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What are the Driving Forces of the Economic Downturn in Korea during COVID-19?*

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We investigate the main driving forces of business cycles and heterogeneity across industries during the COVID-19 crisis in Korea. We build a small open economy model, solved up to the second-order, to fit the stylized facts of business cycles and employ several structural shocks as candidates of driving forces. In contrast to the financial crisis in 2008, the transitory productivity shock is the predominant source, but the permanent productivity shock is assigned less importance during the pandemic. In addition, negative preference shocks rapidly reduce consumption in 2020Q1 and bounce back with upward pressure on consumption growth in 2020Q2 over the pandemic cycle. The service sector, especially accommodation and food, is the most adversely affected by structural shocks at the onset of the COVID-19 outbreak.

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I. Introduction

The world has experienced an unprecedented economic recession caused by the outbreak of coronavirus disease 2019 (COVID-19). To mitigate the spread of the virus, government authorities around the world have enforced social distancing and lockdown measures such as stay-at-home and travel restrictions, temporarily closing manufacturing facilities, and restricting movements and operations of small businesses. These series of measures have triggered an unexpected recession,

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causing a collapse in the supply chain, leaving many workers jobless, and worsening consumer sentiments.

The COVID-19 crisis combines both supply and demand shocks. For instance, negative supply shocks arise from lockdown measures that restrain workers from traveling to their workplaces and firms from producing goods and services. The shocks disrupting the supply chain shift the production possibility frontier inward during a crisis. The disease that restricts consumers' accessibility or willingness to purchase non-essentials, and even essentials, cause negative demand shocks. The fear of infection changes consumers' behavior voluntarily via precautionary savings motive and involuntarily via social distancing, which immediately and severely contract aggregate consumption.

In this paper, we aim to discuss the main driving forces of business cycles during the COVID-19 crisis in Korea. First, we quantify the role of several structural shocks on business cycles by differentiating the supply and demand shocks in the pandemic. Second, we explore an economic mechanism to determine which frictions amplify the shocks triggered by COVID-19. Third, we estimate the heterogeneous responses of the industrial sector to the estimated economic shocks identified from a structural model. To do so, we employ a financial frictions model of a small open economy proposed by Garcia-Cicco et al. (2010). To enable the benchmark model suitably reflect the Korean economy, we not only adopt a recursive utility as Rhee (2017) but also allow various structural shocks. We apply a second-order approximation to the model and employ the Gaussian Mixture Filter (GMF) for the evaluation of the likelihood within Markov Chain Monte Carlo (MCMC) proposed in Noh (2019). The quadratic approximation is more suited to characterize macroeconomic dynamics in emerging countries, capturing the precautionary behaviors of economic agents (Fernández-Villaverde and Rubio-Ramírez, 2005; Noh and Baek, 2020). The last step of our empirical analysis is to estimate a VAR model using the estimated structural shocks and the sectoral output growth.

Consequently, our quadratic financial frictions model accounts for the Korean economic downturn during the pandemic by assigning a dominant role to transitory productivity shocks. The outbreak of the disease instantly contracts economic activities associated with production, consumption, and investment mainly because of a fall in the transient component of total factor productivity. Preference shocks are also important driving forces of the reduction in consumption unlike in the case of the financial crisis. Although country premium shocks caused a significant fall in investment together with a collapse of the mortgage market during the financial crisis, they do not bear an adverse influence during the pandemic. Moreover, as the pandemic has resulted in economic costs emerging from working from home, the mandated social-distancing, and the fear of infection at the workplace, the influence of labor supply shocks is more amplified than the previous crises, although the magnitude is limited. The shocks triggered by COVID-19 are largely amplified by capital adjustment costs, the elasticity of intertemporal substitution (EIS), and working capital constraints. Even though the role of financial frictions on debt elasticity has been ambiguous in the Korean economy, our comprehensive DSGE model concludes that its effect is negligible or small, except for the dynamics of trade balance-to-output ratio.

It is well-known that an individual and a group having different characteristics make different optimal decisions on the impact of shocks. The extreme shocks on the economy, especially such as COVID-19, create heterogeneous responses across countries, industries, demographics, and employment, as described in various studies, including Adams-Prassl et al. (2020) and Guerrieri et al. (2020). Our estimated result also bolsters their arguments on the heterogeneity during the pandemic. After the outbreak of COVID-19, the decline in the service sector output growth was immediate and larger than that in the manufacturing sector. A predominant share of the decline in the output level of the service sector is attributed to the accommodation and food services sector given that social distancing measures primarily target high physical-contact services, and people might voluntarily avoid close contact with each other.

Since the recent COVID-19 outbreak hit the global economy, several studies have attempted to understand the aggregate macroeconomic effects of the unprecedented pandemic and its propagation mechanisms. Stiglitz (2020) argues that precautionary savings against uncertainty with sectoral technologies and constraints on resource allocations deteriorate the recessions during the COVID-19 pandemic. Baqaee and Farhi (2020) build a general disaggregated model to understand how sectoral supply and demand shocks from COVID-19 affect aggregate macroeconomic variables and how they create spillovers with complementarities in production. Céspedes et al. (2020) emphasize the interaction of productivity in the labor market with credit market imperfection, which generate vicious economic cycles during COVID-19. However, to the best of our knowledge, studies on the identification of the main drivers among the various structural shocks and their quantitative roles during the pandemic are scarce. As COVID-19 is one of the most unusual macroeconomic shocks in the living memory, distinguishing which shocks render the COVID-19 crisis different from previous crises can help provide insights into policy alternatives.

The remainder of the paper is organized as follows: Section 2 presents the financial frictions model with recursive preferences. Section 3 describes how we estimate the model solved up to second order. Section 4 discusses the estimation results. Section 5 investigates the sources of business cycles, which structural parameters matter for the shock amplification, and heterogeneity for an industrial sector during COVID-19. Finally, Section 6 summarizes and concludes.

II. Theoretical Model

The basic framework follows the vintage of an RBC model for a small open economy proposed by Mendoza (1991). A strand of literature, such as Schmitt-Grohé and Uribe (2003), Aguiar and Gopinath (2007), Garcia-Cicco et al. (2010), and Chang and Fernández (2013), has attempted to quantitatively evaluate the salient mechanisms of the business cycle fluctuations in emerging countries by imposing structural shocks, real frictions, or other constraints including financial frictions and imperfect information. Our workhorse model has a largely similar structure as that suggested by Garcia-Cicco et al. (2010), which includes financial frictions on the domestic interest rate.

The model is characterized by three distinct features to account for observed aggregate dynamics in the Korean economy. First, we employ Epstein and Zin (1991)'s recursive preferences to separate the degree of relative risk aversion from the EIS. As described in Rhee (2017), we can avoid a situation in the steady state, where the discount factor is larger than one, for Korean data. Second, the model is equipped with financial frictions on the domestic interest rate, implying that the country premium increases as the level of external debt rises. This mechanism plays an important role in amplifying structural shocks and generating the business cycles observed in emerging countries. As additional friction, we impose working capital constraints that force firms to finance a fraction of their wage bill and payments for imported intermediate goods in advance. Although the financial frictions suggested by Garcia-Cicco et al. (2010) show a good fit for the model on the emerging countries in Latin America, the role of financial frictions in the Korean economy is ambiguous (Jung and Yang, 2013; Rhee, 2017). Thus, we embed the financial frictions in our model to fill this gap and investigate how structural shocks during COVID-19 are amplified. Lastly, we characterize our model abundant by adding many possible exogenous shocks to gauge their quantitative importance during economic downturns. The seven structural shocks comprise transitory and permanent productivity shocks, preference shock, country-premium shock, domestic spending shock, labor supply shock, and imported intermediate goods price shock.

2.1. Preferences

We assume that a large number of infinitely-lived households inhabit a small open economy and want to optimize an identical Epstein-Zin preference as a specification of the recursive utility:

$$V_t = \left\{ (1-\beta) v_t [C_t - \zeta_t \omega^{-1} G_{t-1} h_t^{\omega}]^{\frac{1-\gamma}{\theta}} + \beta [E_t (V_{t+1}^{1-\gamma})]^{\frac{1}{\theta}} \right\}^{\frac{\theta}{1-\gamma}}, \tag{1}$$

where $0 < \beta < 1$ denotes the discount factor, γ determines the degree of relative risk aversion of households to static gambles, and $\kappa = \frac{\theta}{\theta+\gamma-1}$ represents the EIS. Considering $\theta = \frac{1-\gamma}{1-\frac{1}{\kappa}}$, if $\gamma > \frac{1}{\kappa}$, households prefer an early resolution of uncertainty, but if $\gamma < \frac{1}{\kappa}$, they prefer a late resolution. ω is related to the Frisch labor supply elasticity. C_t and h_t denote consumption and hours worked, respectively. G_{t-1} is a trend component, which we elaborate in more detail in Section 2.2. We allow for three sources of uncertainty on households: a preference shock, v_t, a labor supply shock, ζ_t, and a shock to domestic spending, S_t. A labor supply shock leads to an exogenous shift in labor supply, possibly because of unmodeled labor market imperfections created by unexpected events such as the pandemic. For example, a labor supply shock can be interpreted as a time-varying wage markup shock under the imperfectly competitive labor market as usual in the New Keynesian framework. Households reduce total hours worked by weighing more disutility on labor supply in response to a positive labor supply shock, and finally, the fall in labor supply induces an increase in firms' marginal costs (Del Negro et al., 2013).

Given that income is the result of providing labor force, households accumulate physical capital and manage the stock of debt by rolling over to the next period over their lifetime. They determine the amount of consumption and investment at time t, which formulates the budget constraint in the economy as follows:

$$\frac{D_{t+1}}{1+r_t} = D_t - Y_t + C_t + S_t + I_t + \frac{\eta r_t}{1+r_t}(w_t G_t h_t + q_t X_t) + \frac{\phi}{2}\left(\frac{K_{t+1}}{K_t} - \mu_g\right)^2 K_t, \tag{2}$$

where μ_g denotes the growth rate of a trend component. D_{t+1} denotes the households' debt acquired in period t, r_t denotes the domestic interest rate on bonds held between periods t and $t+1$, and I_t denotes gross investment. S_t represents domestic spending shocks. A domestic spending shock can be interpreted as a fiscal or net export shock as in Garcia-Cicco et al. (2010) and Benigno et al. (2020).[1] The term $\frac{\eta r_t}{1+r_t}(w_t G_t h_t + q_t X_t)$, which we describe in more detail in Section 2.2, describes a working capital constraint, stating that a fraction of the wage and intermediate good bill must be paid in advance of production with borrowed funds. The relative price of labor (h_t) and imported intermediate goods (X_t) are given by

[1] By the interpretation of a domestic spending shock, a subtraction of consumption and investment from output determines the trade balance or government spending, respectively.

w_t and q_t, resepectively, both of which are determined endogenously.[2] The last term on the right-hand side of equation (2) incurs capital adjustment costs, which are common in a small open economy model to avoid the excessive response of investment to the changes in the interest rate. Households are charged the convex quadratic adjustment costs on a change in capital stock, and the parameter ϕ determines sensitivity to capital adjustment. Based on the budget constraint, the trade balance, TB_t, is defined as the present value of the net debt.[3] The law of motion of capital stock is as follows:

$$K_{t+1} = (1-\delta)K_t + I_t, \tag{3}$$

where $\delta \in [0,1)$ denotes the depreciation rate of physical capital.

The households are also subject to a no-Ponzi game constraint,

$$\lim_{j\to\infty} \frac{D_{t+j}}{\prod_{s=0}^{j}(1+r_s)} \le 0. \tag{4}$$

The exogenous shocks, v_t, ζ_t, and S_t, evolve by following a first-order autoregressive process as below:

$$\begin{aligned}
\ln v_{t+1} &= \rho_v \ln v_t + \varepsilon_{t+1}^{v}, \\
\ln(\zeta_{t+1}/\mu_\zeta) &= \rho_\zeta \ln(\zeta_t/\mu_\zeta) + \varepsilon_{t+1}^{\zeta}, \\
\ln(s_{t+1}/\mu_s) &= \rho_s \ln(s_t/\mu_s) + \varepsilon_{t+1}^{s},
\end{aligned} \tag{5}$$

where $s_t = S_t / G_{t-1}$, $|\rho_v| < 1$, $|\rho_\zeta| < 1$, $|\rho_s| < 1$, $\varepsilon_{t+1}^{v} \sim iidN(0,\sigma_v^2)$, $\varepsilon_{t+1}^{\zeta} \sim iidN(0,\sigma_\zeta^2)$, and $\varepsilon_{t+1}^{s} \sim iidN(0,\sigma_s^2)$. Both μ_ζ and μ_s denote the deterministic values of labor supply and domestic spending.

2.2. Technology

The firms produce output according to the technology in the form of Cobb–Douglas with capital K_t, imported intermediate goods X_t, and labor h_t, as inputs. Gross domestic product, Y_t, is defined as follows:

$$Y_t = a_t K_t^{\alpha_1} X_t^{\alpha_2} (G_t h_t)^{1-\alpha_1-\alpha_2} - q_t X_t, \tag{6}$$

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[2] The relative price of imported intermediate goods q_t is predetermined.

[3] By following equation (2), the present value of the net debt, $D_t - \frac{D_{t+1}}{1+r_t}$, is equivalent to $Y_t - C_t - S_t - I_t - \frac{\phi}{2}(\frac{K_{t+1}}{K_t} - \mu_g)^2 K_t - \frac{\eta r_t}{1+r_t}(w_t G_t h_t + q_t X_t)$.

where α_1 and α_2 the shares of capital and imported intermediate goods in output, respectively. We allow exogenous stochastic shocks to the relative price of imported intermediate goods, q_t, that follows a first-order autoregressive process with μ_q, the average level of the relative price of imported intermediate goods:

$$\ln(q_{t+1} / \mu_q) = \rho_q \ln(q_t / \mu_q) + \varepsilon_{t+1}^q . \tag{7}$$

where $|\rho_q| < 1$ and $\varepsilon_{t+1}^q \sim iidN(0, \sigma_q^2)$. The productivity along the balanced growth path has two persistence-sensitive shocks. While productivity, a_t, is a common transitory shock showing mean-reverting property, the labor-augmented productivity, G_t, regulates the trend of productivity path over periods.

To provide a degenerating property after the realization of the transitory shock, a_t, we assume that it follows a first-order autoregressive process:

$$\ln a_{t+1} = \rho_a \ln a_t + \varepsilon_{t+1}^a , \tag{8}$$

with $|\rho_a| < 1$ and $\varepsilon_{t+1}^a \sim iidN(0, \sigma_a^2)$. The trend shock on productivity, G_t, is accumulated with the rate of gross growth, g_t. The labor-augmented trend shocks follow two steps to pass the one-time shock to the future as follows:

$$G_t = g_t G_{t-1} . \tag{9}$$

The natural logarithm of g_t follows a first-order autoregressive process:

$$\ln(g_{t+1} / \mu_g) = \rho_g \ln(g_t / \mu_g) + \varepsilon_{t+1}^g , \tag{10}$$

where $|\rho_g| < 1$ and $\varepsilon_{t+1}^g \sim iidN(0, \sigma_g^2)$. The term μ_g is the deterministic gross growth rate of permanent productivity.

Given the production technology, we introduce a working capital constraint, $\kappa_t \geq \eta(w_t G_t h_t + q_t X_t)$. It implies that firms are constrained to hold a certain amount of working capital, κ_t, to the proportion of the wage bill, $w_t G_t h_t$, and the payments for imported intermediate goods, $q_t X_t$, in each period. In turn, the constraint limits firms' ability to choose imported intermediate goods and labor input optimally because of additional financing costs of imported intermediate goods and labor as follows (see the details in Uribe and Yue, 2006):

$$E_0 \sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0} \left[a_t K_t^{\alpha_1} X_t^{\alpha_2} (G_t h_t)^{1-\alpha_1-\alpha_2} - u_t K_t - \left(1 + \frac{\eta r_t}{1+r_t}\right) [w_t G_t h_t + q_t X_t] \right], \tag{11}$$

where λ_t denotes the stochastic discount factor (household's marginal utility of wealth), u_t the rental rate of capital, q_t the relative price of imported intermediate goods, and w_t the wage rate. Working capital incurs financial costs for the unit labor and imported intermediate goods by $\eta r_t / (1 + r_t)$, which generates the wedge between the marginal product of labor (or imported intermediate goods) and real wage (or the price of imported intermediate goods) in the first-order necessary condition with respect to labor (or imported intermediate goods); this, in turn, amplifies the effect of the change in international financial markets. The firms' initial net liabilities are assumed to be zero, which leads to no liabilities for all next periods as in Uribe and Yue (2006).

2.3. Domestic Interest Rate

Our model for the Korean economy is equipped with mechanisms for financial frictions on external debt and country premium shocks. We employ these features as in Garcia-Cicco et al. (2010) that could make the cost of foreign debt in emerging economies countercyclical. Also, they might play an important role in explaining stylized facts of business cycles in emerging countries: the excess volatility of consumption, countercyclical behavior of the current account, and autocorrelation of the trade balance-to-output ratio. Although some studies explore the role of financial frictions in the Korean economy, the agreement on the effectiveness of the frictions is lacking. Jung and Yang (2013) argue that financial frictions play a negligible role. However, Rhee (2017) explains the potential of financial frictions and imperfection as the major propagation channel of economic shocks in the Korean economy.

The domestic interest rate comprises the world interest rate, a debt-elastic country's risk premium, and exogenous country premium shocks. The financial frictions increase in the level of detrended aggregate debt and the parameter ψ in equation (12), which regulates the debt-elasticity of the domestic interest rate, determines the size of financial frictions. The estimation of ψ ensures stationarity of the equilibrium dynamics as in Schmitt-Grohé and Uribe (2003), and enables the model to incorporate the reduced form of financial frictions to capture the dynamic behavior of the Korean economy. We add an exogenous stochastic country-premium shock, η_t, to implant the remaining fluctuations on the interest rate. The country premium shocks can be interpreted as the financial imperfection that is independent of the state of domestic fundamentals. The financial imperfection could reflect political factors, the fear of contagion or commodity prices (Letendre and Obaid, 2020). The domestic interest rate is defined in the model as follows:

$$r_t = r^* + \psi \left[\exp\left(\frac{\tilde{D}_{t+1} / G_t - \bar{d}}{\bar{y}} \right) - 1 \right] + \exp(\eta_t - 1) - 1 , \tag{12}$$

where r^* denotes the world interest rate, $\tilde{D}_{t+1}$ denotes the country's aggregate debt ($\tilde{D}_{t+1} = D_{t+1}$ in equilibrium), and $\bar{y}$ and $\bar{d}$ denote the steady state level of the detrended output and debt, respectively. The shock follows a first-order autoregressive process:

$$\ln \eta_{t+1} = \rho_\eta \ln \eta_t + \varepsilon^\eta_{t+1}, \tag{13}$$

where $|\rho_\eta| < 1$ and $\varepsilon^\eta_{t+1} \sim iidN(0, \sigma^2_\eta)$. The country premium, $r_t - r^*$, is determined by the level of the country's foreign aggregate debt and country premium shocks. As the trade balance deficit is financed by foreign borrowing, the trade balance deficit increases the country premium.

III. Empirical Methodology

We solve the model around the deterministic steady state up to the second order (Schmitt-Grohé and Uribe, 2004). To obtain a stationary competitive equilibrium, we detrend all trending variables by dividing them by G_{t-1} when solving the model. By employing a second-order approximation, the model can not only consider imposed precautionary behaviors of economic agents but also match empirical data better (Fernández-Villaverde and Rubio-Ramírez, 2005; Amisano and Tristani, 2010; Noh and Baek, 2020). The dynamics of the solution can be described by two systems of equations: the dynamics of the non-predetermined endogenous variables, y_t, and those of the predetermined endogenous and exogenous variables, x_t.

[Table 1] Calibration

Parameter	Description	Value
δ	Depreciation rate	0.025
α_1	Capital share of income	0.35
α_2	Imported intermediate input share of income	0.124
ω	Labor supply elasticity	1.6
μ_ζ	Labor parameter	2.24
r^*	World interest rate	0.0067
β	Discount factor	$\dfrac{\mu_g^{\frac{\gamma+\theta-1}{\theta}}}{1+r^*}$

The model solution is given by the following nonlinear state-space representation:

$$y_t = \frac{1}{2} g_{\sigma\sigma} + G_x(x_t) + \frac{1}{2} G_{xx}(x_t \otimes x_t) + \varepsilon_t ,$$
$$x_{t+1} = \frac{1}{2} h_{\sigma\sigma} + H_x(x_t) + \frac{1}{2} H_{xx}(x_t \otimes x_t) + \sigma\eta_{t+1} , \quad (14)$$

where x_t with dimension $n_x \times 1$ denotes a set of state variables that contains predetermined endogenous and exogenous variables, y_t with dimension $n_y \times 1$ is a set of observable variables, $\varepsilon_t \sim i.i.dN(0, \mathbf{R}_\varepsilon)$, and $\eta_{t+1} \sim i.i.dN(0, \mathbf{R}_\eta)$. All constant terms and coefficients, $\{g_{\sigma\sigma}, G_x, G_{xx}, h_{\sigma\sigma}, H_x, H_{xx}\}$ that are functions of structural parameters are $n_y \times 1$, $n_y \times n_x$, $n_y \times n_x^2$, $n_x \times 1$, $n_x \times n_x$, and $n_x \times n_x^2$ matrices, respectively. The scalar σ is the perturbation parameter. As noted by Kim et al. (2008), the second-order approximations could generate explosive sample paths when the accumulation of higher-order effects is significantly large, generating unstable steady states. To solve this problem, we apply a pruning procedure to a second-order approximation that eliminates terms of higher-order effects than the approximation order (Kim et al., 2008; Andreasen et al., 2017).

We calibrate parameters following Garcia-Cicco et al. (2010) and Rhee (2017). Table 1 describes our calibration. The depreciation rate, δ, is set to 0.025, which is frequently used in the literature. We set the capital share of income to 0.35, based on the National Accounts and set the imported intermediate input share of income to 0.124, based on the Input-Output Statistics. The parameter ω, which is related to the labor supply elasticity, is set to 1.6. This value is commonly used in the small open economy literature. The steady state of labor supply shock is set to 2.24.[4] The real interest rate in the steady state is set to the average quarterly real interest rate. The discount factor, β, is determined by $\frac{\mu_g^{\frac{\gamma+\theta-1}{\theta}}}{1+r^*}$.

For the estimation, we use five observable variables as follows: growth rates of output, consumption, and investment, trade balance-to-output ratio, and the relative price of imported intermediate goods, which is calculated by the log-difference between the price of imported intermediate goods and final goods and services,

$$\text{Output growth} = \Delta \ln Y_t = \ln(y_t) - \ln(y_{t-1}) + \ln(g_{t-1}) ,$$
$$\text{Consumption growth} = \Delta \ln C_t = \ln(c_t) - \ln(c_{t-1}) + \ln(g_{t-1}) ,$$
$$\text{Investment growth} = \Delta \ln I_t = \ln(i_t) - \ln(i_{t-1}) + \ln(g_{t-1}) ,$$
$$\text{Trade balance-to-output} = TB_t / Y_t = tb_t / y_t ,$$
$$\ln(\text{Imported intermediate goods price/Final goods price}) = \ln(q_{t+1}) . \quad (15)$$

[4] The real interest rate is calculated as the difference between the nominal interest rate for AA– rated corporate bonds [CB(AA–)] and the four-quarter moving average of the GDP deflator inflation rates.

The dataset spans from 2000Q1 to 2020Q3. We obtain the dataset from the Economic Statistics System of the Bank of Korea. We allow for measurement errors in all observable variables whose variance is set to be 1% of the variance of the observables.[5]

We additionally consider other observable variables such as wage and employment in the measurement equation of the extended model for robustness check. In the extended model, we consider capacity utilization following Schmitt-Grohé and Uribe (2012). The main implications do not differ from those in our benchmark model with five observables (see Fig. 13 in Appendix E obtained from the extended model using wage inflation and employment growth rate). The identified labor supply shocks in the extended model positively affect output growth with little fluctuations during COVID-19. However, in our benchmark model, the labor supply shocks are more increased during COVID-19 than other crises and negatively affect output growth. These results which will be discussed in the later section are rather consistent with our economic intuitions.[6]

We estimate the model using the Random-Walk Metropolis-Hastings (RWMH) algorithm. We employ the GMF for the evaluation of the likelihood $\hat{p}^{GMF}(y_{1:T} \mid \theta^*)$ and embed the GMF within the RWMH algorithm. The acceptance ratio of the RWMH is as follows:

$$\hat{r}^{GMF}(\theta^* \mid \theta) = \frac{\hat{p}^{GMF}(y_{1:T} \mid \theta^*) p(\theta^*) q(\theta \mid \theta^*)}{\hat{p}^{GMF}(y_{1:T} \mid \theta) p(\theta) q(\theta^* \mid \theta)}. \tag{16}$$

The basic idea of the GMF is to approximate the likelihood function by a mixture of Gaussian distributions (Alspach and Sorenson, 1971, 1972; Lo, 1972). Each Gaussian distribution is evaluated using the Central Difference Kalman filter (CDKF). The first and second moments estimated by the CDKF are accurate up to at least the second order and are accurate up to the third order when the state vector is approximately Gaussian (Andreasen, 2013). The CDKF approximates each

[5] Any small amount of measurement error would be needed to avoid degeneracy of the GMF. The size of measurement errors (1% of the variance of the observables) is reasonable given that measurement issues could be large in emerging economies. We tested 5%, 10%, and 20% of the variance of the observables. The main results are robust regardless of the size of measurement errors. These results are available upon request.

[6] Although the extended model considers additional observable variables, such as wage inflation and employment, it might be ill-suited to identify labor supply shocks or distort other shocks without considering a stochastic trend component of hours worked. Hours worked potentially have a trend component possibly due to structural changes in demography, government policies on the labor market, household production technology, or preferences (Chang et al., 2007). Therefore, it would be required to have a nonstationary labor supply shock to match labor market-related variables. This shock, which differs from a trend component of technology, induces an additional stochastic trend into hours worked and other macroeconomic variables.

likelihood function of the mixture component based on a standard Kalman filtering and updating procedure. As the GMF is considered as a global filtering method similar to the particle filter, the GMF approximately evaluates the exact likelihood. Noh (2019) applies this feature to the MCMC sampler and demonstrates that the GMF with the RWMH algorithm can converge to the true posterior density when the number of mixture components goes to infinity.

Although the GMF with a finite and small number of mixture components has an approximation error, it is a deterministic filtering method, implying that the evaluated likelihood has no uncertainty that might reduce the efficiency of the RWMH algorithm. To reduce the approximation errors, we adaptively refine the GMF by splitting a mixture component into new mixture components based on the Binomial Gaussian mixture (see the details of the GMF in Appendix B; Raitoharju et al., 2015; Noh, 2019). We generate 200,000 draws from the posterior distribution and use 150,000 draws to calculate the point estimates.

IV. Empirical Analysis

In this section, we present the empirical results obtained from the Bayesian estimation and discuss properties of business cycles in the Korean economy under the small economy model with various frictions compared with observed Korean data such as output, consumption, investment, and the trade balance-to-output ratio.

Table 2 lists the priors, the median, and the 5 and 95 percentiles of the posterior distributions obtained by the RWMH algorithm. Although we apply rather diffuse priors for all parameters, data seem to be fairly informative because simulated posteriors generate a reasonable range of credible intervals.[7] Our parameter estimate of the mean of trend productivity growth, μ_g, is precisely estimated in a second-order approximation contrary to the result in Garcia-Cicco et al. (2010).

Several estimated results are worth mentioning. The volatilities of both productivity shocks have a similarity in estimated values. The estimation results illustrate the different degrees of persistence on transitory and permanent productivity shocks. The two productivity shocks have distinct properties in terms of persistence. The estimated coefficient of the AR(1) process on the transitory shocks is 0.957, which makes shocks to transitory productivity linger for a relatively long time. The permanent labor-augmented productivity shocks have moderate persistence, with an estimated value of 0.632. When the growth rate of the

[7] The parameter for risk aversion looks weakly identified showing a rather wide credible interval range. This result is consistent with the fact that macro data have little information on risk aversion (Van Binsbergen et al., 2008).

productivity trend is highly persistent, a positive shock to the trend component of productivity generates positive growth rates in productivity not only in the current period but also in the future. Except for both productivity shocks, the process on imported intermediate prices is estimated to be the most persistent, with an AR(1) coefficient of 0.973 and a narrow range for the 5 and 95 percentiles of the posterior distributions.

[Table 2] Priors and posteriors on model parameters

Parameter	Prior Dist.	Posterior Dist.		
		Median	5%	95%
σ_g	Inv. Gamma(0.01,1)	0.004	0.002	0.007
ρ_g	Beta(0.7,0.2)	0.632	0.385	0.835
σ_a	Inv. Gamma(0.01,1)	0.005	0.003	0.006
ρ_a	Beta(0.7,0.2)	0.957	0.761	0.983
σ_v	Inv. Gamma(0.01,1)	0.028	0.017	0.044
ρ_v	Beta(0.7,0.2)	0.861	0.741	0.959
σ_s	Inv. Gamma(0.01,1)	0.063	0.054	0.075
ρ_s	Beta(0.7,0.2)	0.840	0.719	0.910
σ_η	Inv. Gamma(0.01,1)	0.002	0.001	0.003
ρ_η	Beta(0.7,0.2)	0.419	0.225	0.620
σ_ζ	Inv. Gamma(0.01,1)	0.006	0.002	0.014
ρ_ζ	Beta(0.7,0.2)	0.803	0.393	0.979
σ_q	Inv. Gamma(0.01,1)	0.029	0.025	0.033
ρ_q	Beta(0.7,0.2)	0.973	0.939	0.993
ϕ	Uniform(0,8)	4.533	3.107	6.583
ψ	Uniform(0,10)	0.004	0.002	0.012
θ	Normal(2,0.5)	1.669	1.029	2.718
γ	Normal(5,2.5)	3.999	1.600	7.120
μ_g	Normal(1.0089,0.002)	1.000	1.000	1.001
η	Uniform(0,1)	0.306	0.024	0.866
Marginal likelihood			1070.7	

Another salient point is that the estimated parameter governing the debt elasticity on the domestic interest rate is quantitatively negligible with a value of 0.004 and high credibility based on the small range of the posterior. This result suggests that, although Korea is categorized into the group of emerging countries, unlike other emerging countries such as Mexico and Argentina, the fluctuations in South Korea's trade balance have been rather stable since 2000; sudden stops have been a rare event, which means that there have been no significant and exogenous halts to the flow of international credit to the Korean economy until the recent period. This fact lends rather little support to the role of financial friction in the Korean economy as in Jung and Yang (2013). However, a parameter, η, governing working capital constraints is large enough to generate financial costs for the unit labor and imported intermediate goods.

Other than productivity shocks and financial frictions, the estimated shock processes display a high persistence of preference shocks and domestic spending shocks, 0.861 and 0.840, respectively, and a low persistence of country premium shocks, 0.419. Their volatilities are 0.028, 0.063, and 0.002, respectively, and precisely estimated in terms of the 90% credible intervals. Further, as we have $\gamma \leq \frac{1}{\kappa}$, households prefer an early resolution of uncertainty.

Table 3 reports the moments generated by the model with their empirical counterparts, regarding standard deviations, cross-correlations, and first-order autocorrelations. The estimated model explains most of the stylized facts about business cycles in the Korean economy, which resemble the patterns in other emerging countries such as Argentina and Mexico: (1) high volatility of consumption and investment and (2) countercyclical trade balance. Our model generates quantitatively similar patterns on volatilities of consumption and investment, which are larger than the standard deviation of output. The model also confirms that consumption and investment are procyclical, although the trade balance is countercyclical. However, the model fails to match the observed serial correlation of consumption growth.

[Table 3] Statistics

Statistics	Output Growth	Consumption Growth	Investment Growth	Trade Balance to Output ratio
Standard deviation				
Financial frictions model	1.272	1.725	5.326	2.350
Data	0.988	1.258	4.768	2.439
Correlation with output growth				
Financial frictions model		0.735	0.634	-0.261
Data		0.524	0.511	-0.188
Correlation with TB/Y				
Financial frictions model		-0.272	-0.275	
Data		-0.213	-0.220	
Serial correlation				
Financial frictions model	0.016	-0.036	-0.161	0.756
Data	0.187	0.159	-0.069	0.786

Next, we assess the relative role of structural shocks in explaining the fluctuations of aggregate variables by presenting variance decompositions in the overall sample period. Table 4 provides the standard deviations of simulated data by each shock and the fractions explained by each structural shock for the fluctuations in the output, consumption, investment, and trade balance-to-output ratio. The fractions are calculated as the ratio of the standard deviation of simulated data by a shock to the total sum of the standard deviations. They are represented in percentage terms.

Table 4 illustrates that productivity shocks explain a relatively large fraction of variations in economic fundamentals although the fluctuations in real variables do not depend only on a one specific structural shock. In detail, both productivity shocks determine 54% of the fluctuations in output and over 30% of the fluctuations in rest of the observables. Rhee (2017) also argues that the majority of output fluctuations are caused by the productivity shocks based on the RBC model with an endogenous risk premium channel. Besides productivity shocks, other structural shocks have their own role in driving the business cycle fluctuations in the Korean economy. Preference shocks are responsible for a large share (28%) of consumption fluctuations. This result is consistent with that in Kim (2014), who contends that shocks to intertemporal preference lead to consumption fluctuations. Moreover, country premium shocks explain a sizable share of the fluctuations of investment growth and the trade balance-to-output ratio in Korea as in other emerging countries such as Argentina and Mexico (Uribe and Yue, 2006). As high persistence of a shock implies a large fraction of forecast error variances over long horizons, the shocks to imported intermediate price have become important in the Korean economy. Although domestic spending shocks do not provide a noticeable contribution to aggregate fluctuations, the shocks help explain a significant portion of the fluctuations in the trade balance-to-output ratio.

[Table 4] Variance Decomposition

Nonlinear	Output Growth	Consumption Growth	Investment Growth	Trade Balance to Output ratio
Permanent prod.	0.39 (15.79)	0.39 (9.85)	2.37 (19.95)	1.56 (28.94)
Transitory prod.	0.96 (38.87)	0.94 (23.74)	2.25 (18.94)	0.58 (10.76)
Labor supply	0.35 (14.17)	0.3 (7.58)	0.42 (3.54)	0.09 (1.67)
Imported intermediate price	0.65 (26.32)	0.67 (16.92)	1.67 (14.06)	0.54 (10.02)
Preference	0.03 (1.21)	1.1 (27.78)	0.63 (5.30)	0.58 (10.76)
Country premium	0.05 (2.02)	0.33 (8.33)	3.67 (30.89)	1.2 (22.26)
Domestic spending	0.04 (1.62)	0.23 (5.81)	0.87 (7.32)	0.84 (15.58)
All shocks	1.27	1.72	5.33	2.35

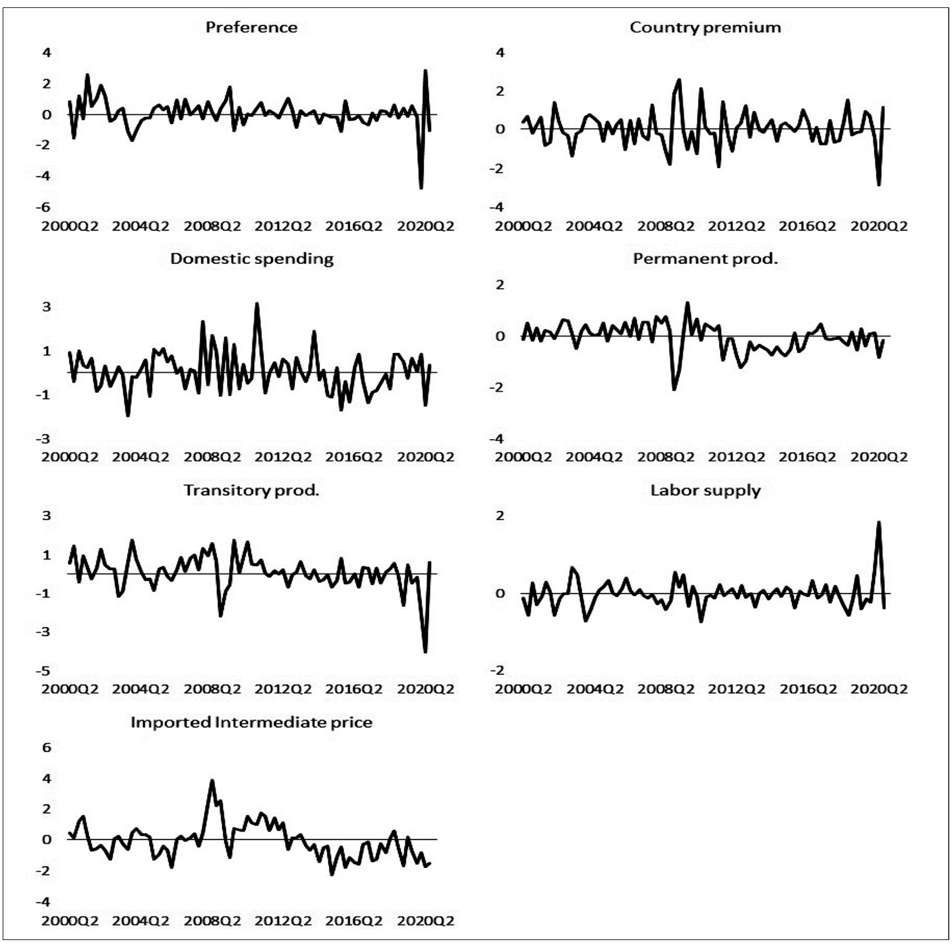
Notes: We calculate the standard deviations (A) of simulated data by each shock. We add up all standard deviations (B) of simulated data by each shock to measure the effect of all shocks. The value in parenthesis is A/B in percentage terms.

V. Sources of Business Cycles during COVID-19

5.1. Simulating COVID-19 Crisis

Fig. 1 provides an overview of all simulated historical structural shocks and depicts three periods with substantial fluctuations, presenting economic downturns after 2000 in the Korean economy: the credit crisis in 2003, the financial crisis in 2008, and the COVID-19 crisis in 2020. Both the financial crisis and the COVID-19 crisis commonly exhibit severe fluctuations in most of the shocks, but the credit crisis, triggered by over-borrowing of households, does not show salient fluctuations in the structural shocks, except for preference shocks.

[Figure 1] Estimated structural shocks



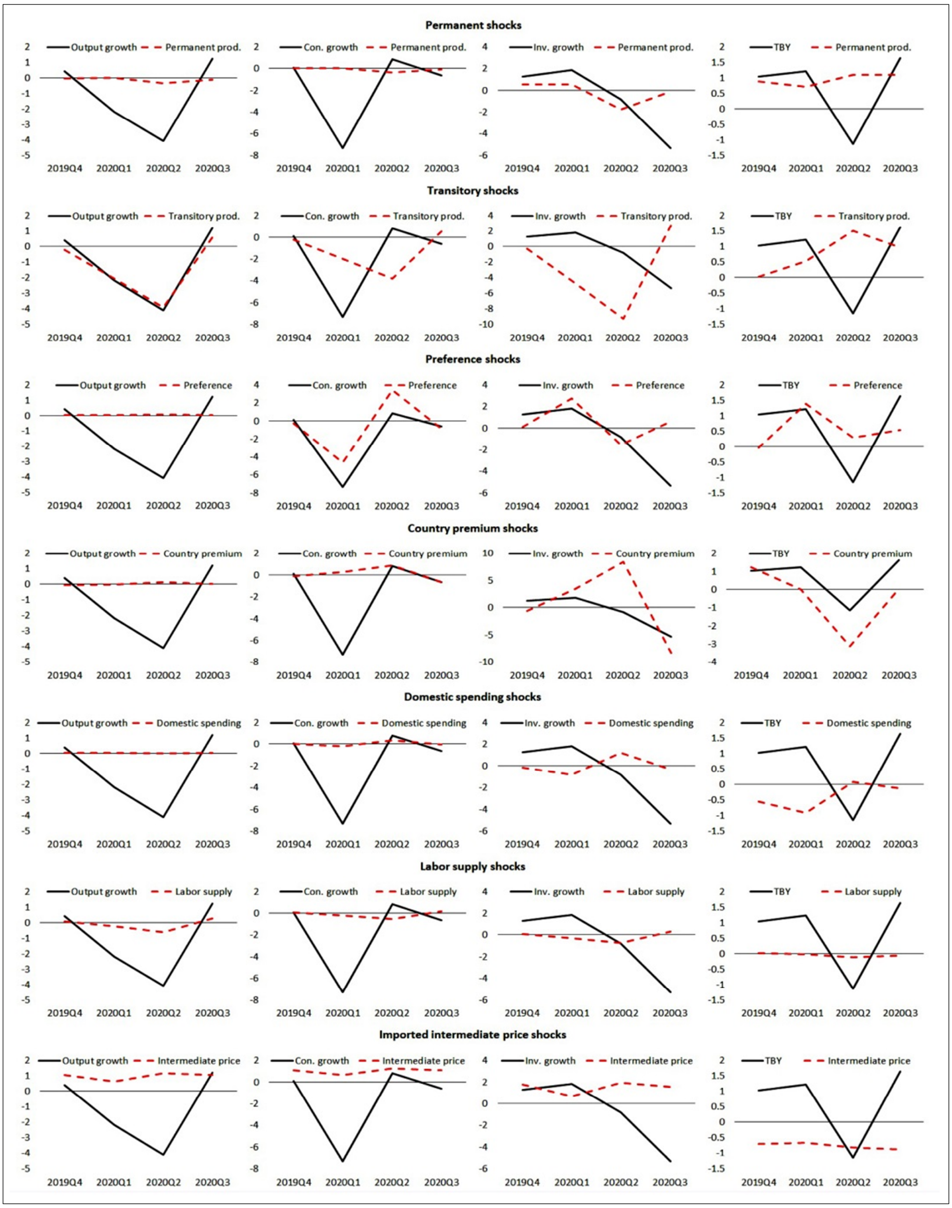
Notes: We obtain the estimated structural shocks via the Gaussian mixture smoothing given the posterior medians of parameters. The unit of the y-axis is percentage.

A closer scrutiny provides noteworthy facts about the shock patterns in response to the crises. First, both transitory and permanent shocks to productivity suitably capture the economic sufferings of output growth. Despite a lack of explanation about the credit crisis, the large movements of the estimated transitory productivity shocks coincide with the periods of the financial crisis and the pandemic. The permanent productivity shocks lead to a sharp decrease in economic growth during the financial crisis and possibly contribute to tapered economic growth from 2011 to 2015. Second, the shocks associated with household economic activities, such as preference and labor supply, respond excessively to the pandemic to avoid viral infection. Households' willingness to consume outside and provide labor force decreases as the health risk expands. Moreover, households postpone current consumption to future under the pandemic uncertainty, which consequently changes the pattern of the intertemporal preference. Third, the country premium declines during COVID-19. Goodell (2020) suggests that COVID-19 may increase country risk as in the case of the 2002-2004 SARS outbreak in China and Hong Kong. However, our finding contradicts this conjecture. This might be because of the worldwide spread of the virus, which possibly increases the overall risk of other countries more significantly than that of Korea. It could generate negative shocks to the country premium that are uncorrelated with the state of domestic fundamentals. Lastly, the imported intermediate goods price has a negative shock, reflecting a lack of global demand for intermediate goods during COVID-19.

Fig. 2 provides the quantitative importance of the structural shocks by generating the counterfactual path of variables of interest by turning on a shock after setting other shocks equal to zero during the pandemic. Each row tracks the simulated macro-variables for each shock against the observables and graphically depicts how closely these series match. It allows us to infer which structural shocks generate the targeted variables. The second row in the figure reveals that transitory productivity shocks come close to reproducing the deep fall in total output. That is, the Korean economy has recognized the outbreak of the virus as being transient, temporarily affecting production technology, instead of a permanent change in economic growth path. We can think of the reason for a sudden drop in transitory productivity shocks from supply disruption caused by shutdowns, layoffs, and firm exits. Céspedes et al. (2020) argue that productivity would exacerbate if the pandemic forces to shed labor beyond a threshold level.

The same mechanism may have occurred during COVID-19 in Korea. The government announced the mandatory social distancing policy from February to May 2020 to prevent and control the spread of the infectious disease, which resulted in a surge in the unemployment rate from 3.3% to 4.5% in Korea and likely triggered an inward shift of the production possibility frontier. After the end of the enforcement, unemployment rate returned to the earlier level along with the stabilization of the transitory productivity shocks in 2020Q3. In addition to the transitory shocks, the figure shows that permanent productivity shocks and labor supply shocks marginally reduce output growth in 2020Q2.

[Figure 2] Shock comparison during COVID-19



Notes: We obtain a historical decomposition of the structural shocks via the GMF and smoothing. We then back out the state variables and shocks based on the information contained in the entire sample. Finally, we use the estimated structural shocks to simulate the output growth, consumption growth, investment growth, and trade balance-to-output ratio. The unit of the y-axis is the percentage point deviation from steady state.

The third row in the figure compares paths simulated by the preference shocks with the data. The preference shocks closely generate the shape and quantities of consumption growth. The dynamics of the preference shocks indicate that, at the onset of the pandemic, households spontaneously change their behavior of intertemporal preference on consumption to prevent an abrupt decrease in their future utility. Although households aggressively reduce their consumption in response to the pandemic, the effect of preference shocks is not maintained longer than one quarter. Simulated investment by the preference shock generates an increase in investment in 2020Q1 as evidence of an increase in savings by changes in household preference. However, a rise in country premium in 2020Q3 has a negative impact on investment growth. We also find that the evolution of the simulated trade balance-to-output ratio relies on country premium shocks during the COVID-19 pandemic. Despite the spread of COVID-19 in 2020Q2, a decrease in country premium reduced the trade balance-to-output ratio.

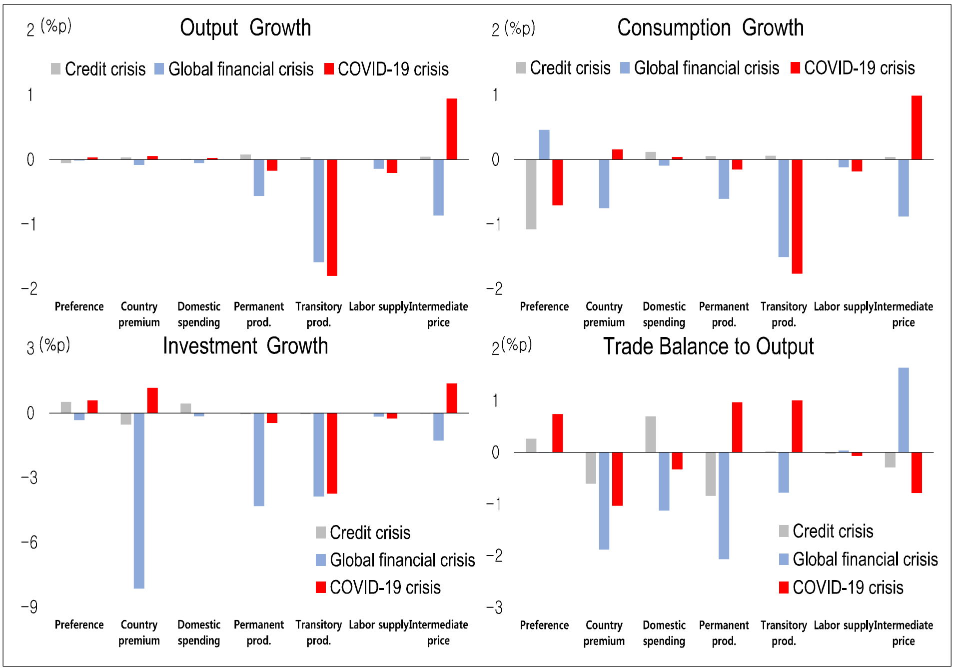
5.2. Counterfactual Analysis by Crisis

What differentiates the pandemic crisis from other economic recessions and which structural shocks are the important drivers? This is an obvious question to ask, given that COVID-19 differs in many aspects from other crises. In this section, we consider the roles of each shock in the order of the crisis occurrence: the credit crisis (2003Q1-2003Q4), global financial crisis (2008Q4-2009Q1), and COVID-19 crisis (2020Q1-2020Q3). These three episodes correspond to a sharp shrinkage in economic activities in Korea. To gauge the role of each shock during the respective episodes, we perform several counterfactual exercises. Each of these counterfactual exercises represents simulations where all the structural shocks, except for the shock of interest, are set to zero over the relevant periods.

Fig. 3 demonstrates that transitory productivity shocks are the main driver of the Korean economy during the COVID-19 pandemic and even the financial crisis. Transitory productivity shocks temporarily produce more severity on the economic downturns during the COVID-19 crisis rather than the financial crisis. Although the decline in the macro variables is less explained by permanent productivity shocks, this does not indicate that these shocks are not important. The permanent productivity shocks exacerbate all the economic aggregates during the global financial crisis, including the trade balance-to-output ratio. One standard deviation shock to permanent productivity has large impacts on macroeconomic aggregates (see Panel B in Appendix C). Further, the shocks to permanent productivity explain a large part of output fluctuations since 2011 in the Korean economy, as shown in Appendix D.[8]

[8] We report impulse responses and historical decompositions of observables to the structural shocks

[Figure 3] Shock impacts during COVID-19



Notes: The graphs show the quarterly average counterfactual simulated using the estimated structural shocks during the credit crisis, the global financial crisis, and the COVID-19 crisis.

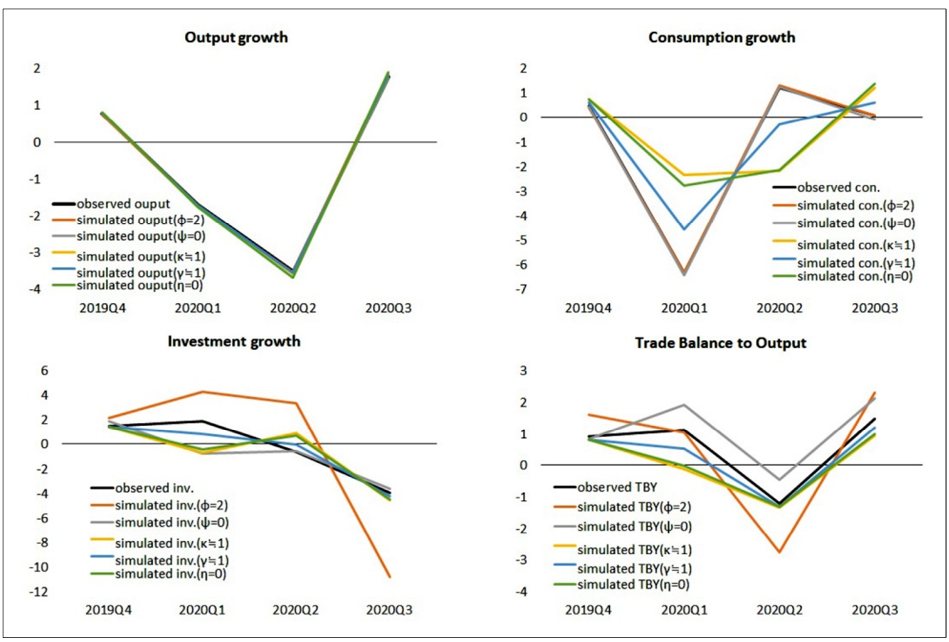
We find the following results that differentiate the COVID-19 crisis from the financial crisis, in terms of shock contributions. First, unlike the financial crisis, preference shocks exert negative pressure on consumption growth, increasing the trade balance-to-output ratio during the COVID-19 crisis. This result is consistent with that in the credit crisis period. Second, the financial crisis and the COVID-19 crisis have opposite signs on the effects of country premium shocks and shocks to imported intermediate goods price on investment growth. Specifically, in response to these shocks, investment growth decreases in the global financial crisis and increases during the COVID-19 pandemic. Therefore, both shocks in the COVID-19 crisis create negative pressures on the trade balance-to-output ratio, possibly reflecting more severe negative impacts of COVID-19 on the global economy than on Korea. Third, it is also noticeable that the contributions of permanent productivity shocks are reduced when we compare the financial crisis with the COVID-19 crisis. The quantitative importance of the permanent shocks has significantly weakened as the Korean economy recognizes the spread of the virus as an instant phenomenon. Lastly, the willingness of households to provide labor force

in Appendix C and D, respectively.

reduces more by the pandemic than any other recent crises. However, its effect is rather limited.

From the perspective of the estimated model, capital adjustment costs (ϕ), EIS (κ), and working capital constraint (η) are the key parameters to generate the business cycles and amplify the exogenous shocks triggered by COVID-19 in Korea. To examine this, we quantify the accuracy of the estimated model in reproducing the Korean economic dynamics during COVID-19. Fig. 4 recomputes the simulation of the COVID-19 crisis allowing all estimated shocks to hit the economy but varying the severity of each parameter of interest separately. The results demonstrate that capital adjustment costs regulate the patterns of investment growth and the trade balance-to-output ratio, but financial frictions have negligible effects on aggregate variables, except for the trade balance-to-output ratio. For preference, the EIS and the working capital constraints are the most relevant parameters for the fluctuations in consumption growth, which is affected by intertemporal decisions of households. Also, the degree of risk aversion matters for consumption growth. However, the plots indicate that none of the parameters in our model show a significant impact on reproducing output growth during the COVID-19 crisis.

[Figure 4] Model comparison during COVID-19 crisis



Notes: We recompute the simulation of COVID-19 crisis allowing all smoothed shocks, but varying the severity of capital adjustment costs, debt elasticity, EIS, risk aversion, and working capital constraints ($\phi = 2$, $\psi = 0$, $\kappa \approx 1$, $\gamma \approx 1$, $\eta = 0$). The unit of the y-axis is the percentage point deviation from steady state.

5.3. Heterogeneous Responses

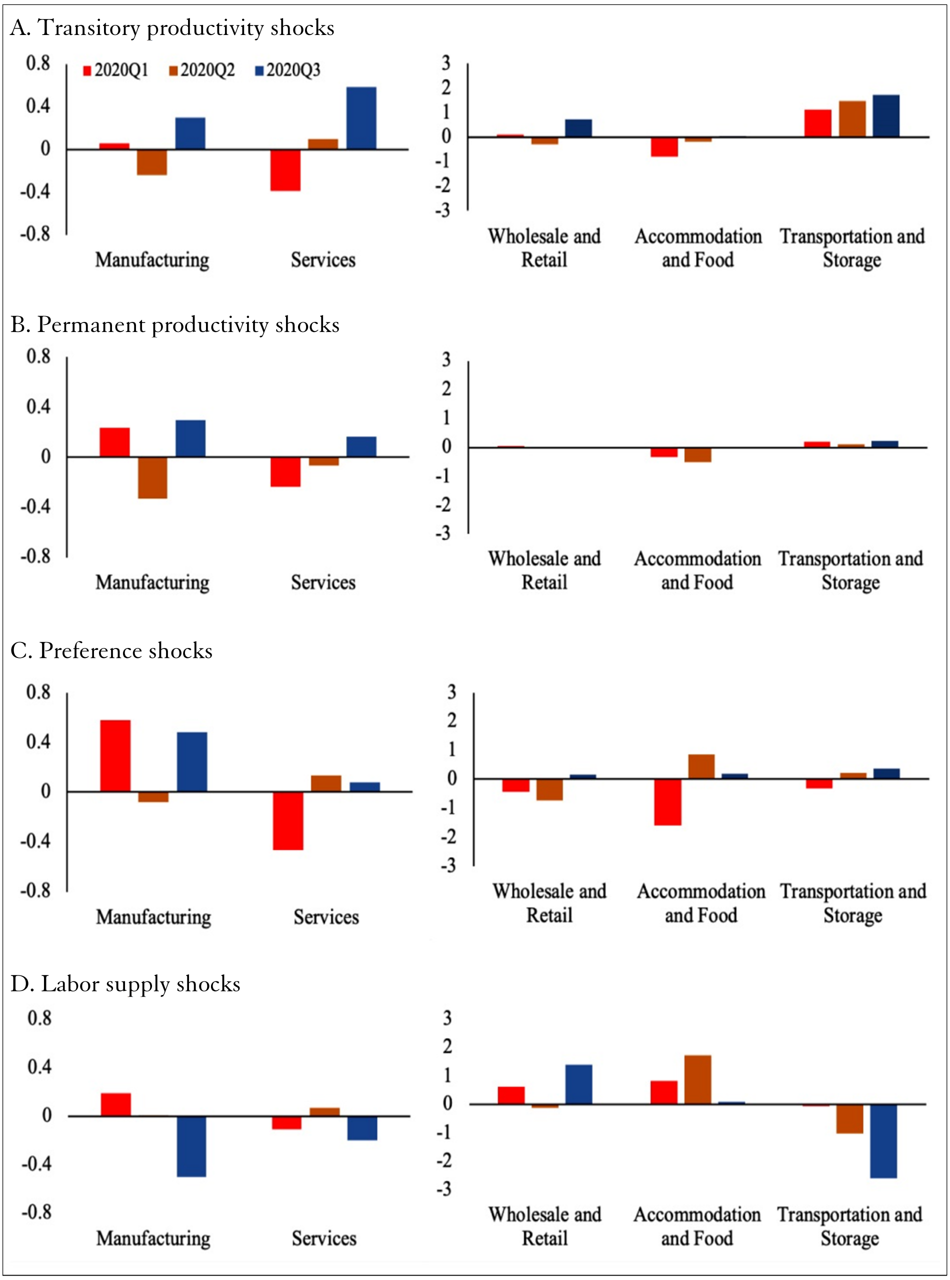
Do unexpected changes in structural shocks affect sectoral output growth differently? Since the outbreak of COVID-19, several studies have investigated aggregate macroeconomic impacts and documented that the differentiated effects of the disease and its associated containment measures have an unequal impact across industrial sectors and individuals. Adams-Prassl et al. (2020) provide evidence that the impact of COVID-19 on labor market noticeably differs across countries, ages, and types of employment contracts in the United Kingdom, the United States, and Germany. Guerrieri et al. (2020) illustrate that the economic shocks associated with COVID-19 epidemic are Keynesian supply shocks in a multi-sectoral environment that simultaneously trigger the reduction in aggregate demand and whose impacts are larger than the shocks themselves.

We answer the question posed at the beginning of this section by estimating an empirical VAR model and investigate how the structural shocks affect sectoral output growth during the COVID-19 crisis. We estimate a quarterly two-lags VAR with a constant and identify the shocks recursively. The endogenous variables in VAR system consist of the estimated main shocks from our DSGE model and growth rates of sectoral outputs. This ordering is motivated based on our view that the estimated structural shocks from the DSGE model are exogenous. Our VAR analysis has two steps. First, we measure the relative importance of each shocks for two sectors: manufacturing and services. Then, considering the high sensitivity of the service sector to the pandemic, we investigate three sub-levels of the service sector by replacing the output growth rate of the aggregate service sector with the output growth rate of each sub-level of the service sector.

Fig. 5 depicts our main set of results and plots the medians of the historical decomposition of the growth rate of sectoral output during the COVID-19 crisis. We report four sets of estimation results for transitory and permanent productivity shocks, preference shocks, and labor supply shocks. It presents the evidence of heterogeneity across sectors in response to the shocks. We find that different sectors respond differently depending on the timing. Manufacturing is negatively affected by all shocks in 2020Q2, but the negative impact of the shocks on the service sector is more instant in 2020Q1. The potential explanation of the immediate response of the service sector is that the spread of the virus leads people to avoid a close contact from purchase of services, which reduces overall level of consumption in the service sector.

When we examine the responses of each sub-level of the service sector closely, the accommodation and food sector is the most negatively affected. These results are consistent with the narrative regarding the introduction of the social distancing measures: the accommodation and food sector experiences large negative shocks to preferences. Further, labor supply shocks that reduce labor force affect both the manufacturing and service sector (especially large negative impacts on transportation and storage) largely in a negative direction during 2020Q3.

[Figure 5] Historical decompositions of sectoral output



Notes: The value of y-axis denotes the percentage point deviation from the average growth rate. We normalize each variable for the purpose of comparison across sectors.

VI. Conclusion

We present the results of an empirical analysis on the small open economy model with a second-order approximation. With recursive preference and financial frictions, we document the main driving forces of the COVID-19 crisis among a variety of structural shocks. In addition, we investigate the heterogeneity in sectoral responses to the estimated shocks from the model by using the empirical VAR model.

The financial frictions model accounts for the Korean economic downturn during the COVID-19 crisis by assigning a dominant role to the transitory productivity shocks. Both preference shocks and transitory productivity shocks play an important role in explaining the variations in consumption growth during the COVID-19 crisis. In addition, transitory productivity shocks during COVID-19 put downward pressure on investment, but the shocks to preference and country premium put upward pressure on investment. These results somewhat differ from those obtained from the global financial crisis. The parameters governing capital adjustment costs, EIS, and working capital constraints, matter the most for the amplification of the shocks during the COVID-19 crisis. In the empirical analysis based on VAR specification, we demonstrate heterogeneous sectoral responses to the shocks in terms of timing and magnitude. The service sector, especially the accommodation and food services sector, is affected the most during the COVID-19 crisis.

Consequently, the economic downturn induced by COVID-19 instantly impacts business cycles in contrast to the financial crisis which creates rather permanent impacts on economic activities. As the coronavirus tends to show a recurrence in its spread with time interval, the Korean government needs a combination of swift actions, such as financial assistance and flexible social distancing measures by the degree of the spread of the disease, to stabilize the economic impact of the COVID-19 crisis. As it is evident that the influence of the spread of the virus is heterogeneous across sectors, the government needs to recognize this fact when designing various policy measures.

A Equilibrium conditions in stationary form

Variables Y_t, C_t, S_t, I_t, X_t, D_t, K_t, TB_t, and V_t are scaled by G_{t-1} and expressed as y_t, c_t, s_t, i_t, x_t, d_t, k_t, tb_t, and $\tilde{v}_t$. Agent's objective function is re-expressed as:

$$\tilde{v}_t = \left\{ (1-\beta) v_t [c_t - \zeta_t \omega^{-1} h_t^{\omega}]^{\frac{1-\gamma}{\theta}} + \beta g_t^{\frac{1-\gamma}{\theta}} [E_t(\tilde{v}_{t+1}^{1-\gamma})]^{\frac{1}{\theta}} \right\}^{\frac{\theta}{1-\gamma}},$$

with the stochastic discount factor,

$$m_{t,t+1} = \beta E_t \left[\left(\frac{v_{t+1}(c_{t+1} - \zeta_{t+1}\omega^{-1} h_{t+1}^{\omega})}{v_t (c_t - \zeta_t \omega^{-1} h_t^{\omega})} g_t \right)^{\frac{1-\gamma-\theta}{\theta}} \frac{(\tilde{v}_{t+1} g_t)^{\frac{(\theta-1)(1-\gamma)}{\theta}}}{[E_t(\tilde{v}_{t+1} g_t)^{1-\gamma}]^{\frac{\theta-1}{\theta}}} \right].$$

Stationary competitive equilibrium is given by the following equations:

$$\zeta_t h_t^{\omega-1} = (1-\alpha_1-\alpha_2) a_t g_t^{1-\alpha_1-\alpha_2} \left(\frac{k_t}{h_t} \right)^{\alpha_1} \left(\frac{x_t}{h_t} \right)^{\alpha_2} \frac{1}{1 + \frac{\eta r_t}{1+r_t}},$$

$$\left[1 + \phi \left(\frac{k_{t+1}}{k_t} g_t - \mu_g \right) \right] =$$

$$E_t \left[m_{t,t+1} \left[\begin{array}{c} 1 - \delta + \alpha_1 a_{t+1} \left(\frac{k_{t+1}}{g_{t+1} h_{t+1}} \right)^{\alpha_1 - 1} \left(\frac{x_{t+1}}{g_{t+1} h_{t+1}} \right)^{\alpha_2} \\ + \phi \frac{k_{t+2}}{k_{t+1}} g_{t+1} \left(\frac{k_{t+2}}{k_{t+1}} g_{t+1} - \mu_g \right) - \frac{\phi}{2} \left(\frac{k_{t+2}}{k_{t+1}} g_{t+1} - \mu_g \right)^2 \end{array} \right] \right],$$

$$d_t - \frac{d_{t+1}}{1+r_t} g_t = y_t - c_t - s_t - i_t - \frac{\eta r_t}{1+r_t}(w_t g_t h_t + q_t x_t) - \frac{\phi}{2} \left(\frac{k_{t+1}}{k_t} g_t - \mu_g \right)^2 k_t,$$

$$tb_t = d_t - \frac{d_{t+1}}{1+r_t} g_t,$$

$$r_t = r^* + \psi \left[\exp\left(\frac{d_{t+1} - \bar{d}}{\bar{y}} \right) - 1 \right] + \exp(\eta_t - 1) - 1,$$

$$k_{t+1} g_t = (1-\delta) k_t + i_t,$$

$$y_t = a_t k_t^{\alpha_1} x_t^{\alpha_2} (g_t h_t)^{1-\alpha_1-\alpha_2} - q_t x_t.$$

Factor prices:

$$w_t = (1-\alpha_1-\alpha_2)a_t\left(\frac{k_t}{g_t h_t}\right)^{\alpha_1}\left(\frac{x_t}{g_t h_t}\right)^{\alpha_2}\frac{1}{1+\frac{\eta r_t}{1+r_t}},$$

$$q_t = \alpha_2 a_t\left(\frac{k_t}{g_t h_t}\right)^{\alpha_1}\left(\frac{x_t}{g_t h_t}\right)^{\alpha_2-1}\frac{1}{1+\frac{\eta r_t}{1+r_t}}.$$

Auxiliary variable as an observable variable:

$$\tilde{q}_t = q_{t+1},$$

Exogenous processes:

$$\ln v_{t+1} = \rho_v \ln v_t + \varepsilon^v_{t+1},$$
$$\ln(\zeta_{t+1}/\mu_\zeta) = \rho_\zeta \ln(\zeta_t/\mu_\zeta) + \varepsilon^\zeta_{t+1},$$
$$\ln(s_{t+1}/\mu_s) = \rho_s \ln(s_t/\mu_s) + \varepsilon^s_{t+1},$$
$$\ln(q_{t+1}/\mu_q) = \rho_q \ln(q_t/\mu_q) + \varepsilon^q_{t+1},$$
$$\ln a_{t+1} = \rho_a \ln a_t + \varepsilon^a_{t+1},$$
$$\ln(g_{t+1}/\mu_g) = \rho_g \ln(g_t/\mu_g) + \varepsilon^g_{t+1},$$
$$\ln \eta_{t+1} = \rho_\eta \ln \eta_t + \varepsilon^\eta_{t+1}.$$

The above expressions comprise 19 equations in 19 variables: y_t, c_t, i_t, h_t, x_t, d_t, r_t, k_t, tb_t, w_t, $\tilde{q}_t$, $\tilde{v}_t$, v_t, ζ_t, s_t, q_t, a_t, g_t, and η_t.

B Gaussian Mixture Filter

The model solved using second-order approximation with pruning is given by the following state space representation,

$$\mathbf{Y_t} = \mathbf{G}(\mathbf{X_t},\sigma) + \varepsilon_t,$$
$$\mathbf{X_{t+1}} = \mathbf{H}(\mathbf{X_t},\sigma) + \sigma\eta_{t+1}, \tag{17}$$

where $\mathbf{X_t}$ denotes a set of state variables that contain pre-determined endogenous and exogenous variables, $\mathbf{Y_t}$ is a set of observable variables, $\varepsilon_t \sim i.i.dN(0,\mathbf{R}_\varepsilon)$, and $\eta_{t+1} \sim i.i.dN(0,\mathbf{R}_\eta)$.

Since we employ a pruning method to the terms of higher-order effects than the second-order, the state-space representation is re-expressed as follows:

$$\mathbf{X}_{\mathbf{t+1}} = \begin{bmatrix} \hat{\mathbf{x}}^{f}_{t+1} \\ \hat{\mathbf{x}}^{s}_{t+1} \end{bmatrix} = \begin{bmatrix} \mathbf{h}_{\mathbf{x}}\hat{\mathbf{x}}^{f}_{t+1} + \sigma\boldsymbol{\eta}_{t+1} \\ \mathbf{h}_{\mathbf{x}}\hat{\mathbf{x}}^{s}_{t} + \tfrac{1}{2}\mathbf{H}_{\mathbf{xx}}(\hat{\mathbf{x}}^{f}_{t} \otimes \hat{\mathbf{x}}^{f}_{t}) + \tfrac{1}{2}\mathbf{h}_{\sigma\sigma}\sigma^{2} \end{bmatrix}, \tag{18}$$

$$\mathbf{Y}_{\mathbf{t}} = \mathbf{g}_{\mathbf{x}}(\hat{\mathbf{x}}^{f}_{t} + \hat{\mathbf{x}}^{s}_{t}) + \frac{1}{2}\mathbf{G}_{\mathbf{xx}}(\hat{\mathbf{x}}^{f}_{t} \otimes \hat{\mathbf{x}}^{f}_{t}) + \frac{1}{2}\mathbf{g}_{\sigma\sigma}\sigma^{2} + \boldsymbol{\varepsilon}_{t}, \tag{19}$$

where we eliminate the terms of higher-order effects than the second-order by using a pruning method (see, in particular Kim et al., 2008; Andreasen et al., 2017).

To evaluate the likelihood function of the above state-space representation, we apply the GMF. The GMF approximates distributions with a finite Gaussian mixture. This strategy is based on the fact that any continuous density can be obtained by infinitely mixing Gaussian densities in the sense of L^1 norm with the covariance matrix of every mixture component approaching zero (Alspach and Sorenson, 1971, 1972; Lo, 1972). This fact is based on the Wiener's theorem on approximation (Achieser, 2013),

$$\int \left| p(x) - \sum_{l=1}^{L} w_l N(\mu_l, \Sigma_l) \right| dx \to 0 \quad \text{as} \quad L \to \infty \quad \text{and} \quad \Sigma_l \to \infty. \tag{20}$$

Given equations (14), we assume that the filtering density $p(x_{t-1} \mid y_{1:t-1};\theta)$, the density for exogenous shocks $p(\eta_t)$, and the density for measurement errors $p(\varepsilon_t)$ are approximated by mixing L-components of Gaussian distributions, M-components of Gaussian distributions, and N-components of Gaussian distributions, respectively. In this study, the initial number of mixture components of $p(x_1 \mid y_1;\theta)$ is seven and split into new mixture components over iterations. Since the structural shocks and the measurement errors are assumed to follow the Gaussian distributions, we set $M = 1$ and $N = 1$.

The prediction and filtering density also can be expressed by the mixture of Gaussian densities:

- Prediction density

$$p(x_t \mid y_{1:t-1};\theta) \approx \sum_{l'=1}^{L'} w_t^{[l']} N(x_t; \tilde{\mu}_t^{[l']}, \tilde{P}_t^{[l']}), \tag{21}$$

- Filtering density

$$p(x_t \mid y_{1:t};\theta) \approx \sum_{l''=1}^{L''} w_t^{[l'']} N(x_t; \mu_t^{[l'']}, P_t^{[l'']}), \tag{22}$$

where $L' = LM$ and $L'' = LMN$.

We compute the mean and covariance matrix of $p(x_t \mid y_{1:t-1};\theta)$ and $p(x_t \mid y_{1:t};\theta)$ using the Central Difference Kalman filtering method. The mixing weights are determined by $w_t^{[l']} = \frac{\alpha_{t-1}^{[l]}\beta_t^{[m]}}{\sum_{l=1}^{L}\sum_{m=1}^{M}\alpha_{t-1}^{[l]}\beta_t^{[m]}}$ and $w_t^{[l'']} = \frac{w_{t-1}^{[l']}\gamma_t^{[n]}S_t^{[n]}}{\sum_{l'=1}^{L'}\sum_{n=1}^{N}w_t^{[l']}\gamma_t^{[n]}S_t^{[n]}}$ where $\alpha_{t-1}^{[l]}$, $\beta_t^{[m]}$, and $\gamma_t^{[n]}$ denote the mixture weights of the filtering density at time $t-1$, the density for exogenous shocks at time t, and the density for measurement errors at time t, respectively. $S_t^{[n]} = p(y_t \mid x_t;\theta)$ evaluated at $x_t = \tilde{\mu}_t^{l'}$ for the current observation y_t. The conditional marginal likelihood is obtained as follows:

$$\hat{p}^{\text{GMF}}(y_t \mid y_{1:t-1};\theta) = \int p(y_t \mid x_t;\theta)p(x_t \mid y_{1:t-1};\theta)dx_t$$
$$= \sum_{l'=1}^{L'}\sum_{n=1}^{N} w_t^{[l']}\gamma_t^{[n]} N(\hat{y}_{t|t-1}^{[l'\times n]}, P_{t|t-1}^{y,[l'\times n]}). \tag{23}$$

To make the mixture components well-dispersed with small component covariance matrices while doing the GMF, we apply a splitting procedure on $p_{l''}(x_t \mid y_{1:t};\theta)$ for each mixture component based on the Binomial Gaussian mixture (Raitoharju et al., 2015). When the degree of nonlinearity of the measurement equation is greater than a pre-specified threshold (η_{limit}), we implement the splitting and approximate each mixture component of $p_{l''}(x_t \mid y_{1:t};\theta)$ by a weighted sum of Gaussian distributions whose component means, covariance matrices, and weights are determined based on the Binomial Gaussian mixture. The parameters for the Binomial Gaussian mixture are chosen such that the mean and covariance of $p_{l''}(x_t \mid y_{1:t};\theta)$ are preserved. The resulting density function from the Binomial Gaussian mixture converges to the original Gaussian distribution (Raitoharju et al., 2015). We employ a nonlinearity measure of Raitoharju and Ali-Loytty (2012) and normalize the measure by dividing it by measurement error variance. The measure is based on the comparison between the Extended Kalman filter and the Second Order Gaussian filter:

$$NL^l = \frac{trace(Q^l Q^l)}{h^4}, \tag{24}$$

where $h = \sqrt{3}$, l indicates the lth measurement equation. Q^l is defined as

$$Q_{[c,d]}^l = \begin{cases} g_l(\chi_{t|t-1}^a + hS_{i,t|t-1}^a) + g_l(\chi_{t|t-1}^a - hS_{i,t|t-1}^a) - 2g_l(\chi_{t|t-1}^a) & c = d \\ \frac{1}{2}[g_l(\chi_{t|t-1}^a + hS_{i,t|t-1}^a + hS_{i,t|t-1}^a) + g_l(\chi_{t|t-1}^a - hS_{i,t|t-1}^a - hS_{i,t|t-1}^a) - \\ 2g_l(\chi_{t|t-1}^a) - Q_{[c,c]}^l - Q_{[d,d]}^l] & c \neq d \end{cases}$$

When splitting a mixture component, the total number of components is chosen such that the nonlinearity is reduced to a given threshold (η_{limit}). If the total number of mixture components in the splitting procedure exceeds the specified threshold (m_{limit}), we set the number of components to m_{limit}. As the splitting procedure creates a large number of mixture components, we implement a component reduction procedure for computational efficiency. When the number of components exceeds a certain criterion (m_{reduce}), or the Kullback-Leibler (KL) divergence between two mixture components exceeds the specified threshold (B_{limit}), the component pair are merged such that the mean and covariance of the mixture is preserved. In this paper, we set the thresholds η_{limit} and B_{limit} to 0.3 and 0.01, respectively. The thresholds, m_{limit} and m_{reduce}, for splitting and reduction procedures, are set to 16 and 8, respectively.[9] Since the measurement errors are assumed not to be correlated with each other, we separately implement the updating procedure over each measurement equation following Raitoharju et al. (2015).

C Impulse responses

Productivity shocks (one-standard-deviation shocks): Fig. 6 shows cumulative impulse responses to transitory and permanent productivity shocks, obtained from our financial frictions model with second-order approximation. A transitory productivity shock in the quadratic model leads to more significant and persistent consumption responses than output responses. This fact results in a sharp fall in the trade balance-to-output ratio below the trend. Contrary to the transitory shocks, the permanent shocks have prolonged impacts on all observables.

Other exogenous shocks (one-standard-deviation shocks): Fig. 7 displays cumulative impulse responses to country premium shocks, preference shocks, and domestics spending shocks. Panel A shows that consumption, investment, and trade balance-to-output ratio are, to a large extent, driven by innovations to the domestic interest rate. A one-standard-deviation shock to country premium increases the interest rate at which the country borrows from financial markets. Elevated interest rates curb consumption and investment more strongly than output, thereby

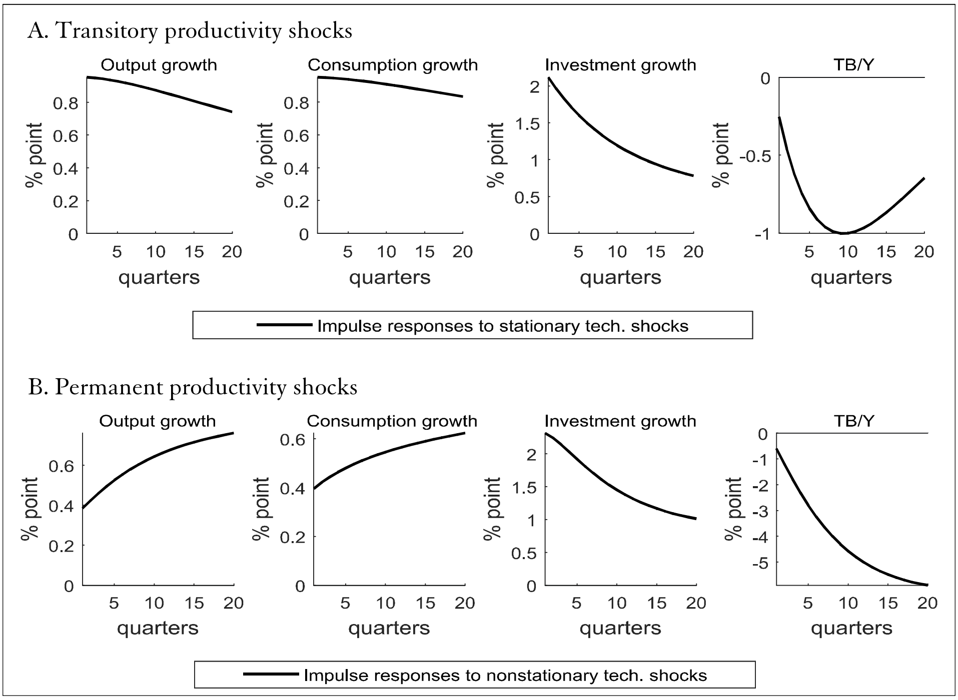
9 Runnalls (2007) proposes the following KL-based discrimination measure:

$$B_{i,j} = \frac{1}{2}[(w_i + w_j)\log\det P_{i,j} - w_i \log\det P_i - w_j \log\det P_j]$$

$$P_{i,j} = \frac{w_i P_i + w_j P_j}{w_i + w_j} + (\mu_i - \mu_j)(\mu_i - \mu_j)',$$

where μ_i, w_i, and P_i are the mean, the weight, and the covariance matrix of a component *i*'s predictive or filtered density, respectively.

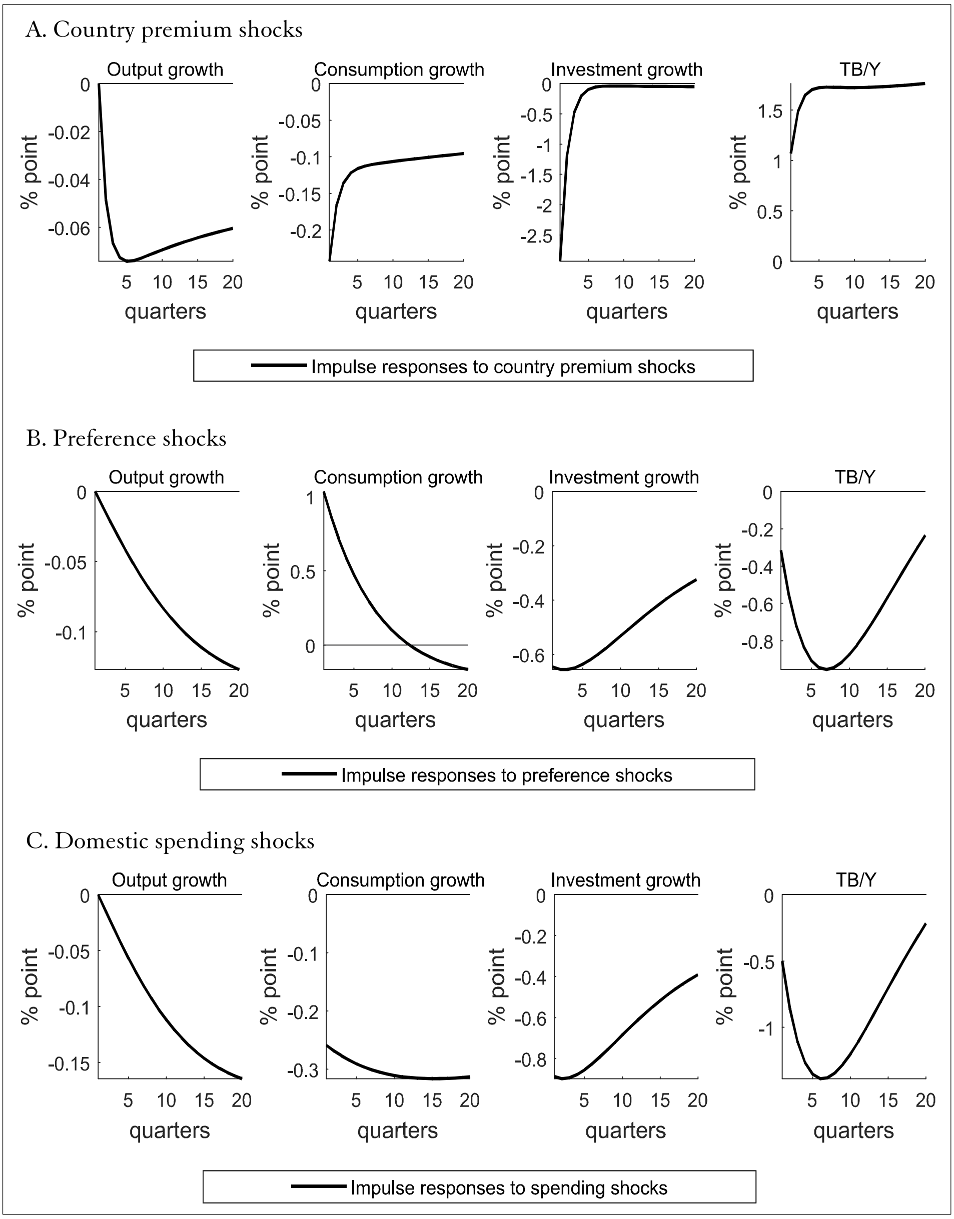
[Figure 6] Impulse responses to productivity shocks



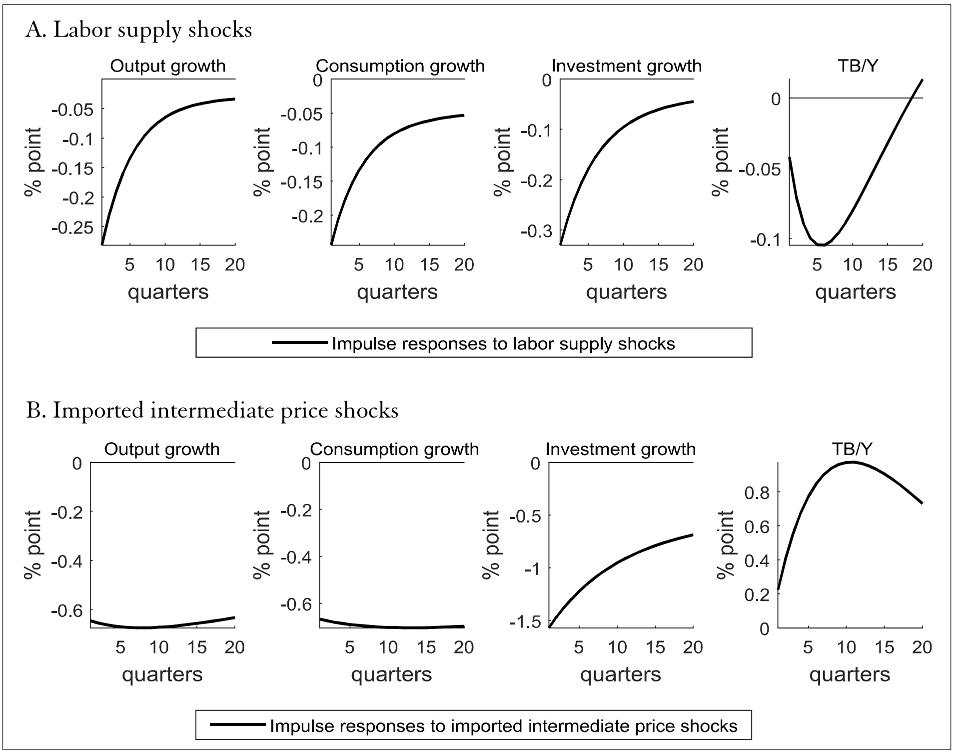
inducing the trade balance-to-output ratio to be positive. Panel B shows that a preference shock increases consumption initially, and hence reduces the trade balance-to-output ratio. The decrease in the trade balance-to-output ratio causes the external debt to increase, leading to an increase in the interest rate. This effect reduces consumption and investment. Finally, a domestic spending shock that can be possibly interpreted as government purchase shocks tends to crowd out consumption and investment. The shock reduces the trade balance-to-output ratio and hence increases the level of the external debt.

Lastly, we consider the impulse responses of both labor supply shocks and shocks to the relative price of imported intermediate goods in Panel A and B of Fig. 8. The labor supply shocks lead to a reduction in all variables of interest. An increase in labor supply shocks indicates that people are reluctant to provide labor relatively more − this means naturally that they want to work less. An exogenous inward shift in labor supply causes a fall in output, consumption, and investment. In Panel B, an increase in the price of intermediate imported goods discourages the intention to produce output and invest in capital stock. This leads to a persistent drop in output and consumption. A fall in the demand for imported intermediate goods improves the trade balance.

[Figure 7] Impulse responses to other shocks

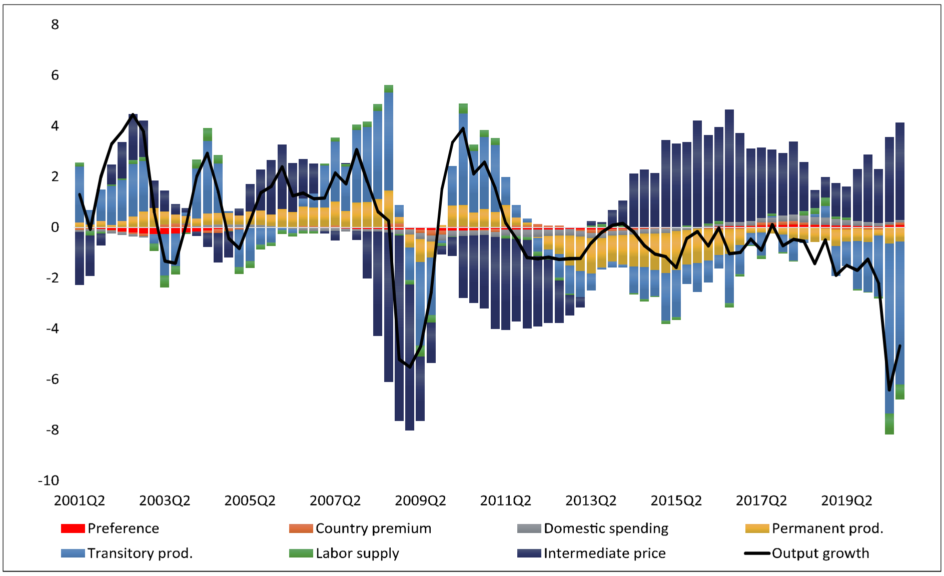


[Figure 8] Impulse responses to other shocks

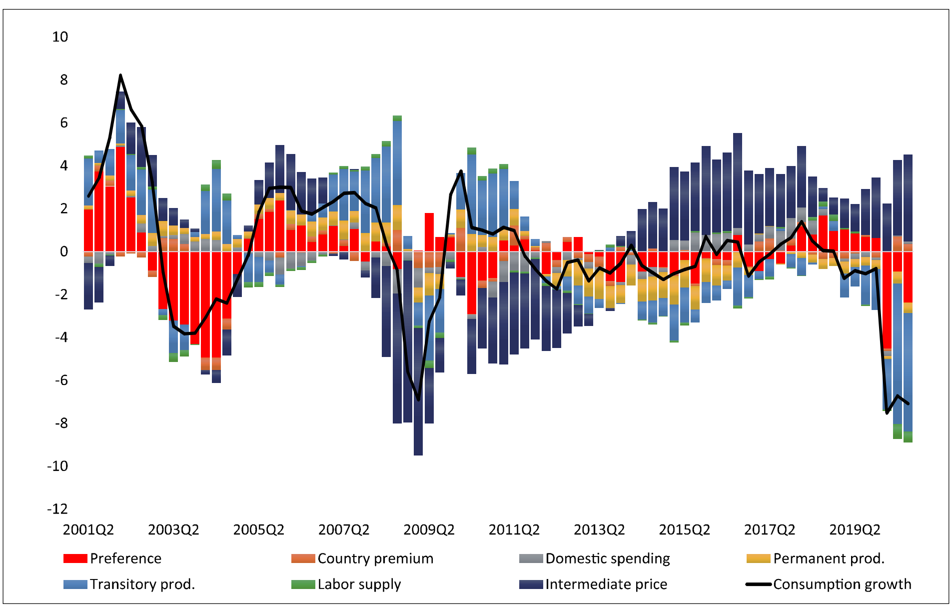


D Historical decomposition

[Figure 9] Historical decomposition: output growth

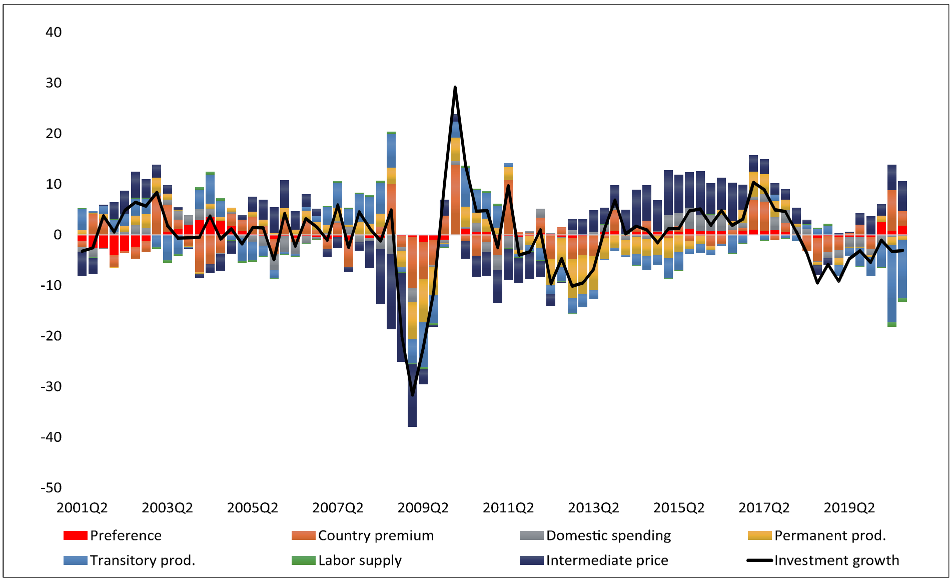


[Figure 10] Historical decomposition: consumption growth

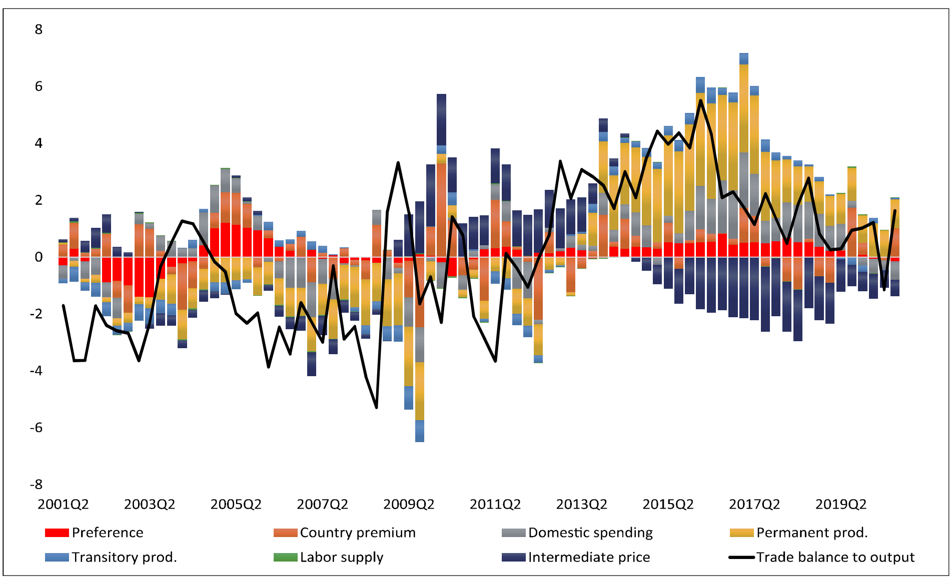


Notes: We obtain a historical decomposition of the structural shocks via the Gaussian mixture filtering and smoothing. We then back out the state variables and shocks based on the information contained in the entire sample. Finally, we use the structural shocks to simulate the growth rate of output and consumption.

[Figure 11] Historical decomposition: investment growth



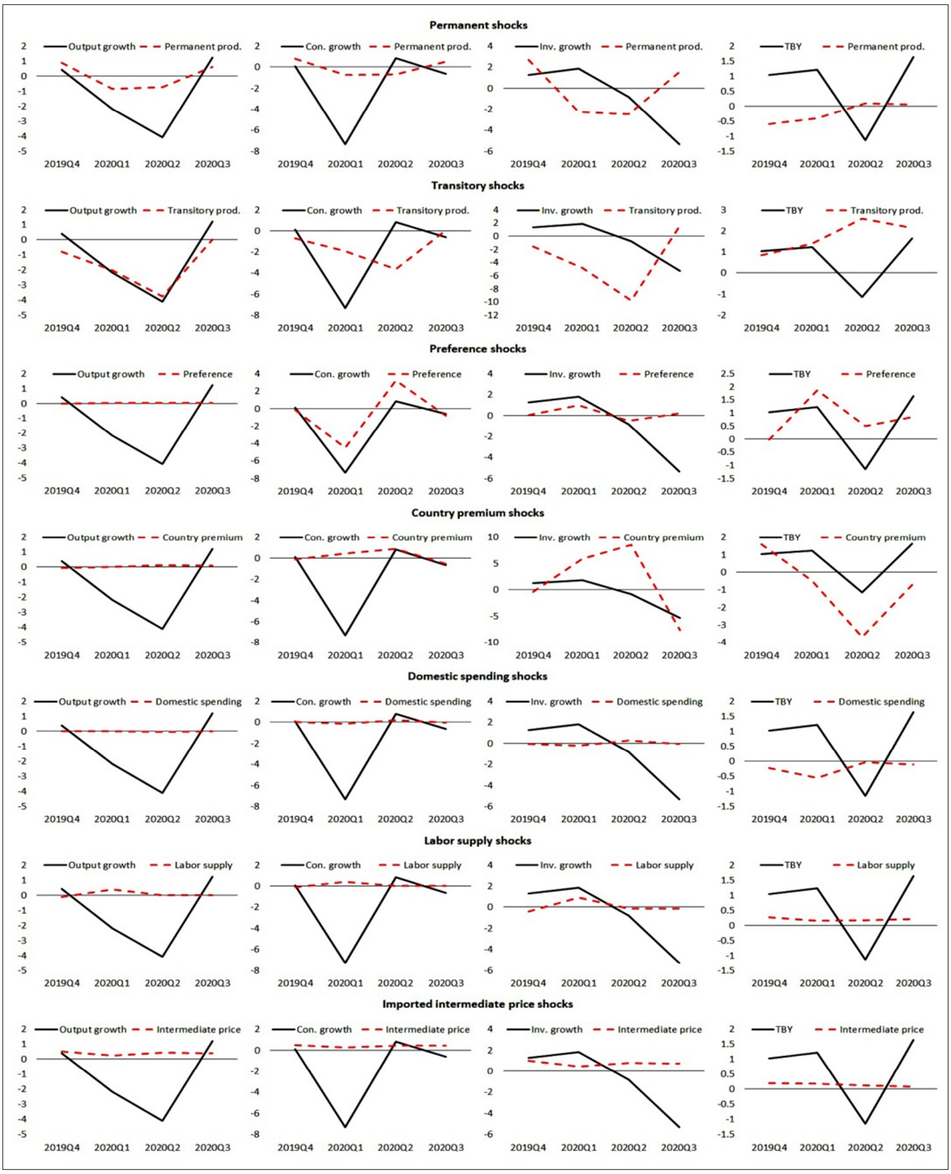
[Figure 12] Historical decomposition: trade balance-to-output ratio



Notes: We obtain a historical decomposition of the structural shocks via the Gaussian mixture filtering and smoothing. We then back out the state variables and shocks based on the information contained in the entire sample. Finally, we use the structural shocks to simulate the growth rate of investment and the trade balance to output ratio.

E Robustness check

[Figure 13] Robustness check for shock comparison during COVID-19



Notes: For robustness analysis, we consider capacity utilization in the benchmark model and additionally employ wage inflation and the growth rate of employment as observables. We obtain a historical decomposition of the structural shocks via the GMF and smoothing. We then back out the state variables and shocks based on the information contained in the entire sample. Finally, we use the estimated structural shocks to simulate the output growth, consumption growth, investment growth, and trade balance-to-output ratio. The unit of the y-axis is the percentage point deviation from steady state.

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COVID-19 확산으로 인한 한국 경기침체의 거시경제적 주요 동인 분석*

노 산 하** · 백 인 걸***

초 록 본 연구는 2020년 본격적으로 시작된 전 세계적인 COVID-19 팬데믹이 유발한 경기침체의 주요 동인을 분석하고, 또한 이로 인해 발생하는 산업별 차별화된 영향도 함께 살펴본다. 한국경제의 구조적 충격 변화를 분석하기 위해 7개의 거시경제 동인(Driving forces)을 포함한 소규모개방경제 모형을 구축한 뒤, 2차 근사(2nd-order approximation)를 통해 모형을 추정하였다. 분석결과, 팬데믹 기간 동안 일시적 생산성 충격이 주요 동인으로 작용하였으나, 2008년 금융위기와 다르게 영구적(추세적) 생산성 충격은 큰 역할을 하지 못하였다. 또한, 가계의 소비선호 충격은 코로나 확산기와 휴지기의 주기적인 변화에 따라 급격하게 변동하였다. 팬데믹 기간 동안 산업별로는 서비스 부문 중 숙박 및 요식업 분야가 거시경제 충격에 가장 민감하게 반응한 것으로 나타났다.

핵심 주제어: COVID-19, 소규모개방경제, 실물경기변동

경제학문헌목록 주제분류: E33, F4, H8

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