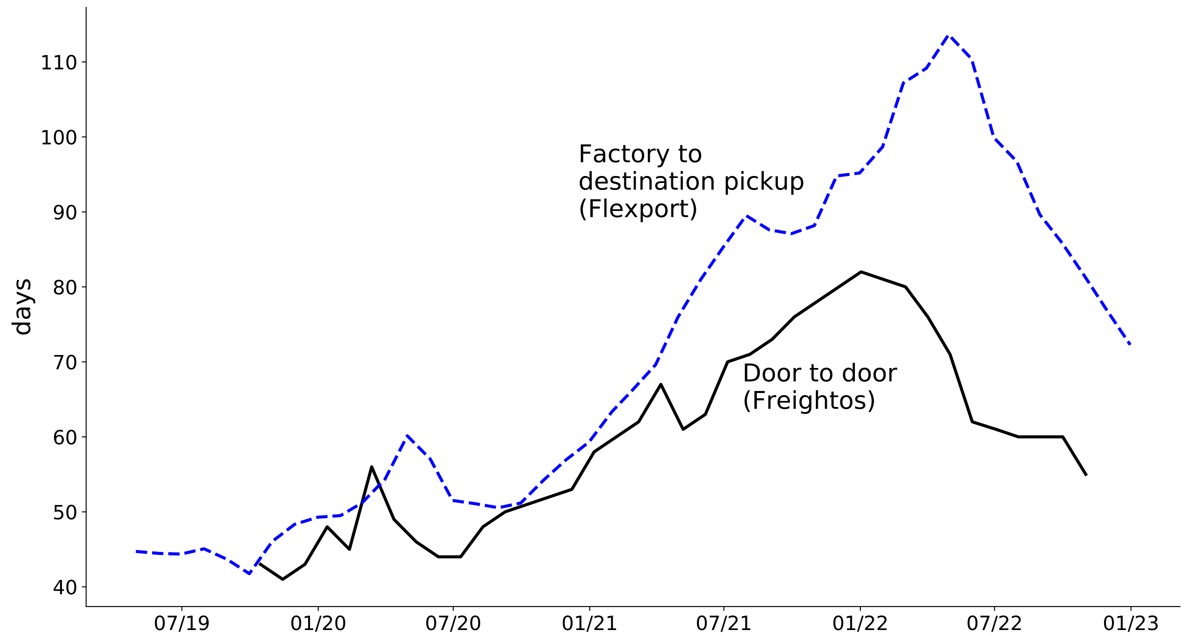
Source: Unfilled orders are from the U.S. Census Bureau's Manufacturers' Shipments (last obs. 10/2022), Inventories, and Orders. Lead times are from the Institute for Supply Management (last obs. 11/2022).

Figure 5: In the last week, did this business have any of the following?



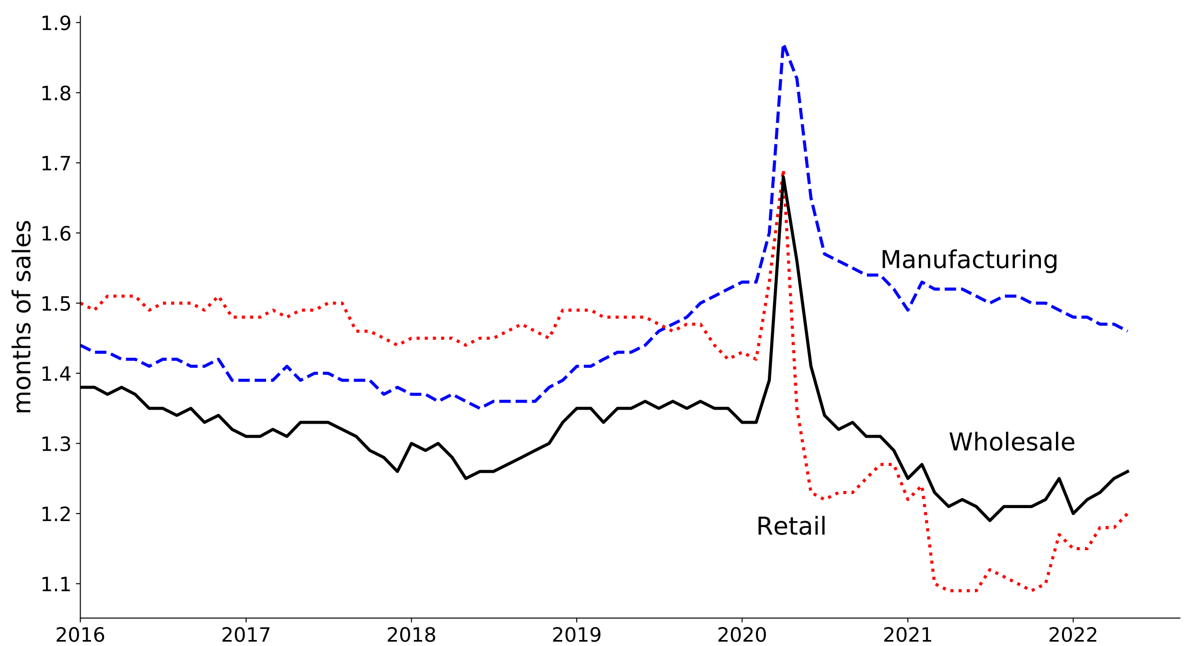
Source: U.S Census Bureau's Pulse Surveys (last obs. 4/11/2022)

Figure 6: Ocean shipping time to United States from China



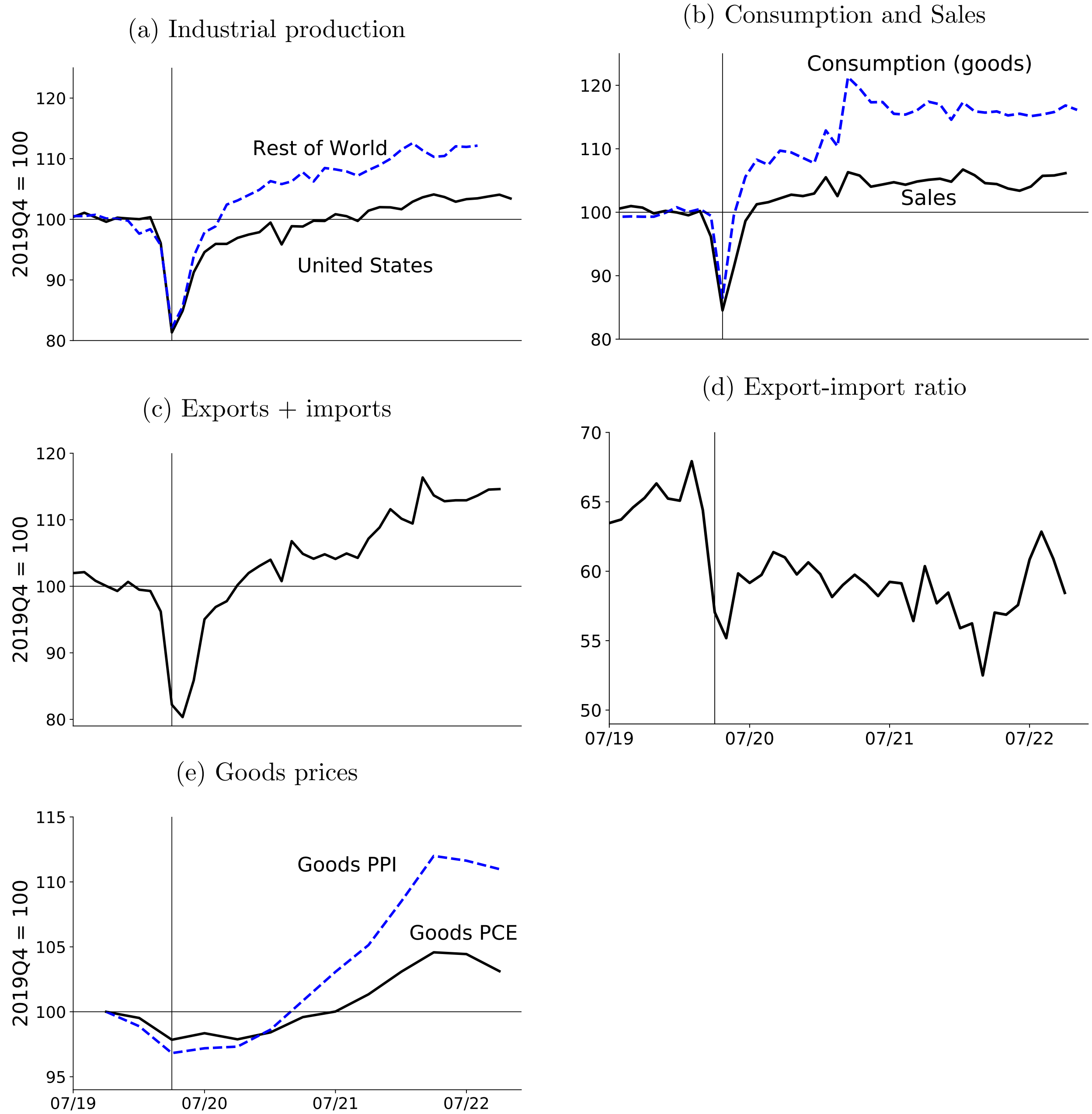
Source: Freightos (freightos.com; last obs. 11/2022) and Flexport (flexport.com; last obs. 12/09/2022)

Figure 7: U.S. inventory-sales ratio



Source: U.S. Census Bureau (last obs. 10/2022)

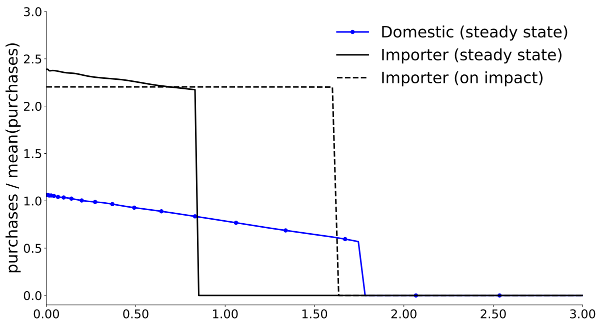
Figure 8: Salient features



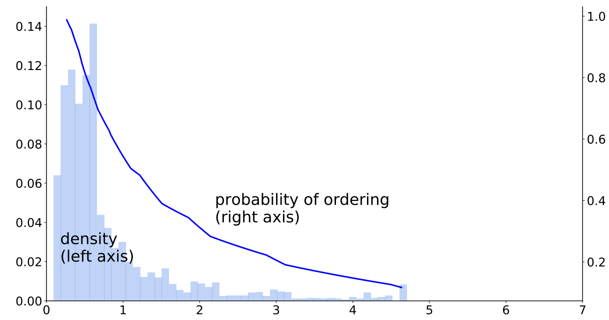
Source: U.S. industrial production from Board of Governors of the Federal Reserve System (last obs. 11/2022); Rest of World industrial production from the Dallas Federal Reserve Bank (last obs. 08/2022); consumption is from the St. Louis Federal Reserve Bank (last obs. 11/2022); sales is from the U.S. Bureau of Economic Analysis (last obs 10/2022); exports and imports are from the U.S. Census Bureau (last obs. 10/2022); Goods PPI from U.S. Bureau of Labor Statistics (last obs. 10/2022); Goods PCE from U.S. Bureau of Economic Analysis (last obs 10/2022);

Figure 9: Decision rules and steady-state inventory distributions

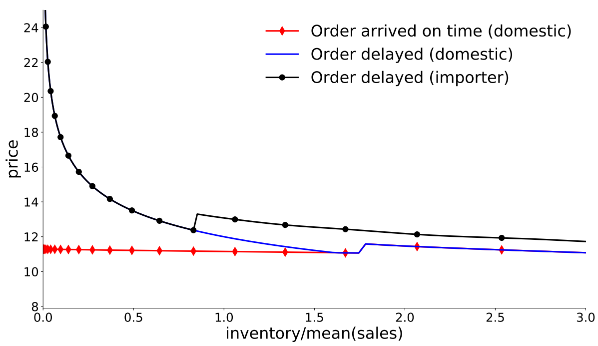
(a) Order-size policy function



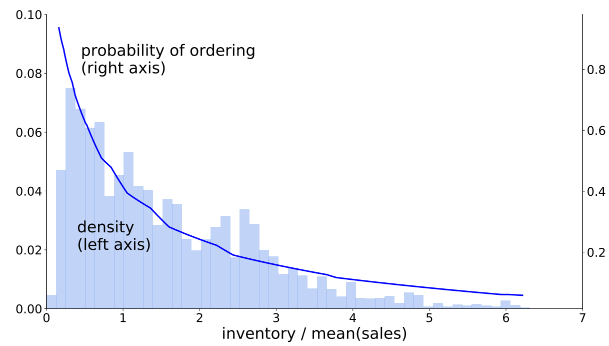
(b) Domestic retailer inventories



(c) Pricing policy function



(d) Importing retailer inventories



Notes: The order hazard functions in panels (b) and (d) have been smoothed.

Figure 10: International delay shock

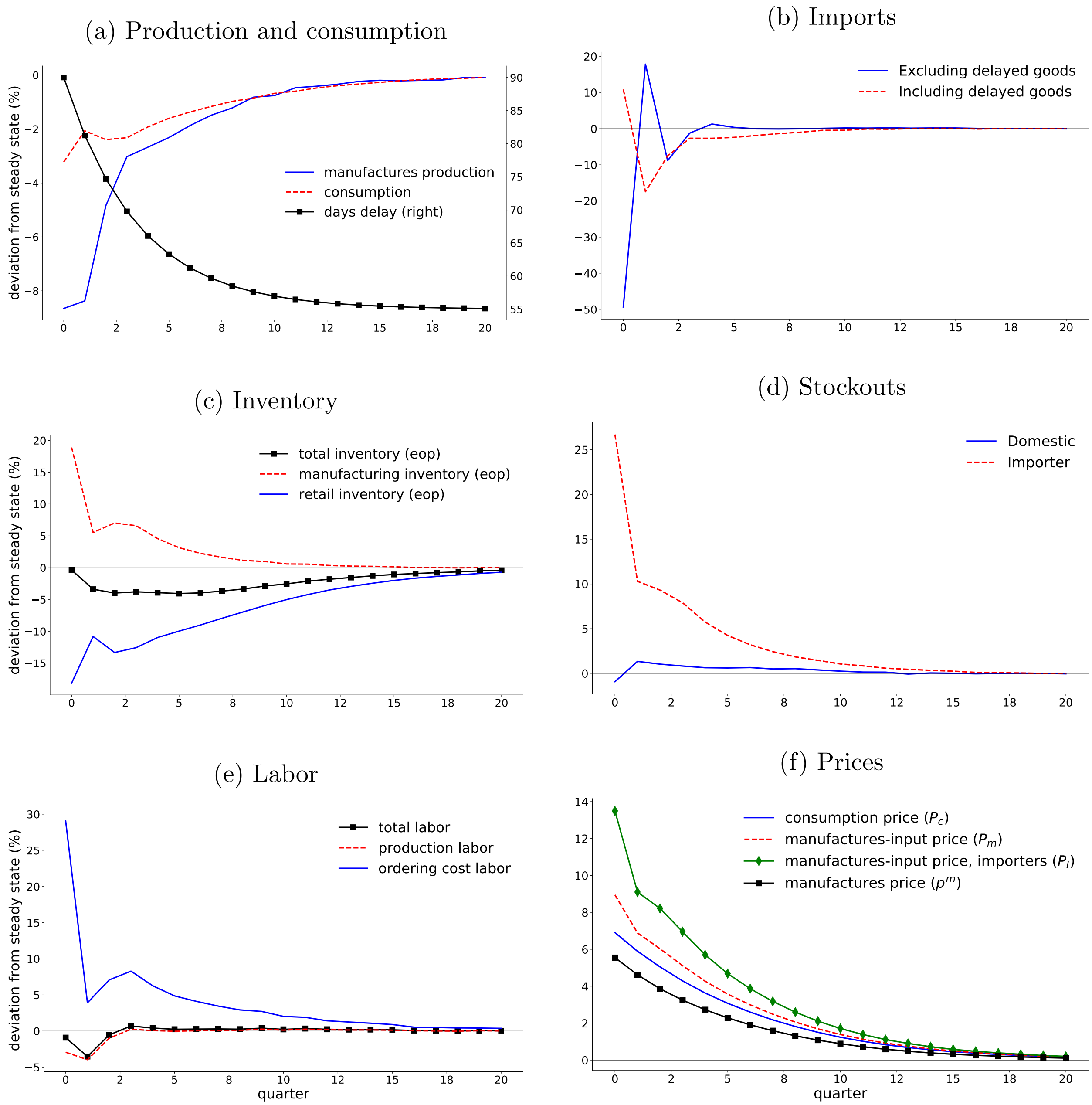
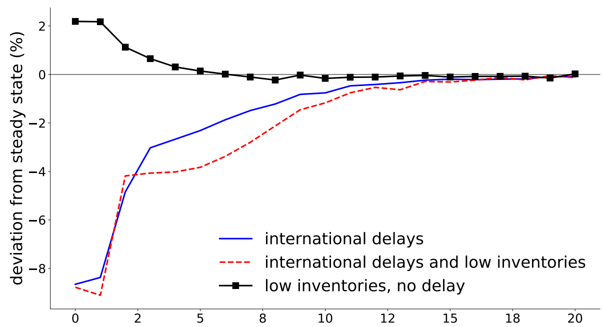
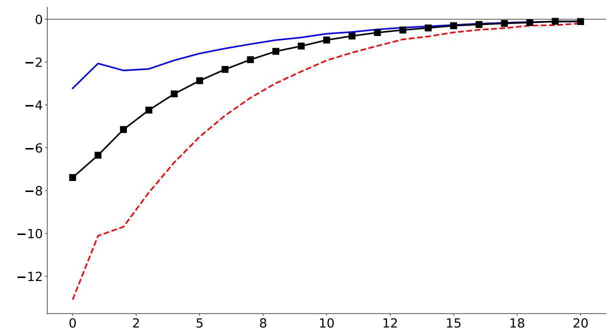


Figure 11: International delay shock and low inventories

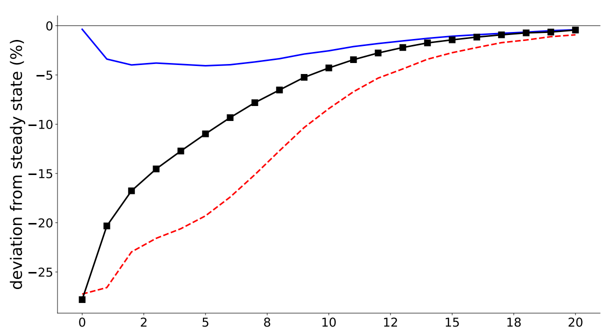
(a) Manufacturing production



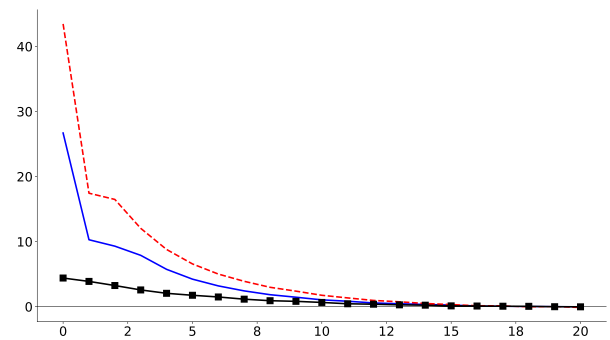
(b) Consumption



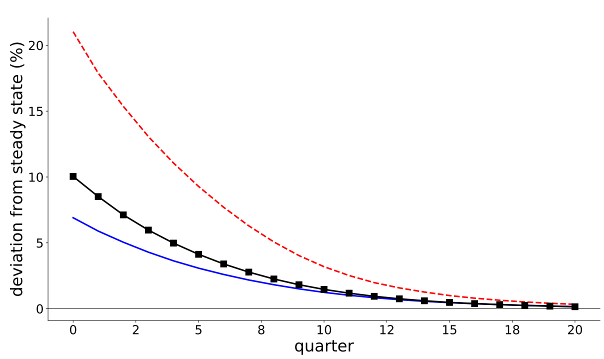
(c) Total inventories (eop)



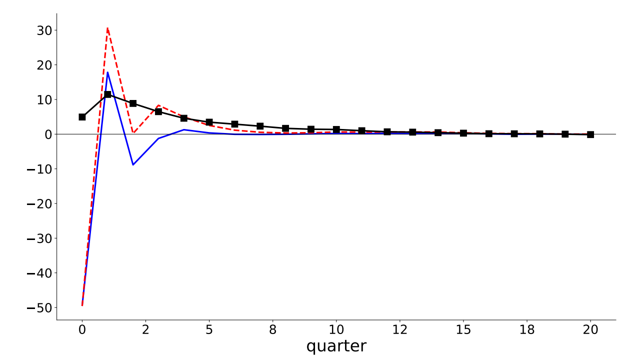
(d) Importer stockouts



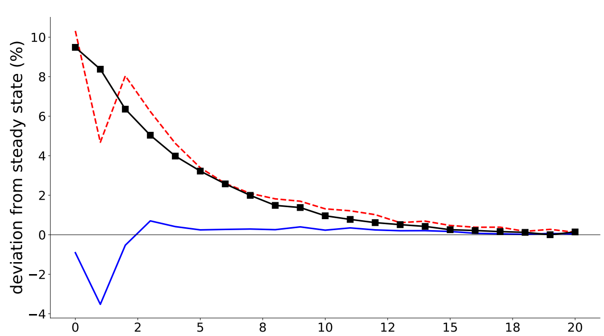
(e) Consumption price



(f) Imports



(g) Total labor



(h) Labor used for ordering

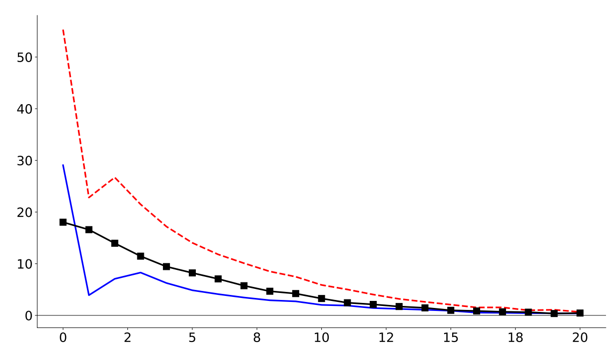


Figure 12: International delay shock and consumption stimulus

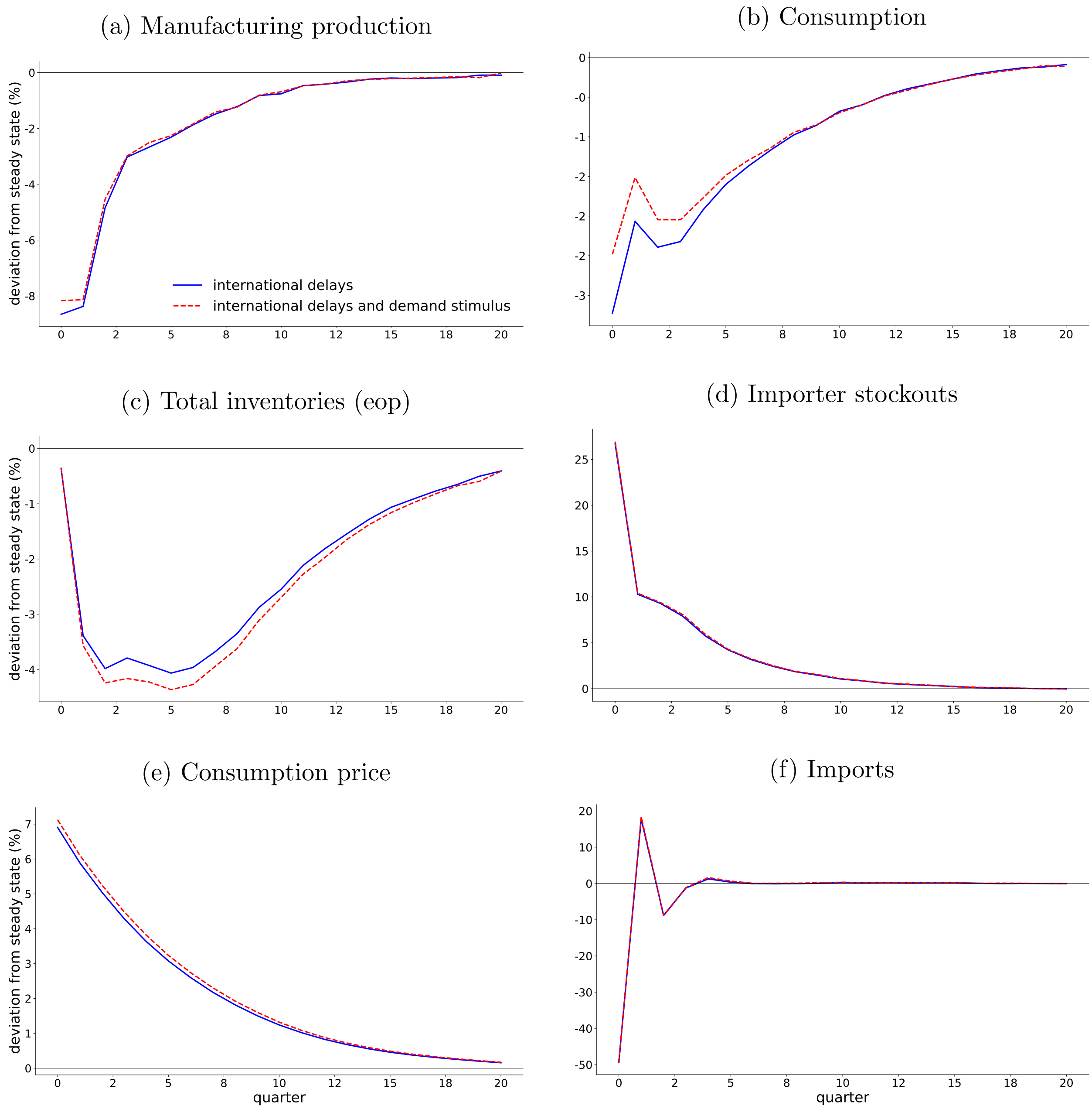


Figure 13: International delay shock and reduced labor supply

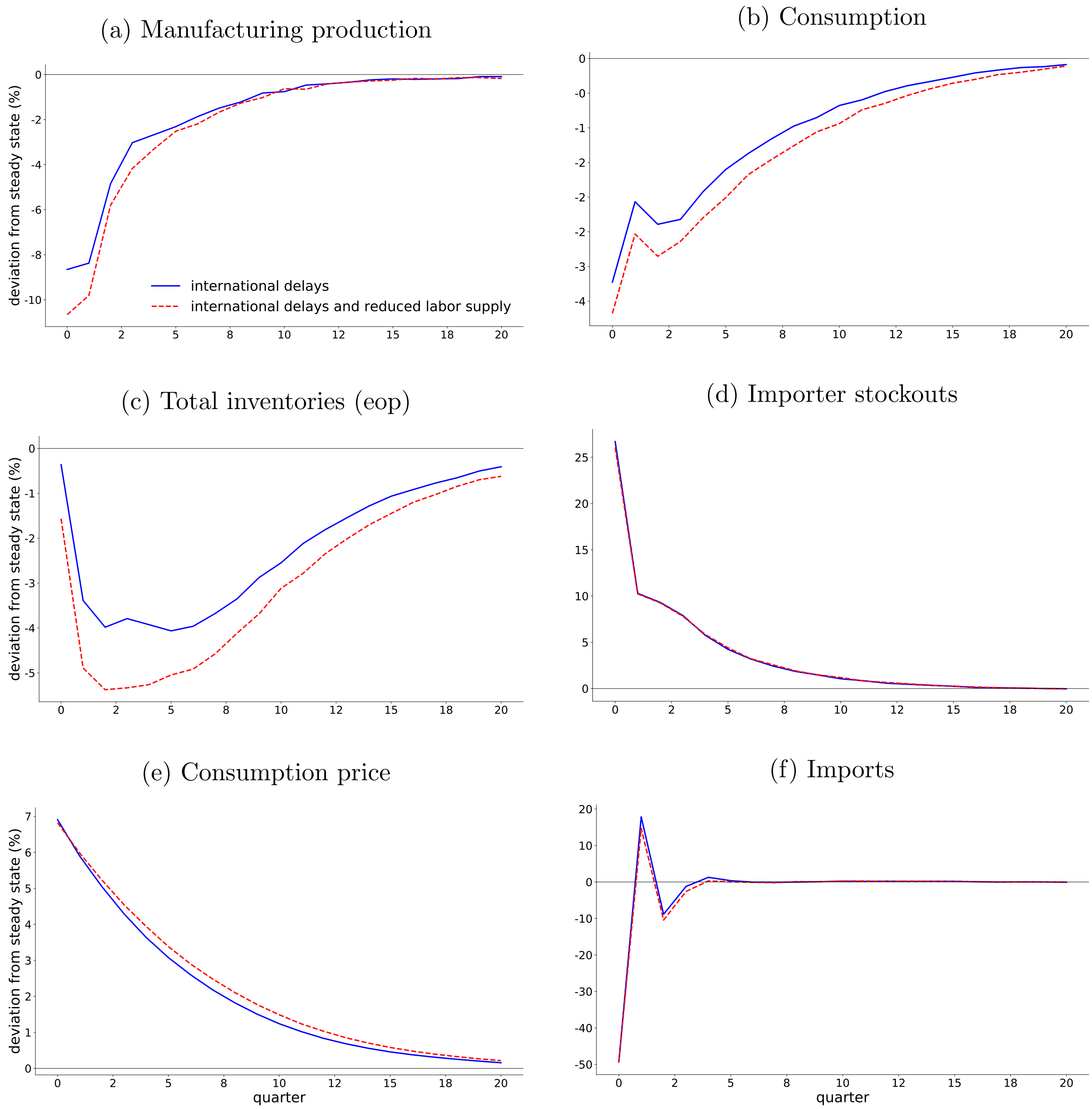
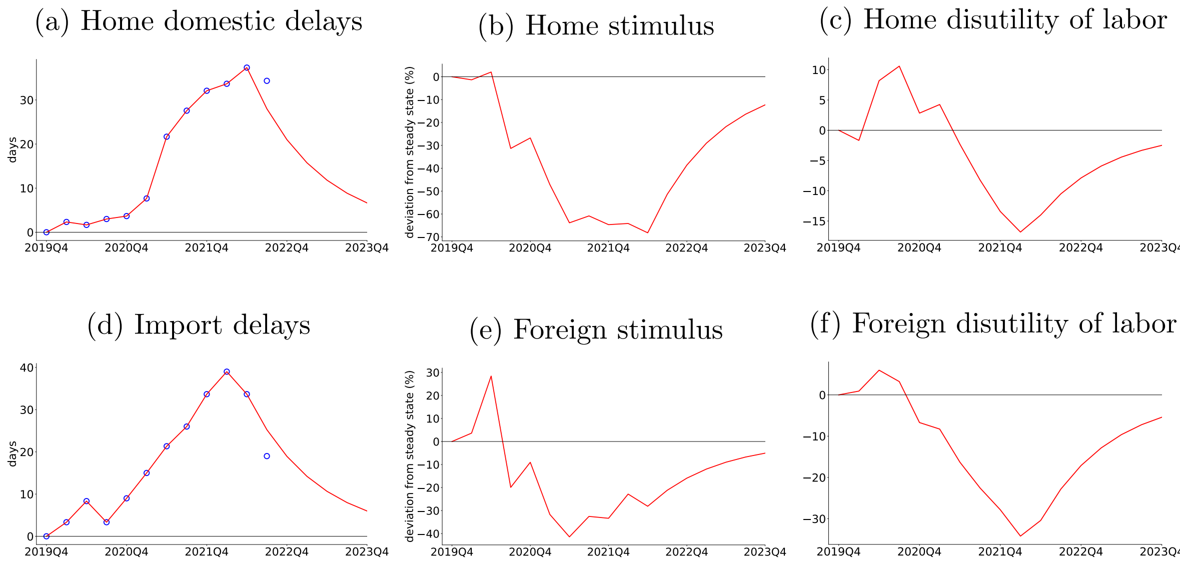
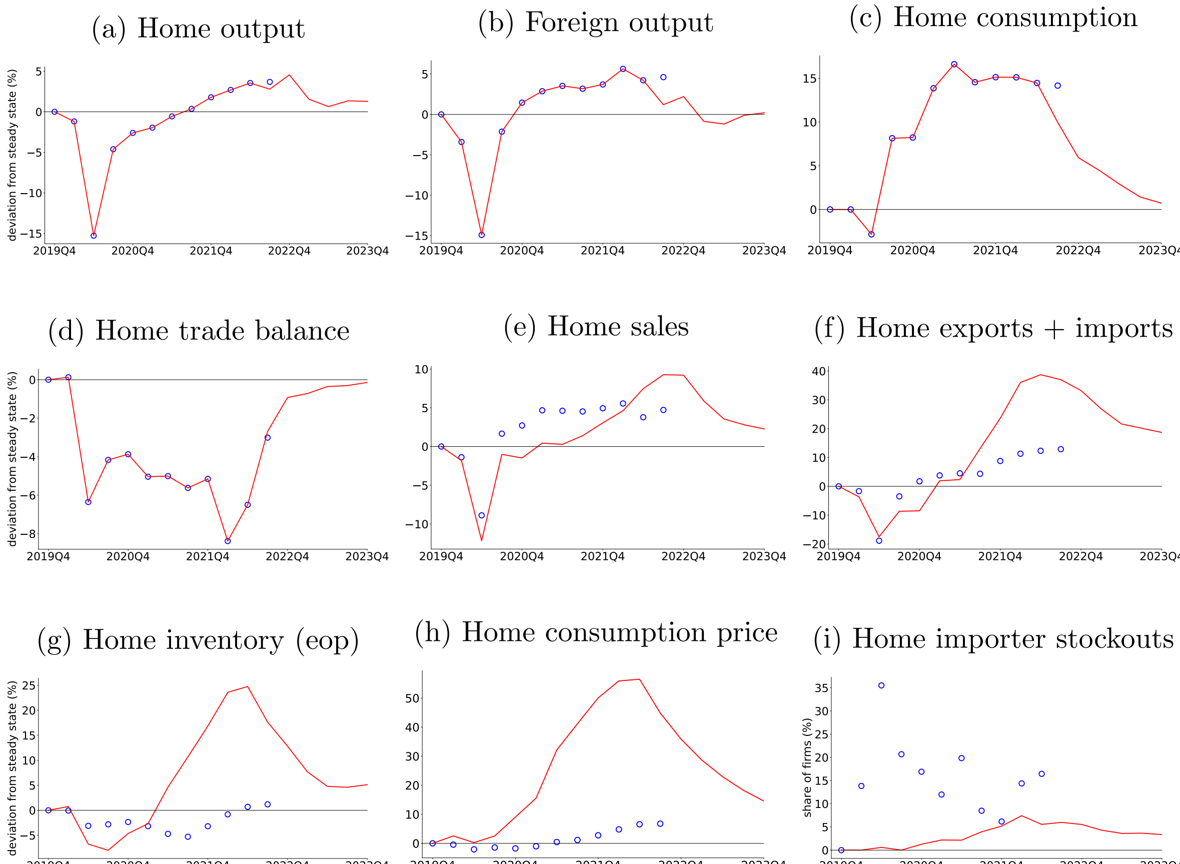


Figure 14: Exogenous shocks



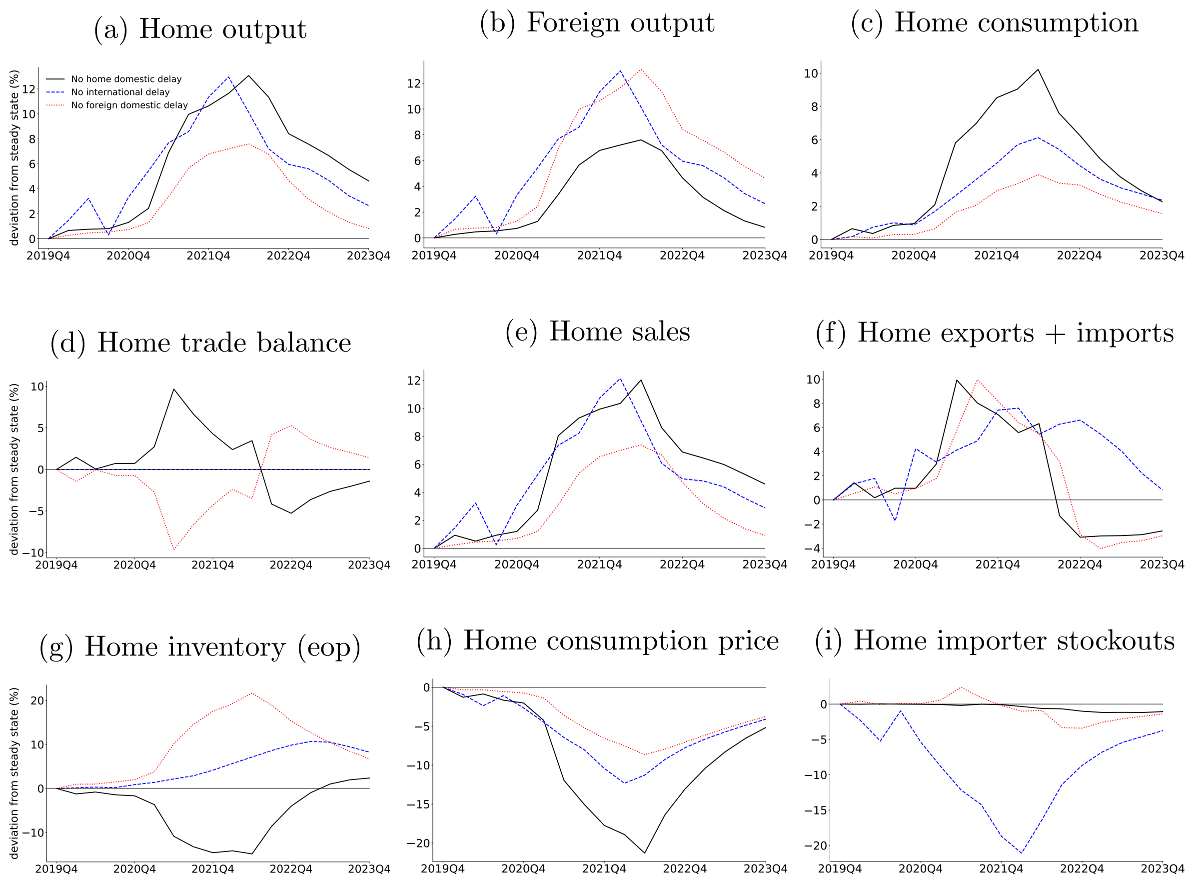
Notes: In panels (a) and (d), targeted data 2019Q4–2022Q2. Data for 2022Q3 are untargeted.

Figure 15: Endogenous variables



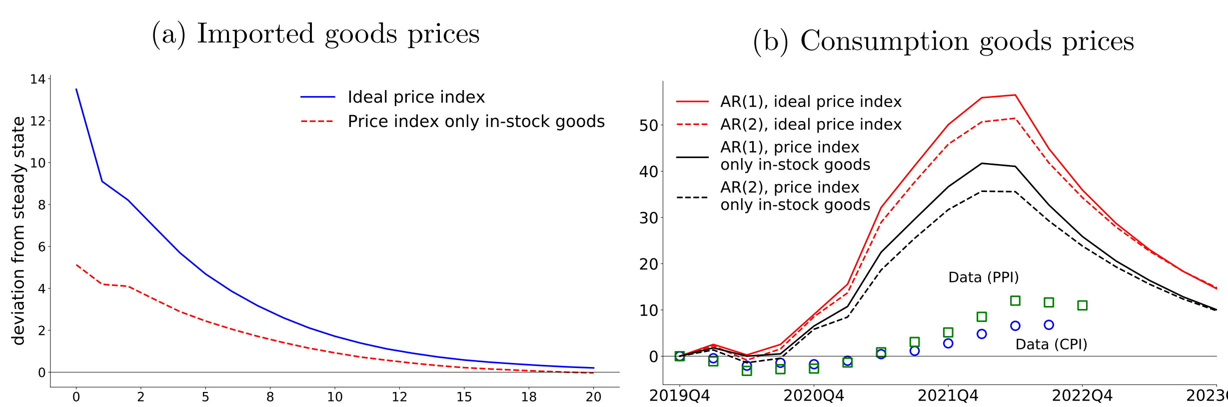
Notes: In panels (a)–(d), targeted data 2019Q4–2022Q2. Data for 2022Q3 are untargeted.

Figure 16: The effect of delays



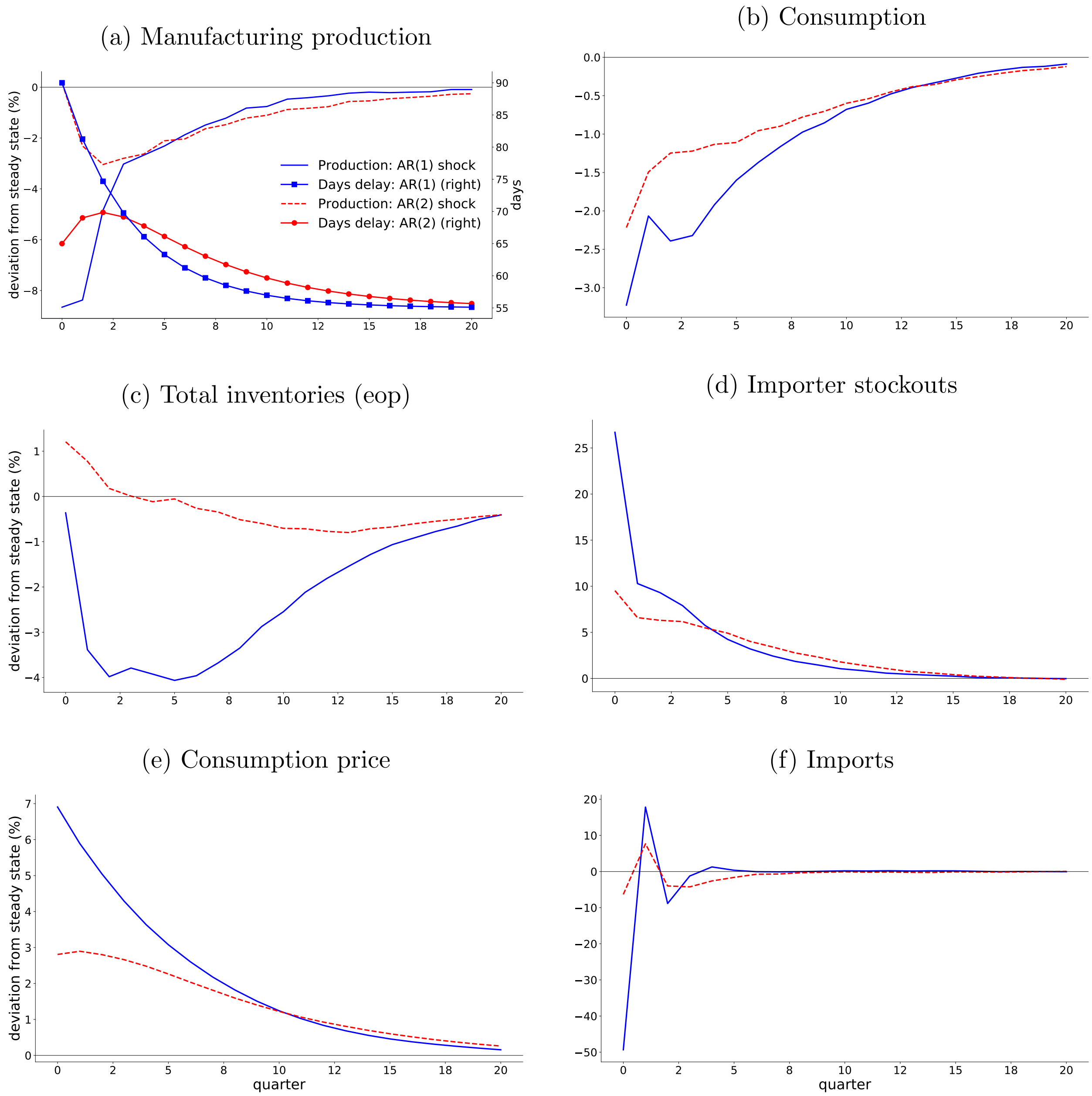
Notes: Each line is the difference between the variable in the economy without one of the delays minus the variable in the baseline economy.

Figure 17: Adjusting for stocked-out goods in prices



Notes: In panel (a), we plot the impulse response function from a delay in imported goods. In panel (b), we plot the consumption goods prices from our model fitted to the 2019–2022 data.

Figure 18: AR(1) versus AR(2) import delay shocks



(a) Manufacturing production

(b) Consumption

(c) Total inventories (eop)

(d) Importer stockouts

(e) Consumption price

(f) Imports

Figure 19: The effect of import delays: AR(1) versus AR(2)