Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
From SARS to COVID-19: The evolving role of China-ASEAN production network☆

Ammu George a, Changtai Li b, Jing Zhi Lim a, Taojun Xie a,∗

a Asia Competitiveness Institute, Lee Kuan Yew School of Public Policy, National University of Singapore, 469 Bukit Timah Road, 259772, Singapore
b School of Social Sciences, Nanyang Technological University, 48 Nanyang Ave, 639818, Singapore

ARTICLE INFO
Jel classifications:
E2
F1
I1

Keywords:
COVID-19
Production network
China
Susceptible-infected-recovered model

ABSTRACT
Two decades after the severe acute respiratory syndrome (SARS) outbreak, Asia is confronted with the coronavirus disease 2019 (COVID-19) that has significantly affected the region’s economy. In a novel general equilibrium model, we introduce epidemiological dynamics to the production network between China and the Association of Southeast Asian Nations (ASEAN). In this model, agents’ risk-averse behavior during pandemics leads to shifting demands across economic sectors. We calibrate the model with the Organisation for Economic Co-operation and Development (OECD) inter-country input-output tables for pre-SARS and pre-COVID-19 periods and control for disease dynamics across years. Findings show that in the absence of policy interventions, China’s greater significance in global value chains is associated with substantial economic impacts, within China and the ASEAN region. Our sensitivity analyses further show that China’s containment efforts reduce the spillover effects on ASEAN.

1. Introduction
Two decades after the outbreak of the Severe Acute Respiratory Syndrome (SARS), Asia was confronted again with the Coronavirus Disease 2019 (COVID-19). The World Health Organization data show 82.4 million people have been infected with COVID-19 by the end of 2020, with 1.8 million deaths worldwide. Similar to the SARS pandemic, immediately after the COVID-19 outbreak in China, countries in the Association of Southeast Asian Nations (ASEAN), were first affected because of their geographical proximity, business travel, tourism and supply chain links to China. In addition to the human costs, shown in Fig. 1, economies had suffered. Fig. 2 illustrates a comparison between the SARS and COVID-19 episodes, thereby showing more synchronized decline in gross domestic product growth at the beginning of the COVID-19. Some have ascribed the heavy economic damage to high contagiousness of COVID-19, whereas others have attributed it to the government-mandated lockdowns worldwide. Whether China’s increasing importance in the global value chains (GVCs) contributed to the current global economic downturn is debated.

In this paper, we focus on the production network channel of shock transmission. We ask the following: What is the role of an international production network in the propagation of an epidemic shock? We derive answers from China and the ASEAN countries’ experiences during the SARS and the COVID-19 periods.

Thus far, existing empirical analyses on the impact of disease outbreaks have encountered a few challenges. First, epidemics, such as SARS and the 1918 Spanish Flu, have unique characteristics that differ in terms of contagiousness or spreading media. Without sufficient incidents of such pandemics, these characteristics are difficult to control in an empirical analysis. This challenge implies that findings from historical events may not apply to new emerging epidemics. Second, production and consumption associations among and within countries have evolved. For example, China’s growing importance in GVCs was coupled with the domestic expansion of the services sector (Liao, 2020). Simultaneously evolving international and domestic economic conditions raise challenges in establishing the transmission channels of an economic impact.

This paper provides an analysis by using a set of counterfactual simulations to identify a specific transmission channel. Accordingly, an analytical framework is required to control for the aforementioned variables. We construct a multi-country and multi-sector model with production networks. Eichenbaum et al. (2020)
susceptible–infected–recovered macroeconomic (SIR-macro) framework is used to capture epidemiological dynamics. We calibrate the population dynamics by using this model to acquire the same human costs of a disease outbreak across scenarios, thereby addressing the challenge of different disease characteristics. We then focus on sectoral dynamics by using Krueger et al. (2020) framework: agents voluntarily substitute consumption in more contagious sectors with those in less contagious sectors. The international production network in our model translates the shifts in the domestic demand into cross-border demand changes for intermediate goods. Then, the reallocation effect of the pandemic is spilled among trading partners. We select the pre-SARS and pre-COVID-19 years as normal-time scenarios in model calibration. In the case of China and the ASEAN countries, these two time periods are largely similar in terms of domestic consumption and output patterns, although the pre-COVID-19 period is characterized by more integrated GVC networks. In this paper, we create a toolkit for analyzing the transmission of an epidemic’s economic impacts via global production networks.

Numerous studies have examined the macroeconomic impact of COVID-19, such as Alvarez et al. (2020); Atkeson (2020); Baker et al. (2020); Eichenbaum et al. (2020); Fernandes (2020); Getachew (2020); Guerrieri et al. (2020); Krueger et al. (2020), and McKibbin and Fernando (2020). We contribute to this growing discussion of the macroeconomic impact of COVID-19 in the context of production networks (see Atkeson, 2020; Baqae and Farhi, 2020; Bonadio et al., 2020; Çakmakli et al., 2020; Hsu et al., 2020; Kimura et al., 2020; Luo et al., 2020; and
Most of these studies, including Baqee and Farhi (2020), Bonadio et al. (2020), and Luo et al. (2020), have examined the impact of COVID-19 on aggregate output based on the US economy. The most closely related studies are Çakmaklı et al. (2020); Luo and Tsang (2020). Çakmaklı et al. (2020) considered the context of a small, open economy with trade and capital flows. Funke and Tsang (2020) examined China’s swift policy measures to combat the macroeconomic impact due to the outbreak. Luo and Tsang (2020) studied the global impact of China’s labor shortage.

Our model dynamics are driven only by a small zoonotic infection, unlike other papers, such as Guerrieri et al. (2020); del Río-Chanona et al. (2020); McKibbin and Fernando (2020), which assume exogenous demand or supply shocks. Following the initial infection in the population, economic agents make decisions based on their current and future health risks. Consequently, economic dynamics are the results of all agents’ behaviors.

Our innovation also builds on the synthesized study of historical global pandemics. As discussed, because of heterogeneity in disease characteristics, conclusions from historical analyses are generally inapplicable to new events. Case studies on China and ASEAN are among the exceptions because of their common experiences with SARS and COVID-19 and the similarity between the two viruses. Comparing the economic impacts between the SARS pandemic and the present across countries is necessary. The infection parameters are modified for our counter-factual simulations to facilitate such comparisons by providing controlled settings across the two events. Our model can also be calibrated against actual population dynamics in a specific event.

The primary findings of the paper show that the increasingly integrated production networks would contribute to the significant economic impacts of COVID-19. First, the economic impacts within China during the COVID-19 period are greater than those during the SARS period, whereas the ASEAN countries experienced similar impacts across the two periods. Second, despite the limited sizes, the spillover effects between China and the ASEAN countries are greater during the COVID-19 period than during the SARS period. We argue that these greater spillover effects are due to the evolving production associations and trading patterns. Third, containment efforts in China helped reduce economic costs in the ASEAN region.

Before proceeding to the remainder of the paper, it is important to note that we develop only a stylized model to address the key objective of our study, namely to understand the transmission mechanism via the production networks. However, producing precise empirical results requires models to examine complex interactions. Therefore, we leave complex models for future research.

The remainder of this paper is organized as follows: Section 2 provides facts on recent GVC trends, particularly in China and the ASEAN countries. Section 3 describes the model. Section 4 discusses simulation results. Section 5 conducts sensitivity analyses on parameter values. Finally, Section 6 concludes.

### 2. China and ASEAN in global value chains

In the recent two decades, China and the Southeast Asian countries have worked toward building additional integrated production networks (Huang et al., 2017) that substantially emphasize regional collaborations. Abiad et al. (2020) reported that trade and service associations between China and the ASEAN countries have become stronger in recent years, and these associations are driven by GVCs.

China has recently become a crucial demand-supply hub in international trade and GVC networks. According to UNIDO (2018), China is at the heart of GVCs given its numerous goods in supply and demand. For example, China has an extensive consumer market for global commodities and industrial products. Moreover, the country is the primary producer of numerous high-value intermediate and final products. China has a relative high GVC participation rate at 34.8% in 2015. GVC participation indicates an economy’s exports that are a part of multi-stage production processes of goods and services. GVC participation rate increases with the foreign value added used in exports and domestic value added supplied to partner economies’ exports. The GVC participation rate is a measure of a country’s involvement in international production networks.

Fig. 3 illustrates the examination of the change in China’s GVC pa-
participation with the world, which shows a declining trend. China’s forward GVC participation rate increases from 15.6% in 2005 to 17.5% in 2015. Forward GVC participation corresponds to the ratio of domestic value added exported to third economies to the economy’s total exports. It captures the domestic value added in inputs sent to third economies for further processing and exports through value chains. China’s increasing forward GVCs indicate that the country is improving its upstream position in the production network by strengthening its domestic value added in exports (Chor et al., 2021).

However, China’s backward GVC participation rate decreased from 26.3% to 17.3% between 2005 and 2015. Backward GVC participation is the ratio of foreign value-added content of exports to the economy’s total exports. It indicates an economy’s reliance on foreign inputs. China’s declining GVC participation in the world is driven by the decline in backward participation. China is participating more in the regional production network than in the global network. Fig. 3 shows that the GVC participation ratio between China and ASEAN increased from 4.8% in 2005 to 5% in 2015 because of the increasing forward participation ratio of China to ASEAN countries. However, China’s GVC participation with rest of the world (ROW) declined in 2005–2015.

As China’s top trade partner, ASEAN have been moving toward becoming a highly integrated and cohesive economy by increasing their participation in GVCs and international trade. In 2015, ASEAN accounted for 7.2% and 6.6% of the global exports and imports, respectively. A total 28.2% in overall ASEAN exports comprise foreign value added. The role of China as an important source of value added in ASEAN, especially in the consumer goods sector, needs to be recognized. Fig. 4 shows that China’s share in the foreign value-added content of ASEAN exports of goods increased from 3.6% in 2005 to 8% in 2015. The increase in China’s share in the foreign value added of ASEAN services is relatively small, from 0.9% to 2.1%. Therefore, inputs from China have become increasingly important to ASEAN exports in the consumer goods and service sectors. In addition to the trend of the increasing share of foreign value added from China, domestic and intra-regional value added in exports have a high and stable ratio. This finding is primarily attributed to the deeper regional integration and increasing intra-regional trade. This phenomenon has enabled countries to specialize and create favorable conditions for the trade of intermediate goods and services within ASEAN.

The ASEAN’s GVC integration is deeper than other regions. Yamaguchi (2018) states that more than 60% of ASEAN’s gross exports are associated with GVCs. ASEAN exhibited a relatively high GVC participation rate at 45.9 in 2015 (see Fig. 5; ASEAN–World). The ASEAN’s GVC participation rate has been declining over time because of decreasing backward GVC participation as shown in Fig. 5. The region’s forward GVC participation remains consistently lower than its backward participation, thereby indicating its substantial involvement in downstream economic activities. Although ASEAN’s GVC participation on the global level declined, the value chain associations between ASEAN and China strengthened in 2005–2015. The increase in the ratio was primarily driven by backward participation, which is consistent with the previous argument that inputs from China increasingly contribute to ASEAN’s value added exports. By contrast, backward ratio between ASEAN and ROW decreased from 28.5% in 2005 to 22.7% in 2015. In addition to the international production networks, the ASEAN countries have been integrated into a regional production network. Regional value chains (RVCs) are a part of GVCs. During 2005–2015, ASEAN’s RVCs increased from 13% to 15.2%, whereas its GVCs decreased from 48.4% to 45.9%. Overall, Fig. 5 shows that ASEAN countries emphasize more on regional production networks with China and intra-ASEAN over time than those with ROW.

Therefore, ASEAN and China have strengthened their relationship in recent years. This closer association has important implications for the spillover of epidemic shocks. Epidemic shocks lead to economic activity reallocation, which is discussed in the subsequent sections of this paper. The reallocation of one activity leads to the varying demands of another activity for final and intermediate goods because of the production network that exists between two economies. Therefore, the evolving role of one economy in GVCs may lead to different impacts across time.

![Fig. 4. Value added of ASEAN exports by origin in goods and service sectors. Source: OECD TiVA database](image-url)
3. An SIR-Macro model with international production networks

The SIR-macro framework was first developed by Eichenbaum et al. (2020). It integrates a conventional neo-classical macroeconomic model with an epidemiological SIR model. Susceptible economic agents may contract an epidemic when interacting with infected agents in consumption activities. An infected agent has a non-negligible probability of dying from the epidemic, although the agent may not contract the epidemic again if recovered. When making economic decisions, all agents consider their future health risks, thereby voluntarily adjusting their consumption activity levels. As a result, the agents’ decisions translate into a recession in the aggregate economy.

We examine the propagation of an epidemic shock in an international production network via an SIR-macro model with three countries and two sectors. Although it is a stylized model, it can be extended to feature arbitrary numbers of countries and sectors. Agents consume from all economic sectors during normal times. These sectors sell composite items produced by domestic and foreign firms. Furthermore, domestic firms of all sectors produce heterogeneous outputs by using household labor and intermediate outputs from all economic sectors during normal times. Intermediate outputs can be domestically produced or imported, thereby generating a competitive market. This paper does not focus on the exchange rate channel of shock transmission. Therefore, nominal variables, including prices, wages, and nominal exchange rates, are assumed to be constant.

Agents become heterogeneous during a pandemic because of their health status. They contract the disease when interacting with infected agents in the same economic sector. This mechanism is described in Eichenbaum et al. (2020). Furthermore, following Krueger et al. (2020), we differentiate the economic sectors by the degree of consumer interaction. A sector is highly infectious if its consumers need to extensively interact with each other and vice versa. An agent faces an increased risk of infection by consuming goods from high-infection sectors, thereby reducing future welfare. All agents are initially susceptible. They become infected after contracting a disease and subsequently recover or die. The aggregate economic outcomes are the resultant interactions of all agents.

Two key margins at work must be highlighted when agents decide among sectors. During normal times, demands for goods in the economic sectors are associated with the elasticity of substitution similar to that in conventional macroeconomic models. The parameter for the elasticity of substitution determines the ease of replacing goods in one sector with those from another without changing the utility. However, agents will also consider the relative contagiousness during a pandemic. Agents are likely to consume less in a more contagious sector than in a less contagious one. We describe the model in this section.

3.1. Normal times

The economy is a standard neo-classical model in the absence of an epidemic. A representative agent in country $\ell$ derives utility and disutility from a consumption bundle and supplying labor, respectively. The agent’s lifetime utility is given by

$$U_0(\ell) = E_0 \sum_{t=0}^{\infty} \beta^t u(C_t(\ell), N_t(\ell))$$

(1)

$$u(C_t(\ell), N_t(\ell)) = \log C_t(\ell) - \frac{\theta(\ell)}{2} N_t(\ell)^2$$

(2)

where $\beta$ is the discount factor, $C_t(\ell)$ is an aggregate of goods from all sectors, and $N_t(\ell)$ is the labor supply to domestic firms. The consumption bundle aggregates goods from all sectors indexed by $j$ with a constant elasticity of substitution (CES):

$$C_t(\ell) = \left( \sum_j \psi(j, \ell)^\frac{1}{\gamma} \cdot c_t(\ell, j)^{1-\frac{1}{\gamma}} \right)^{\frac{\gamma}{\gamma-1}}$$

(3)

where $\psi(j, \ell)$ is the share of sector-$j$ goods in the consumption basket in the steady state, $\sum_j \psi(j, \ell) = 1$, and $c_t(\ell, j)$ is country $\ell$’s demand for goods from sector $j$. $\eta$ is the elasticity of substitution across various goods. Sector-$j$ goods are packaged by an entrepreneur who aggregates the same goods from around the world as follows:

$$c_t(\ell, j) = \left( \sum_m \psi^m(j, \ell, m)^\frac{1}{\gamma} \cdot c^*_t(j, \ell, m)^{1-\frac{1}{\gamma}} \right)^{\frac{1}{\gamma}}$$

(4)
where \( u^j(\ell, m) \) is the share of sector-\( j \) goods imported from country \( m \) in the steady state; \( \sum_m u^j(\ell, m) = 1 \); and \( c^j_t(\ell, m, \ell) \) is country \( \ell \)'s final demand for sector-\( j \) goods produced in country \( m \). When \( \ell \neq m \), goods are imported from country \( m \) to country \( \ell \). \( \zeta \) is the elasticity of substitution among goods of different origins. Assume that all prices equal 1. The budget constraint of the agent in country \( \ell \) is then given as follows:

\[
\sum_j \left[ c_j(\ell, \ell) + k\alpha(\ell) \right] w_j(\ell) - N_j(\ell) + trf_j(\ell) = 0
\]

(5)

where \( k\alpha(\ell) \) is the capital account balance; \( w_j(\ell) \) is the nominal wage; and \( trf_j(\ell) \) is the transfer payment from the government. Firms produce output by using domestic labor and intermediate outputs from all sectors, with a Cobb-Douglas production function as follows:

\[
y_j(\ell, \ell) = A(j, \ell) \cdot n_j(\ell, \ell)^{1-a(j, \ell)} \cdot \left( \prod_{k,m} z_k(k, m, j, \ell)^{\gamma(k,m,j,\ell)} \right)^{\omega(j, \ell)}/(k,m,j,\ell)
\]

(6)

where \( A(j, \ell) \) is the technology level and \( n_j(\ell, \ell) \) is the labor input for sector \( j \). Sector \( k \) produces intermediate output \( z_k(k, m, j, \ell) \) in country \( m \) for use in sector \( j \) in country \( \ell \). Similar to the case of consumption, when \( \ell \neq m \), the intermediate goods are imported, and when \( k \neq j \), the intermediate output is produced by a different sector. \( \gamma(k, m, j, \ell) \) and \( a(j, \ell) \) are the share of intermediate output required for production in the steady state and the share of intermediate outputs as production inputs, respectively. The firms’ objective is to maximize the profits as follows:

\[
\max_{n_x} \prod_j y_j(\ell, \ell) - w_j(\ell) \cdot n_j(\ell, \ell) - \sum_j z_j(k, m, j, \ell)
\]

(7)

Under perfect competition, all firms set price at the marginal cost of production as follows:

\[
p(j, \ell) = \frac{1}{A(j, \ell)} \left( \frac{w_j(\ell)}{1-a(j, \ell)} \right)^{1-a(j, \ell)} \cdot \left( \prod_{k,m} \frac{1}{\alpha(k, m, j, \ell) \cdot \gamma(k, m, j, \ell)} \right)^{\omega(j, \ell)}/(k,m,j,\ell)
\]

(8)

The nominal wage is normalized to 1. The firms’ profit function, Equation (7), is maximized subject to Equation (6). The first-order conditions show that for any sector-\( k \) intermediate output from country \( m \), the marginal product of labor equals that of any intermediate output as follows:

\[
\frac{\partial y_j(\ell, \ell)}{\partial n_j(\ell, \ell)} = \frac{\partial y_j(\ell, \ell)}{\partial z_j(k, m, j, \ell)}
\]

(9)

The market for consumption goods clears when the supply of sector-\( j \) goods meets the demand. This demand comprises intermediate outputs demanded by domestic and foreign firms from all sectors and consumption goods demanded by domestic and foreign households, less a lump-sum tax collected by the government.

\[
y_j(\ell, \ell) = \sum_{j,m} z_j(j, m) + \sum_j c^j_t(j, m, \ell) - trf_j
\]

(10)

The clearing condition in the labor market is as follows:

\[
\sum_j n_j(\ell, \ell) = N_\ell(\ell)
\]

(11)

The current account balance for country \( \ell \) is as follows:

\[
c_{\ell}(\ell) = \sum_{j} \left[ \sum_{k,m} z_j(k, m, \ell) - z_j(k, m, j, \ell) \right]
\]

\[
= m^x_{\ell} + n^x_{\ell}
\]

where \( m^x_{\ell} = \sum_{k,m} \sum_{j} \left[ z_j(k, m, \ell) - z_j(k, m, j, \ell) \right] \) represents the aggregate net exports of intermediate products of country \( j \) and \( n^x_{\ell} = \sum_{k,m} \sum_{j} \left[ c^j_t(j, m, \ell) - c^j_t(j, m, j, \ell) \right] \) represents net exports of final products.

The international goods market clears when \( \sum c_{\ell}(\ell) = 0 \). \( k\alpha(\ell) + c_{\ell}(\ell) = 0 \) because this economy illustrates a hand-to-mouth model with no inter-temporal financial assets.

### 3.2. Epidemic

This section describes agents’ behavior during an epidemic. Four types of agents exist in the society namely, susceptible, \( s \), infected, \( i \), recovered, \( r \), and deceased, \( d \).

A susceptible agent may contract a disease while interacting with an infected agent in any sector \( j \). This phenomenon is captured using the interaction term \( c^j(\ell, \cdot) \cdot c(\ell, \cdot) \) and scaled using a parameter governing the relative infectiousness, \( \varphi(\ell, \cdot) \). Following Krueger et al. (2020), we impose that the relative infectiousness has a mean value 1 as follows:

\[
\sum_j (\ell, \cdot) \cdot \varphi(\ell, \cdot) = 1
\]

(12)

Aggregating the infection risk from all economic sectors, the probability of acquiring an infection in country \( \ell \), \( \tau(\ell) \), is formulated as follows:

\[
\tau_\ell(\ell) = \pi_\ell(\ell)I_\ell(\ell) \sum_j \varphi(\ell, \cdot) \cdot c^j_t(j, \cdot) \cdot c^j_t(j, \cdot)
\]

(13)

where \( \pi_\ell(\ell) \) is the general risk of infection in country \( \ell \) and \( I_\ell(\ell) \) is the size of the infected population. The number of newly infected agents in each period comes from the susceptible group and is given as follows:

\[
T_\ell(\ell) = \tau_\ell(\ell)S_\ell(\ell)
\]

(14)

where \( S_\ell(\ell) \) is the susceptible population size in country \( \ell \).

This equation is a deviation from a standard SIR model. In a conventional SIR model, the newly infected population is given by \( T_\ell = S_\ell - S_\ell \cdot I_\ell \), which captures the interaction between susceptible and infected agents. Agents’ economic decisions do not influence disease dynamics. By substituting Equation (13) into Equation (14), static parameter \( S_\ell \) in the conventional SIR model becomes dynamic and contingent on agents’ economic behavior \( \pi_\ell(\ell) \sum \varphi(\ell, \cdot) \cdot c^j_t(j, \cdot) \cdot c^j_t(j, \cdot) \). Therefore, the infected population changes as agents adjust their consumption levels.

The population dynamics evolve as follows:

\[
S_\ell(\ell) = S_{\ell-1}(\ell) - T_{\ell-1}(\ell)
\]

(15)

\[
I_\ell(\ell) = I_{\ell-1}(\ell) + T_{\ell-1}(\ell) - (\pi_\ell + \pi_d)I_{\ell-1}(\ell)
\]

(16)

\[
R_\ell(\ell) = R_{\ell-1}(\ell) + \pi_dI_{\ell-1}(\ell)
\]

(17)

\[
D_\ell(\ell) = D_{\ell-1}(\ell) + \pi_dI_{\ell-1}(\ell)
\]

(18)

Following Eichenbaum et al. (2020), we assume a small zoonotic infection at the beginning of the pandemic. This condition is represented by the initial state: \( I_0(\ell) = \epsilon \), \( S_0(\ell) = 1 - \epsilon \), \( R_0(\ell) = D_0(\ell) = 0 \). This small population shock is added to Equation (16), thereby triggering the epidemic outbreak.

In this paper, we do not model infections through travelers across countries. The infection is assumed to be contained within country \( \ell \)’s geographic boundary as effective cross-border preventive measures can now be imposed. Accordingly, we focus on the spillover of the economic impacts across countries as agents make their economic choices because of the pandemic. We will now explain the economic decisions by the agents.

Recovered. Recovered agents behave similarly to a representative agent during normal times because they are immune to the disease.
Considering that their future health status can only remain as recovered, their lifetime utility is given by the following Bellman equation:

\[ U_i^t(\epsilon) = u \left( C_j^t(\epsilon), N_j^t(\epsilon) \right) + \beta E_t U_{i+1}^t(\epsilon) \]  

(19)

When Equation (19) is iterated forward, it becomes identical to Equation (1). The recovered agents maximize Equation (19) subject to the budget constraint. The first-order conditions with respect to sectoral consumption goods \( c_j(\epsilon, \ell) \) and labor supply \( N_j(\ell) \) imply the following:

\[ \nu(j, \ell) \frac{1}{C_j^t(\epsilon)} \left( \frac{c_j^t(j, \epsilon)}{C_j^t(\epsilon)} \right)^{\frac{1}{\gamma}} = \theta(\epsilon) N_j^t(\epsilon) \]

where the Lagrangian multiplier for the budget constraint has been eliminated. Under the constant-price setup in our model, the solution where the Lagrangian multiplier for the budget constraint has been eliminated. Under the constant-price setup in our model, the solution

\[ \frac{c_j^t(j, \epsilon)}{c_j^t(\epsilon)} = \theta(\epsilon) C_j^t(\epsilon) \]

which resembles the allocation of sector \( j \) goods during normal time.

The optimal labor supply for the recovered agent is as follows:

\[ N_j^t(\epsilon) = \frac{1}{\theta(\epsilon)} \frac{1}{C_j^t(\epsilon)} \]

This equation is independent of the sector index \( j \) because of the constant-price setup.

**Infected.** The future health status of the infected agents entails three possibilities. They may recover from the disease, in which case their utility follows that of the recovered agents. They may die from the disease, in which case future periods will have no utility. They may also remain infected, and thus, their current utility continues into the future period. An infected household’s lifetime utility can be expressed using the following Bellman equation:

\[ U_i^t(\epsilon) = u(C_j^t(\epsilon), N_j^t(\epsilon)) + \beta E_t \left\{ \frac{1 - \pi_r - \pi_d}{\pi_r} U_{i+1}^t(\epsilon) + \frac{\pi_d}{\pi_r} U_{i+1}^t(\epsilon) + \pi_d \times 0 \right\} \]

(20)

where \( \pi_r \) and \( \pi_d \) are the probabilities that the infected agent recovers and dies, respectively. The first-order conditions imply the following:

\[ \nu(j, \ell) \frac{1}{C_j^t(\epsilon)} \left( \frac{c_j^t(j, \epsilon)}{C_j^t(\epsilon)} \right)^{\frac{1}{\gamma}} = \theta(\epsilon) N_j^t(\epsilon) \]

(21)

of which the solutions are as follows:

\[ y_i(j, \ell) = \sum_{k \in m} x(j, k, \ell, \epsilon) + \sum_{m} s_j(m) \cdot c_j^m(j, m, \ell) + (h(m) + R(m)) \cdot c_j^m(i, m, \ell) - \pi_r(i, j, \ell) \]

\[ \sum_{j} n_i(j, \ell) = S_i(\ell) N_j^t(\epsilon) + (I_i + R_i) N_j^t(\epsilon) \]

(22)

\[ c_j^t(j, \epsilon) = \nu(j, \ell) \cdot C_j^t(\epsilon) \]

(23)

\[ N_j^t(\epsilon) = \frac{1}{\theta(\epsilon)} \frac{1}{C_j^t(\epsilon)} \]

The solutions for the recovered and infected agents are identical. Henceforth, we use superscript \( i \) to denote recovered and infected agents’ optimal consumption and labor supply.

It is noteworthy that the recovered and infected agents do not adopt a consumption allocation different from that during normal time because they do not face the risk of reacquiring the infection. Therefore, they do not voluntarily consider health risks when making economic decisions, although reality deviates from our model in that infected agents are subject to penalties such as government-imposed quarantine orders.

**Susceptible.** Susceptible agents’ health status entails two possibilities, that is, they may become infected or remain susceptible. Their probability of getting infected (Equation (13)) is attributed to their interaction with the infected agents via consumption activities. Considering both agents’ health status, susceptible agents’ lifetime utility is expressed in the following Bellman equation:

\[ U_i^t(\epsilon) = u \left( C_j^t(\epsilon), N_j^t(\epsilon) \right) + \beta \left\{ (1 - \pi_r(\epsilon)) U_{i+1}^t(\epsilon) + \pi_r(\epsilon) U_{i+1}^t(\epsilon) \right\} \]

(24)

With probability \( \pi_r(\epsilon) \), a susceptible agent contracts the disease in the future and becomes an infected agent, whereas with a probability \( 1 - \pi_r(\epsilon) \), the agent remains susceptible. The susceptible agents’ choice of consumption levels influences infection risk. Therefore, Equation (13) comprises an additional constraint in their optimization problem. Maximizing Equation (24) subject to Equations (5) and (13) generates the following first-order conditions:

\[ \nu(j, \ell) \frac{1}{C_j^t(\epsilon)} \left( \frac{c_j^t(j, \epsilon)}{C_j^t(\epsilon)} \right)^{\frac{1}{\gamma}} = \theta(\epsilon) N_j^t(\epsilon) \]

(25)

\[ \beta E_t \left[ U_{i+1}^t(\epsilon) - U_{i+1}^t(\epsilon) \right] + \lambda_{i+1} = 0 \]

(26)

where \( \lambda_{i+1} \) is the Lagrangian multiplier for the constraint in Equation (13).

The first-order condition in Equation (25) shows that susceptible agents’ choice of sectoral goods is influenced by the elasticity of substitution \( \eta \) and the relative contagiousness \( \phi(\epsilon, \ell) \). Despite the constant prices, the relative contagiousness introduces heterogeneity to the sectoral goods, thereby incentivizing agents to substitute goods across sectors. Given the same elasticity of substitution \( \eta \), agents have more consumption in sectors with lower relative contagiousness, \( \phi(\epsilon, \ell) \). For example, households can easily replace their grocery shopping at the supermarket with online platforms because online shopping has lower relative contagiousness. By contrast, Equation (21) shows that the recovered and susceptible agents’ choices of sectoral consumption goods are not influenced by the relative contagiousness because they do not worry about the risk of getting infected. Because of different consumption patterns, susceptible agents’ labor supply differs from that of the infected and recovered agents as seen from their respective optimality conditions.

**Equilibrium.** The market clearing conditions in Equations (10) and (11) are rewritten as follows, considering the population dynamics:

\[ y_i(j, \ell) = \sum_{k \in m} x(j, k, \ell, \epsilon) + \sum_{m} s_j(m) \cdot c_j^m(j, m, \ell) + (h(m) + R(m)) \cdot c_j^m(i, m, \ell) - \pi_r(i, j, \ell) \]

By Walras’s law, the trade balances sum to 0.

### 3.3. Transmission channel via international production network

In our model, decisions made by agents during an epidemic lead to a series of changes spilled over the international production network. As explained in the previous section, an epidemic incentivizes the agents to consume more in low-infection sectors. Such a shift in preferences causes firms to shift output production from a more infectious sector to a less infectious one. Equation (6) shows that firms utilize intermediate inputs for production. Such inputs comprise goods from all sectors (low- and high-infection sectors). In the context of an epidemic, the shift in firms’ production from high-to low-infection sector output would adjust their intermediate input demand, \( \sum_{k, m, \ell} n_i(k, m, j, \ell) \). The magnitude of the impact on intermediate inputs substantially depends on their output production share. For example, the decline in the high-infection sector output does not necessarily imply that intermediate production inputs
of the high-infection sector would decline. This condition is attributed to high-infection sector intermediaries also being the production inputs of the low-infection output that increases during the epidemic.

The impact on intermediate inputs $z_j(k, m, f, \ell)$ in the production function explains an epidemic’s implications on GVCs. Firms utilize imported $(\ell \neq m)$ and domestic $(\ell = m)$ intermediate inputs for production. The output of firm $y_j(f, \ell)$ satisfies other countries’ demand for intermediate production inputs (see goods market clearing Equation (10)). When $\ell \neq m$, $\sum_{k, f, m} \pi_j(k, m, f, \ell)$ constitutes the foreign value-added content of intermediate exports of sector $j$ in country $\ell$. By contrast, when $\ell = m$, $\sum_{k, f, m} \pi_j(k, m, f, \ell)$ comprises the domestic value-added content of intermediate exports of sector $j$ in country $\ell$. The epidemic spillover effects on firms’ intermediate input demand changes the foreign and domestic value added of sector $j$ in country $\ell$. By definition, the GVC participation of country $\ell$ in sector $j$ is determined by domestic and foreign value added (Koopman et al., 2010). In the presence of an epidemic, the change in foreign value added (via impact on imported intermediates) and domestic value added (via impact on domestic intermediates) will have implications on GVC linkages in different sectors worldwide.

### 3.4. Data and parameterization

**Input-output linkages.** Our primary data source is the inter-country input-output (ICIO) database of the OECD. The ICIO has 67 economies, including China and eight ASEAN countries, each with 36 sectors. The ASEAN countries included in the ICIO are Brunei Darussalam, Indonesia, Cambodia, Malaysia, the Philippines, Singapore, Thailand, and Vietnam. The table describes the input-output associations between any pair of sectors from the same or different countries. In this paper, we focus on the linkages among sectors in China and the ASEAN economies.

The parameters pertaining to the model’s steady state are calibrated using the ICIO. We compare the economic environments before both disease outbreaks because both regions experienced SARS and COVID-19. For the impact of the SARS episode, we choose 2002 as the base year because SARS broke out in early 2003. For the COVID-19 outbreak, we select 2015, which is slightly earlier than the beginning of COVID-19. The base year for the COVID-19 is selected for two reasons. First, according to Lu and Tsang (2020), the second half of 2010 saw a series of events that disturbed global trade patterns, particularly the China–US trade war. Data from an earlier year help capture a normal-time scenario before the disease outbreak. Second, the Chinese economy has undergone a transformation with a concentration of the service sector taking over the manufacturing sector since the early 2010s. In 2015, the distribution of goods and service sectors within China was largely similar to that in the pre-SARS period. We focus on the different impacts of cross-nation production networks. Therefore, this similar distribution of domestic sectors helps minimize effects that could arise from a changing domestic economic landscape. In the remainder of the paper, the terms “SARS” and “COVID-19” refer to their time of occurrence because we calibrate the disease dynamics as the same.

We reduce the ICIO dimensions in this paper for a simple exposition. We maintain the elements for China and aggregate those for the ASEAN countries. All elements of the other countries are grouped as the ROW, and sectors are grouped into goods and services. Appendix B summarizes the detailed groupings. The original ICIO tables are expressed in nominal terms. Therefore, we rebase the values for the pre-SARS period to the dollar in 2015 by multiplying them with the gross world consumer price inflation from 2002–2015. Inflation data are obtained from the World Bank, with the deflator at 1.62. Tables 1 and 2 show the reduced input–output tables in 2015 prices. China and ASEAN’s outputs have expanded faster than the ROW from pre-SARS to pre-COVID-19 periods. ASEAN has used considerable intermediate production inputs from China.

Two parameter sets are calculated based on the input–output tables in Tables 1 and 2, which correspond to the pre-SARS and pre-COVID-19 periods, respectively. Tables 3–5 summarize the steady-state parameters. On the consumption side, Table 3 calculates the consumption shares by the source and sector. These values correspond to parameters $v^s(j, f, m)$ and $v^d(j, f)$. The shares of goods in China and ASEAN’s consumption baskets have remained similar between the pre-SARS and
Table 3
Shares of consumption by source and sector.

| ρ (m,j) | Pre-SARS | Pre-COVID-19 |
|---------|----------|--------------|
| | Goods | Services | Goods | Services |
| China | .929 | .618 | .947 | .382 |
| ASEAN | .008 | .006 | .006 | .005 |
| ROW | .064 | .048 | .048 | .050 |
| ASEAN | .010 | .522 | .011 | .478 |
| ROW | .123 | .122 | .122 | .122 |
| China | .011 | .345 | .003 | .655 |
| ASEAN | .008 | .002 | .011 | .003 |
| ROW | .980 | .995 | .948 | .995 |

Table 4
Labor shares in total inputs, 1 − α(j, ρ).

| | Pre-SARS | Pre-COVID-19 |
|---------|----------|--------------|
| | Goods | Services | Goods | Services |
| China | .328 | .532 | .265 | .577 |
| ASEAN | .362 | .561 | .361 | .548 |
| ROW | .389 | .624 | .390 | .608 |

Table 5
Shares of intermediate inputs, γ(k,m,j, ρ).

| k (m, j, ρ) | China | ASEAN | ROW |
|-----------|-------|-------|-----|
| | Goods | Services | Goods | Services | Goods | Services |
| Pre-SARS | | | | | |
| China | .710 | .542 | .016 | .005 | .007 | .002 |
| ASEAN | .169 | .438 | .004 | .000 | .001 | .001 |
| ROW | .010 | .001 | .580 | .313 | .007 | .002 |
| | | | .002 | | |
| | | | | | |
| Pre-COVID-19 | | | | | |
| China | .084 | .007 | .170 | .051 | .642 | .261 |
| ASEAN | .026 | .010 | .066 | .115 | .341 | .712 |

pre-COVID-19 periods at 0.62 and 0.53, respectively. On the production side, Table 4 shows the labor share parameters, 1 − α(j, ρ). China experienced labor share decline in the goods sector, whereas the service sector’s labor share had a slight increase. ASEAN and the ROW have slightly declined in labor share in their service sectors. Table 5 shows the shares of intermediate inputs γ(k,m,j, ρ). The cells for domestic intermediate inputs are shaded for the ease of reading. China has used less foreign intermediate inputs, with the decline being larger for intermediate inputs from the ROW. For ASEAN production, more intermediate inputs were from China than from the ROW.

A measure for forward and backward linkages captures the relationship between a particular sector j and other industries from which it purchases or to which it supplies input. Appendix A presents the derivations, and Table 6 provides the linkages of China and ASEAN. Backward linkages of China’s services decreased from the pre-SARS to pre-COVID-19 period (0.98–0.87). This data implies China’s increased independence and less reliance on ASEAN and the ROW upstream. Furthermore, its R² value increased from 1.53 to 1.74, implying increasingly uneven trading with the different economies. This finding supports the observation of China’s increased uneven participation in trade, with an increasing importance in ASEAN and less with the ROW. For the same period, ASEAN’s backward linkages of goods and forward and backward linkages of services increased between the pre-SARS and pre-COVID-19 periods. The region became highly integrated with other industries, supporting the claim that ASEAN has expanded its integration with China in GVCs.

We use the representative agent’s first-order condition relevant to labor supply to calibrate country-specific labor preference parameter θ(ρ) as follows:

\[ θ(ρ) = \frac{1}{C(ρ) \cdot N(ρ)} \]  

Productivity parameters, A(ρ, ρ), are calibrated according to Equation (8).

Epidemiological parameters. Following Çakmaklı et al. (2020), we calibrate the parameters of consumer interaction degree by using the job proximity index as shown in Appendix B. The proximity index measures the distance between workers in 36 industries. Krueger et al. (2020) showed that infection via the labor market is isomorphic to that in the consumption market. Accordingly, we adopt the proximity index to household consumption and transform it, thereby resulting in the normal distribution of numbers with a mean of 1. Let δj be the original proximity index for sector j. The normalized proximity index is calculated as \( δ_j^* = \frac{δ_j - μ_j}{σ_j} \sim N(1,1) \), where μj is the mean value of the original proximity index and σj is the standard deviation. We then calculate the mean normalized proximity index for the goods and service sector groupings, respectively. The country-invariant normalized
proximity index of sector $j$, $\delta_n^j$, is used with country $\ell$’s sectoral market shares $\nu(j, \ell)$ to calculate the country sector-specific value of $\varphi(j, \ell)$ as follows:

$$\varphi(j, \ell) = \frac{\delta_n^j}{\sum \nu(j, \ell) \cdot \delta_n^j}$$

Table 7 presents the results. Therefore, Equation (12) is satisfied.

**4. Numerical results**

The model is numerically solved in Dynare 4.6.1 by using the perfect foresight solver. We examine the economic impacts of different scenarios of disease outbreaks.

### 4.1. Epidemic in a single country

An epidemic occurs in a country when a small fraction ($\varepsilon$) of the susceptible population is infected by a disease from an unknown source. Equation (15) to Equation (18) provide the detail of the population dynamics following the initial disease outbreak. Fig. 6 shows the hypothetical population dynamics during a single-country epidemic in China and ASEAN at the time of COVID-19. The blue and green lines in Fig. 6 depict China’s equilibrium population dynamics in China and ASEAN following an epidemic in each region, respectively. After controlling for the population dynamics, the infected population peaks at 1%. This method is performed by adjusting the $\pi_s(\ell)$ values for individual countries.

The population dynamics slightly differ because of the varying sectoral distributions in China and ASEAN as shown in Table 3. The

![Image](image-url)

**Fig. 6.** Population dynamics in China and ASEAN following a single country epidemic.
infected population in China peaks at around 1% of the total population in 47 weeks and thereafter falls with fewer susceptible population. By contrast, the infected population in ASEAN peaks earlier at 36 weeks. A large service sector in ASEAN causes a rapid increase in the number of infected population and slow decay. The percentage of susceptible population declines at a faster rate in ASEAN than in China. For all single-country epidemics, the recovery rate in the long run is approximately 30% of the population. For our set of parameters, herd immunity is achieved approximately 3 years after the initial infection, during which the infected population diminishes to zero. The population dynamics for a disease outbreak during the SARS period are set the same as those in Fig. 6.

4.1.1. Within-country impacts

Our first simulation exercise examines the within-country impacts of an epidemic. Fig. 7 shows China (blue lines) and ASEAN’s responses (green lines) to an epidemic in their country, respectively. We conduct

![Fig. 7. Within-country response to an epidemic.](image)
simulations for the SARS (dashed lines) and COVID-19 (bold lines) periods.

The epidemic has an immediate effect on the changes in goods and service consumption. Consumers select less infectious sectors during an epidemic because of different degrees of contagiousness. Appendix B shows that most firms in the service sector are highly infectious, such as accommodation and food services, education, human health and social work, entertainment, recreation, and other activities. The service sector has a higher average proximity index than the goods sectors, thereby indicating a higher physical interaction level in the service sector. The service sector is disrupted by restrictions on people’s movement during a pandemic, thereby directly affecting services, such as in tourism, hotels, entertainment, restaurants, business, and finance. Consumers may substitute service consumption with goods consumption during a pandemic. For example, consumers could cook at home during lockdown periods and completely refrain from dining in restaurants. Therefore, consumption of goods, such as food products and beverages, increased, whereas that of the food services declined. As stated in Baker et al. (2020), at the beginning of the COVID-19 period, household spending increased dramatically because of stockpiling of home

Fig. 8. Cross-country response to an epidemic.
goods. As the virus spread and the number of households staying at home increased, services in restaurants, retail, air travel, and public transport in the US declined sharply. Households’ stockpiling behavior also explains the switch in spending from services to goods. The reallocation of the consumer consumption structure can also be observed in market share changes of different sectors during the pandemic. Carvalho et al. (2020) analyzed Spain’s consumer expenditure data during the COVID-19 period and found that certain goods sectors, such as food, tobacco stores, supermarkets, pharmacy, and parapharmacy, experienced increasing market shares during the pandemic, whereas the sale of goods with scarce utility and personal services suffered the most, particularly after lockdown. Andersen et al. (2020); Hall et al. (2020); Guerrieri et al. (2020) have provided similar evidence supporting the substitution effect. The substitution between goods and service sectors may not be perfect, and certain essential services, including health care and telecommunications, cannot be replaced by goods. Therefore, we conduct sensitivity analyses at different levels of the elasticity of substitution in Section 5 and consider substitute and complement scenarios.
between the goods and service sectors.

We assume constant prices and nominal exchange rates. Therefore, the import of goods and services declined by exactly the same magnitudes as those of domestic goods and services, respectively. The overall consumption declined. In general, ASEAN experienced larger impacts at the sectoral level but smaller impacts in aggregate than China. This result implies that the ASEAN consumers substitute service consumption with goods consumption more extensively, thereby mitigating the aggregate-level adverse effect. A comparison between the SARS and COVID-19 periods shows that the COVID-19 period has greater impacts that are more distinct in China based on the wider gaps between the bold and dashed blue lines.

Accordingly, a larger domestic demand for the goods sector increased the imports of final consumption goods. Moreover, the imports of inputs (goods and services) to the goods sector output increased. Compared with China, the increase in imports was more evident in ASEAN in both periods.

The consumption changes induce dynamics in sectoral industrial outputs. As anticipated, China and ASEAN’s “highly infectious” service sector output declined, whereas the “less infectious” goods sector output increased during an epidemic. ASEAN has a larger increase in goods and decline in service sector output than China. ASEAN’s responses to their within-country epidemics (service and goods sector outputs) do not significantly differ in both periods. However, China’s response to its epidemic is stronger in the COVID-19 period. In particular, China’s response in the goods sector revolved around the steady state in the SARS period. In principle, these equilibrium dynamics are jointly explained by domestic and foreign consumption demands. A comparison between China’s domestic demand for goods and services indicates a negligible change across the two periods. Therefore, foreign consumption and production demands are likely to account for the different impacts of the epidemic within China.

Similar to the case of consumption, China’s input imports for the goods sector output are largely muted in the SARS period. By contrast, imports of services for final consumption and production declined, respectively, with the largest decline in ASEAN during the COVID-19 period.

The increase in China’s goods sector output increased the total exports for final consumption in the COVID-19 period. However, ASEAN’s final consumption exports slightly decreased in the COVID-19 period as service sector output declined. Although China’s final consumption exports increased in this period, the aggregate consumption decline led to the largest decline in the country’s aggregate output in the COVID-19 period.

These results can be summarized in two observations. First, ASEAN has stronger substitution effects between goods and services than China because of the region’s large service sector. Second, COVID-19 pandemic has generated greater impacts on China than the SARS pandemic across time. We further examine the cross-country spillover effect.

![Fig. 10. Effect of substitution elasticity, \( \eta \).](image-url)
4.1.2. Cross-country impacts

Our second set of results provides evidence of the spillover effect of one country’s epidemic shock on another. Fig. 8 shows the responses of the macroeconomic variables, thereby indicating China’s response to an epidemic in ASEAN (blue lines) and vice versa (green lines). We conduct simulations for the SARS (dashed lines) and COVID-19 (bold lines) periods.

A lower and higher demand for the “highly infectious” services and “less infectious” goods, respectively, arise from the ‘other’ country because of the epidemic. Therefore, the immediate impacts observed are an increase in the goods sector output and a decline in the service sector output.

The epidemics in China have generated certain interesting dynamics in ASEAN. ASEAN’s overall consumption increased in the SARS and COVID-19 periods because of two factors: labor hours and net foreign assets. First, Fig. 8 shows that ASEAN’s labor hours declined in both periods as the decline in the service sector output outweighs the rise in the goods sector output. Second, ASEAN experienced a decline in net foreign assets in both periods. Net foreign assets in our model are equivalent to net exports (inputs and final goods). Therefore, ASEAN’s net foreign asset contraction can be attributed to the lower service demand from China. The dynamics of labor hours and net foreign assets affect the total consumption through the budget constraint in Equation (5). With wage normalized as one and constant government transfers, the relatively larger decline in net foreign assets compared with labor hours increased ASEAN’s total consumption.

A comparison between the SARS and COVID-19 periods shows that the impacts are larger for ASEAN during the later period because of two reasons. First, China consumed more goods during the COVID-19 period than during the SARS period as shown in panel (3) of row (1) in Fig. 7. China’s goods sector accounted for more than 60% of overall consumption. Therefore, this increase in goods consumption translated into a huge increase in ASEAN’s goods output demand. Second, ASEAN’s goods sector relies more on China’s intermediate inputs during the COVID-19 period than during the SARS period. Table 5 illustrates this observation, wherein China’s intermediate inputs for ASEAN’s goods production increased from 1.6% to 5.5%. The intermediate input supply for ASEAN’s production increased with China’s goods output. The increased use of intermediate inputs from China further increased the impacts. The combined effect of demand- and supply-side factors explain the substantial increase in ASEAN’s goods output. The increased use of intermediate inputs from China further increased the impacts. The combined effect of demand- and supply-side factors explain the substantial increase in ASEAN’s goods output.

China experienced smaller impacts from disease outbreaks in ASEAN, primarily because of the increased goods demand from ASEAN that caused China to accumulate net foreign assets. As net foreign assets increased more than labor hours, China’s aggregate consumption declined as illustrated in Equation (5). Across the two periods, China imported less from ASEAN for final consumption, whereas ASEAN imported more goods from China. ASEAN’s increased consumption imports from China during the epidemic caused China to increase goods production and output.
4.2. Response to a pandemic

A pandemic arises when ASEAN and China face an epidemic simultaneously. The path of the population dynamics is similar to that in Fig. 6. Therefore, cross-country population dynamics have no observable spillover effects when a pandemic occurs. Fig. 9 illustrates China (blue lines) and ASEAN’s responses (green lines) to a pandemic. The dynamics in Fig. 9 closely follow that in Fig. 7 for all variables, except for exports for final consumption, service and goods exports, and net foreign assets. This illustration indicates the dominance of home country effects (home country epidemic) over cross-country effects (other country epidemic). Exports are primarily driven by the “other country” demand. Therefore, cross-country effects have a larger impact on exports and net foreign assets. The export dynamics of final consumption and service and goods exports in Fig. 9 resemble that in Fig. 8.

Fig. 9 shows that China’s net foreign asset response is similar in both periods. China’s net foreign assets at the peak of the epidemic significantly increased compared with that of ASEAN experiencing a subdued decline in net foreign assets. This finding signifies China’s larger role in trade linkages in the context of a pandemic.

5. Sensitivity analyses

5.1. Elasticity of substitution

Thus far, our previous analyses have assumed the elasticity of substitution between goods and services at $\eta = 10$. This value may differ in practice, thereby leading to varying macroeconomic outcomes. This section discusses a sensitivity analysis conducted on the value of $\eta$, which determines the elasticity of substitution between goods and service consumption. Fig. 10 shows that a high elasticity of substitution leads an epidemic shock to higher goods sector output and lower service sector output. However, this condition results in a smaller decline in aggregate output and consumption. It is noteworthy that an elasticity smaller than unity implies that goods and services are complements rather than substitutes. In such a scenario, the goods sector output declines along with the service sector. Therefore, the infected population is the highest.

5.2. Containment efforts in China

The results in the previous section highlight the larger impact of China’s epidemic on China and ASEAN during the COVID-19 period.
This section examines the response scale in aggregate variables when China contained the in-country epidemic when it broke out. We represent China’s containment efforts with decreasing values of $\pi_s(\ell)$. Fig. 11 shows China’s population dynamics when the infected population peaks at 1% (baseline), 0.75%, 0.5%, and 0.25%. $\pi_s(\ell)$ values are adjusted to obtain the different peaks of the infected population following the epidemic. Fig. 12 shows that high epidemic containment in China (or a low peak in the infected population) leads to substantially small impacts in all the aggregate variables for China and ASEAN during the COVID-19 period.

6. Conclusion

We discuss different economic impacts of a pandemic shock that are associated with evolving economic landscapes and production linkages. We use China and ASEAN in this case study because they have experienced both SARS and COVID-19. We introduce an SIR framework to a general equilibrium model of production networks. We control the population dynamics to ensure that they are similar in China and ASEAN to identify the effect of economic landscapes and production linkages.

Our results indicate that a pandemic’s greater economic impact over the years is associated with China’s evolving role in GVCs. Our results for the in-country impact show that China would experience greater impact on aggregate consumption and production in the COVID-19 period than in the SARS period, whereas the impact on ASEAN would be similar. Moreover, our results for cross-country spillover impact show that ASEAN would experience much greater decline in aggregate output in the COVID-19 period than in the SARS period when a pandemic breaks out in China.

Our paper has a few key limitations that require future research. First, we have ignored frictions in the labor market frictions considering that workers can find jobs freely in less infectious sectors when they leave highly infectious sectors. Our frictionless labor market leads to an underestimation of the level of economic losses. Nevertheless, we derive relative impacts of the pandemic between the scenarios discussed. Second, our analyses do not assume policy interventions. We intended to study only the propagation channels of pandemic shock within and across countries. However, our sensitivity analysis shows that when China’s infection rate decreased, because of a change in the virus’s characteristics or a containment effort by the government, the spillover effect on ASEAN can be reduced accordingly. Therefore, we encourage future research to focus on labor market impacts and the interaction between policy interventions and economic outcomes.

Declaration of competing interest

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers’ bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this paper.

Appendix A. Forward and Backward Linkages

The forward and backward linkages which capture the relationship between a particular sector $j$ and other industries from which it purchases or supplies input to. In an economy with $n$ industries, the vector of sector linkages, $L$ can be given as:

$$L = \frac{n}{[1^1A_1]}A^1I$$

(A.1)

where $A$ is the $n \times n$ matrix of coefficients representing the change in output in response to an increased dollar of final demand (backward linkage)/available input for production (forward linkage). $I$ is a $n \times 1$ column vector of 1s.

The coefficient of variations, $R^2$ can also be calculated and used to compare how evenly a sector interacts with all other sectors. A larger value of $R^2$ implies that the sector mainly trades with a few industries, while a smaller $R^2$ implies that the sector interacts evenly with many industries. The vector of $R^2$ values, $CV$ can be calculated as such

$$CV = \frac{n}{\sqrt{n-1}}(A^1I)^{-1}(I \circ (A^1KA))^2$$

(A.2)

where $I$ is the identity matrix, $K = I - \frac{1}{n}11^T$ and $\circ$ represents the Hadamard product.
Appendix B. Sector Groupings

| IOIO Code | Industry                                                                 | Proximity Index | Broad sector   |
|-----------|---------------------------------------------------------------------------|-----------------|---------------|
| D01T03    | Agriculture, forestry and fishing                                        | 0.86            | Goods         |
| D05T06    | Mining and extraction of energy producing products                       | 1.08            |               |
| D07T08    | Mining and quarrying of non-energy producing products                    | 1.06            |               |
| D09       | Mining support service activities                                        | 1.21            |               |
| D10T12    | Food products, beverages and tobacco                                     | 1.12            |               |
| D13T15    | Textiles, wearing apparel, leather and related products                  | 1.03            |               |
| D16       | Wood and products of wood and cork                                       | 1.03            |               |
| D17T18    | Paper products and printing                                              | 1.08            |               |
| D19       | Coke and refined petroleum products                                       | 1.11            |               |
| D20T21    | Chemicals and pharmaceutical products                                    | 1.06            |               |
| D22       | Rubber and plastic products                                              | 1.10            |               |
| D23       | Other non-metallic mineral products                                      | 1.08            |               |
| D24       | Basic metals                                                             | 1.09            |               |
| D25       | Fabricated metal products                                                | 1.08            |               |
| D26       | Computer, electronic and optical products                                 | 1.03            |               |
| D27       | Electrical equipment                                                     | 1.07            |               |
| D28       | Machinery and equipment, nec                                             | 1.06            |               |
| D29       | Motor vehicles, trailers and semi-trailers                               | 1.09            |               |
| D30       | Other transport equipment                                                 | 1.06            |               |
| D31T33    | Other manufacturing; repair and installation of machinery and equipment   | 1.07            |               |
| D35T39    | Electricity, gas, water supply, sewerage, waste and remediation services | 1.08            | Services      |
| D41T43    | Construction                                                             | 1.21            |               |
| D45T47    | Wholesale and retail trade; repair of motor vehicles                      | 1.13            |               |
| D49T53    | Transportation and storage                                               | 1.18            |               |
| D55T56    | Accommodation and food services                                           | 1.26            |               |
| D58T60    | Publishing, audiovisual and broadcasting activities                       | 1.11            |               |
| D61       | Telecommunications                                                       | 1.07            |               |
| D62T63    | IT and other information services                                        | 1.01            |               |
| D64T66    | Financial and insurance services                                          | 1.02            |               |
| D68       | Real estate activities                                                    | 1.10            |               |
| D69T82    | Other business sector services                                            | 1.09            |               |
| D84       | Public admin. and defence; compulsory social security                    | 1.16            |               |
| D85       | Education                                                                | 1.22            |               |
| D86T88    | Human health and social work                                              | 1.28            |               |
| D90T96    | Arts, entertainment, recreation and other service activities              | 1.18            |               |
| D97T98    | Private households with employed persons                                 | -              |               |

References

Abiad, A., Arao, R.M., Dagli, S., 2020. The Economic Impact of the COVID-19 Outbreak on Developing Asia.
Alvarez, F.E., Argente, D., Lippi, F., 2020. A Simple Planning Problem for COVID-19 Lockdown. National Bureau of Economic Research. Technical Report.
Andersen, A.L., Hansen, E.T., Johannesen, N., Sheridan, A., 2020. Consumer Responses to the COVID-19 Crisis: Evidence from Bank Account Transaction Data. Available at: SSRN 3699814.
Atkeson, A., 2020. What Will Be the Economic Impact of COVID-19 in the US? Rough Estimates of Disease Scenarios. Working Paper 26867. National Bureau of Economic Research, https://doi.org/10.3386/w26867, series: Working Paper Series http://www.nber.org/papers/w26867.
A. George et al.
Economic Modelling 101 (2021) 105510

Baqaee, D.R., Farhi, E., 2020. Nonlinear Production Networks with an Application to the COVID-19 Pandemic. Rev. Asset Pricing Stud. 10, 834–862. https://doi.org/10.1016/j.rbps.2017.03.005, http://www.sciencedirect.com/science/article/pii/S1043951X17300457.

Baker, S.R., Farrokhnia, R.A., Meyer, S., Pagel, M., Yannelis, C., 2020. How does household spending respond to an epidemic? Consumption during the 2020 COVID-19 pandemic. Rev. Asset Pricing Stud. 10, 834-862.

Bonadio, B., Huo, Z., Levenenko, A.A., Pandalai-Nayar, N., 2020. Global Supply Chains in the Pandemic. NBER Working Paper No. 27224.

Çakmaklı, C., Demiralp, S., Kalemlı-Oranç, S., Yalıtslas, S., Yildirim, M.A., 2020. COVID-19 and Emerging Markets: an Epidemiological Multi-Sector Model for a Small Open Economy with an Application to Turkey. National Bureau of Economic Research, https://doi.org/10.3386/w27191, Working Paper 27191 https://www.nber.org/papers/w27191.

Carvalho, V.M., Hansen, S., Ortiz, A., Garcia, J.R., Rodrigo, T., Rodrigo Mora, S., Ruiz de Aguirre, P., 2020. Tracking the COVID-19 Crisis with High-Resolution Transaction Data.

Chor, D., Manova, K., Yu, Z., 2021. Growing like China: firm performance and global production line position. J. Int. Econ. 130, 103445. https://doi.org/10.1016/j.jieco.2019.101385, http://www.sciencedirect.com/science/article/pii/S1043951X19301464.

Containment Policy in Open Economies. National Bureau of Economic Research. Technical Report.

D97T98 Private households with employed persons –
D90T96 Arts, entertainment, recreation and other service activities 1.18
D86T88 Human health and social work 1.28
D90T96 Arts, entertainment, recreation and other service activities 1.18
D97T98 Private households with employed persons –

Eichenbaum, M., Rebelo, S., Trabandt, M., 2020. The Macroeconomics of Epidemics. Draft, Northwestern University.
Fernandes, N., 2020. Economic Effects of Coronavirus Outbreak (COVID-19) on the World Economy. Available at: SSRN 3557504.
Funke, M., Tsang, A., 2020. The people’s bank of China’s response to the coronavirus pandemic: a quantitative assessment. Econ. Modell. 93, 465–473.

Getachew, Y., 2020. Optimal social distancing in SIR based macroeconomic models. Covid Econ. 115.

Guerrini, V., Lorenzoni, G., Straub, L., Werner, I., 2020. Macroeconomic Implications of COVID-19: Can Negative Supply Shocks Cause Demand Shortages? National Bureau of Economic Research. Technical Report.

Hall, M.C., Prayag, G., Fieger, P., Dyason, J., 2020. Beyond panic buying: consumption displacement and COVID-19. J. Serv. Manag.

Hsu, W.T., Lin, H.C.L., Han, Y., 2020. Between Lives and Economy: Optimal COVID-19 Containment Policy in Open Economies.

Huang, Y., Salike, N., Zhong, F., 2017. Policy effect on structural change: a case of Chinese intermediate goods trade. China Econ. Rev. 44, 30–47, https://doi.org/10.1016/j.chieco.2017.03.005, http://www.sciencedirect.com/science/article/pii/S1043951X17300457.

Kimura, F., Thangavelu, S.M., Narjoko, D., Findlay, C., 2020. Pandemic (COVID-19) policy, regional cooperation and the emerging global production network. Asian Econ. J. 34, 3–27.

Koopman, R., Powers, W., Wang, Z., Wei, J.S., 2010. Give Credit where Credit Is Due: Tracing Value Added in Global Production Chains. National Bureau of Economic Research. Technical Report.

Krueger, D., Uhlig, H., Xie, T., 2020. Macroeconomic Dynamics and Reallocation in an Epidemic. Working Paper 27047. National Bureau of Economic Research, https://doi.org/10.3386/w27047, http://www.nber.org/papers/w27047.

Koopman, R., Powers, W., Wang, Z., Wei, J.S., 2010. Give Credit where Credit Is Due: Tracing Value Added in Global Production Chains. National Bureau of Economic Research. Technical Report.

Liao, J., 2020. The rise of the service sector in China. China Econ. Rev. 59, 101385, https://doi.org/10.1016/j.chieco.2019.101385, http://www.sciencedirect.com/science/article/pii/S1043951X19301464.

Luo, S., Tsang, K.P., 2020. China and World Output Impact of the Hubie Lockdown during the Coronavirus Outbreak. Contemporary Economic Policy, https://doi.org/10.1111/coep.12482, https://onlinelibrary.wiley.com/doi/abs/10.1111/coep.12482, https://onlinelibrary.wiley.com/doi/pdf/10.1111/coep.12482.

McKinnon, W., Fernando, R., 2020. The global macroeconomic impacts of COVID-19: seven scenarios. Asian Econ. Jan. 1, 1–55.

UNIDO, 2018. Global Value Chains and Industrial Development: Lessons from China, South-East and South Asia.

Yamaguchi, A., 2018. Global Value Chains in ASEAN. Institute for International Monetary Affairs, Newsletter.