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Keywords

state-dependent pricing, monetary policy, DSGE model for Indonesia, COVID-19 pandemic

JEL Classification

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Implications of state-dependent pricing for DSGE model-based policy analysis in Indonesia*

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1 Introduction

A firm with some degree of market power is regularly faced with two important decisions regarding the price of its product. It first has to decide when or *how frequent* to change the price. Once this adjustment decision is made, it then has to decide by *how much* the price adjustment should be. These two pricing decisions are inseparable and fundamentally affect the demand for its product and hence its overall profit. In macroeconomic theory, the variations in this so-called *extensive margin* and *intensive margin* of price adjustment feed into inflation and give rise to nominal price rigidity. This nominal rigidity in turn allows for a role of monetary policy in regulating output fluctuations over the course of the business cycle.

In spite of these two separate margins of price adjustment, most macroeconomic models with nominal price rigidity—including those categorized as dynamic stochastic general equilibrium (DSGE) models—only consider the intensive margin and mostly ignore the extensive margin. One reason for this trend is models with only intensive margin of price adjustment—*time-dependent pricing* (henceforth, TDP) models—are simpler and easier to solve and analyze. In such a TDP model, there is usually no need to track the price distribution firms and the frequency of price adjustment. For example, under the popular Calvo (1983) model, given the optimal reset price and lagged aggregate price level, a single parameter—the fixed probability of price adjustment—is a sufficient statistic to summarize the entire price distribution. Models with both intensive and extensive margins—*state-dependent pricing* (henceforth, SDP) models—on the other hand are more complex.

Another reason behind the more widespread adoption of TDP models is a belief that such models provide a good approximation to the more-realistic SDP models (see e.g. Klenow and Kryvtsov (2008)).[1] This is, however, only true in an economy with low and stable inflation, e.g. the U.S. economy post-1984 and the Australian economy post-1993. When inflation is historically moderate-to-high and highly variable such as in Indonesia, SDP is a better and more accurate representation of the true firms' price adjustment process. In such an

[1] There is growing evidence, however, documenting state dependence in firms' price adjustment activities. For example, Nakamura and Steinsson (2008) show that it is the frequency, rather than the size of price adjustment, that has a strong positive correlation with inflation. This observation is more consistent with an SDP assumption.

environment, the frequency of price adjustment could vary substantially as relative prices are more likely to be misaligned. Neglecting to incorporate the extensive margin into the model economy would potentially lead to an inaccurate prescription as to the appropriate conduct of monetary policy. It calls into question whether it is necessary for DSGE models specifically constructed to analyze the Indonesian economy to include this extensive margin feature. To the best of my knowledge, all such DSGE models—e.g. the models in Hermawan and Munro (2008), Harmanta, Purwanto and Oktiyanto (2014), Sahminan et al. (2017), Zams (2017), and Lie (2019)—are TDP models and hence only include the intensive margin.[2]

In this paper, I construct a small open-economy DSGE model for Indonesia with state-dependent pricing and analyze its implications for policy analysis. The core of the model is based on the medium-scale DSGE model for Indonesia estimated in Lie (2019). To facilitate the analysis, this base model is extended to include a state-dependent pricing feature, following the seminal approach in Dotsey, King and Wolman (1999).[3] In the Dotsey, King, and Wolman (DKW) SDP model, firms are allowed to endogenously change their timing and frequency of price adjustments by paying a small fixed menu cost. This feature produces endogenous variations in the extensive margin, which in turn affect the fluctuations of various key macroeconomic variables, including inflation and output.

I find that the variations in the extensive margin of price adjustment under SDP non-trivially impact on various results generated by the DSGE model. This in turn has important implications for policy analysis conducted using the model. The SDP assumption leads to disparities in the conditional variance decompositions and the impulse responses to various shocks responsible for the business cycle fluctuations. In particular, under the SDP model, technology shocks are shown to be much more important for output fluctuations, relative to that under the TDP model. Monetary policy shocks become less important, although these shocks are still shown to be a dominant driver of inflation fluctuations in Indonesia. The impulse response functions to various shocks provide an explanation as to the role of extensive margin of price adjustment in generating these disparities. When the economy is

[2]See also Joseph, Dewandaru and Gunadi (2003), Alamsyah (2004), Tjahjono and Waluyo (2010), Harmanta et al. (2013), and Dutu (2016).

[3]Other prominent state-dependent pricing models in the literature include those in Caplin and Leahy (1991), Golosov and Lucas Jr (2007), Woodford (2009), and Midrigan (2011).

hit by a positive technology shock, there is an increase in the fraction of firms in the economy adjusting their prices. This in turn leads to a larger decrease in inflation and a higher increase in output, both of which contribute to the increased contribution of technology shocks to output and inflation variations. Under a positive (expansionary) monetary policy shock, however, the resulting output stimulation is more subdued in the SDP model, compared to that in the standard TDP model. Intuitively, as inflation and aggregate demand increase as a result of the monetary expansion, more firms decide to adjust (increase) their prices. Such a variation in the extensive margin causes a lower increase in the aggregate demand, weakening the stimulation of output.

Using the constructed DSGE model, I also investigate the impact the SDP assumption on policy analysis conducted in response to the COVID-19 pandemic shocks. These pandemic shocks, which are modelled as a combination of negative labor supply and preference shocks in the model, are extraordinarily large, once-in-a-generation shocks that inevitably warrant equally extraordinary policy responses. The investigation in this paper indicates that the variations in the extensive margin of price adjustment non-trivially affect the analysis on the appropriate degree of monetary policy responses to the pandemic shocks. An SDP model would call for a greater degree of monetary easing in response to the COVID-19 pandemic, than that prescribed by a traditional TDP model.

The rest of the paper is organized as follows. Section 2 presents the small open-economy DSGE model with state-dependent pricing and describes its connection to standard time-dependent pricing models. Section 3 analyzes the variance decomposition results and the impulse responses to various shocks. Section 4 investigates the impact of COVID–19 pandemic shocks and the associated policy responses. Section 5 concludes.

2 The DSGE model: A small open-economy model with state-dependent pricing

The baseline model for the analysis is the medium-scale small open economy (SOE) model for Indonesia estimated in Lie (2019).[4] There are two economies in the model: the domestic (home) economy and the foreign economy, representing the rest of the world. The domestic economy consists of a representative household, a continuum of monopolistically-competitive firms producing differentiated varieties, a continuum of importers, and a monetary policy authority. Aggregate fluctuations in the domestic economy are driven by nine exogenous shocks: technology, preference, cost-push, monetary-policy, risk-premium, foreign-output, foreign-inflation, foreign interest-rate, and inflation-target shocks. The size of the domestic economy is much smaller relative to the foreign economy, i.e. shocks originated in the domestic economy do not materially affect the foreign economy. But since it is an open economy, the domestic economy is exposed to shocks originated from abroad (foreign shocks).

To investigate the various implications of SDP for DSGE-based policy analysis in Indonesia, I incorporate the SDP model of Dotsey, King and Wolman (1999) into the SOE model in Lie (2019). In particular, instead of the standard Calvo (1983) price adjustment process, the intermediate-good producing firms adjust their prices in a state-dependent fashion: they are allowed to choose both the size and the timing of their price adjustments. This is in contrast to that in the Calvo pricing—or any TDP model such as the Taylor (1980) model—in which firms have no choice over the timing of their price adjustments, i.e. the timing is exogenous instead of endogenous.

2.1 Intermediate-good firms with state-dependent price adjustment process

I first describe the price adjustment process of the intermediate-good firms based on the Dotsey, King, and Wolman (DKW) SDP model. There is a continuum of monopolistically

[4] The model in Lie (2019) is based on the model in Justiniano and Preston (2010), but extended with a time-varying inflation target. At the core, it is a simplified version of the canonical small open-economy DSGE model in Gali and Monacelli (2005) and Monacelli (2005).

competitive firms in the domestic economy, indexed by $i \in [0, 1]$, each producing a differentiated variety with a production function

$$Y_{H,t}(i) = \tilde{\varepsilon}_{a,t} N_t^p(i), \tag{1}$$

where $Y_{H,t}(i)$ is the production of good i, $N_t^p(i)$ is the associated labor input, and $\tilde{\varepsilon}_{a,t}$ is the aggregate exogenous technology level. The total demand for variety i is the sum of domestic demand $C_{H,t}(i)$ and foreign demand $C^*_{H,t}(i)$, given by

$$C_{H,t}(i) + C^*_{H,t}(i) = \left[\frac{P_{H,t}(i)}{P_{H,t}}\right]^{-\varepsilon} \left(C_{H,t} + C^*_{H,t}\right). \tag{2}$$

$C_{H,t}$ and $C^*_{H,t}$ are the Dixit-Stiglitz CES aggregate consumption index of these domestically-produced varieties for the domestic economy and foreign economy, respectively. $P_{H,t}$ is the aggregate price index of the domestically-produced varieties, i.e. the producer-price index, while $P_{H,t}(i)$ is the nominal price of variety i at time t.[5] In equilibrium, $Y_{H,t}(i) = C_{H,t}(i) + C^*_{H,t}(i)$.

2.1.1 The distribution of firms according to the time since last price adjustment

In addition to being able to choose the price $P_{H,t}(i)$, each firm i can choose when to adjust the price, subject to paying a fixed price adjustment cost. These costs (in labor units) are heterogenous across firms and are drawn each period independently from a time-invariant distribution with a cumulative distribution function (CDF) $G(\cdot)$. Firms that choose not to adjust prices do not need to pay these fixed costs but must keep the nominal price from the previous period. Hence, at the end of any given period t there is a distribution of firms according to the *time since the last price adjustment* $j \in [0..J-1]$, with J denotes the maximum possible period of price fixity. Here, $j = 0$ represents the set of firms who adjust their prices in the current period. Let $\omega_{j,t}$ be the end-of-period fraction of firms that last adjusted their prices j periods ago.[6] These variables summarize the distribution of firms

[5] The equality in (2) holds because the law of one price is assumed to hold at the dock for these varieties. For more detailed description of the demand functions, see the online appendix of Lie (2019).

[6] By end-of-period, I mean that these fractions are observed in the current period t after firms' production and pricing decisions are made.

according to the time since the last price adjustment and evolve according to

$$\omega_{j,t} = (1 - \alpha_{jt})\omega_{j-1,t-1} \ , \tag{3}$$

for $j = 1, ..., J-1$. $\alpha_{j,t}$ is the endogenous fraction of firms j—firms that last adjusted their prices j periods ago—that decide to adjust at the beginning of period t (after observing the fixed cost draw). The fraction of adjusting firms in the current period t is then given by

$$\omega_{0,t} = 1 - \sum_{j=1}^{J-1} \omega_{j,t} \ . \tag{4}$$

Both $\{\alpha_{jt}\}_{j=1}^{J-1}$ and $\{\omega_{j,t}\}_{j=0}^{J-1}$ are determined endogenously and depend on aggregate variables, including the price distribution.

2.1.2 Price-adjusting firms' maximization problem

Once a firm decides to change its price, it chooses the optimal price that maximizes its discounted lifetime profits, much like the profit-maximization problem in the Calvo model. Specifically, the adjusting firms ($j = 0$) solve the dynamic maximization problem,

$$\begin{aligned} v_{0,t} &= \max_{p_{0,t}} \ [z_{0,t} + \beta E_t \frac{\lambda_{t+1}}{\lambda_t}(1 - \alpha_{1,t+1})v_{1,t+1} \\ &\quad + \beta E_t \frac{\lambda_{t+1}}{\lambda_t}\alpha_{1,t+1}\left(v_{0,t+1} - w_{t+1}\Xi_{1,t+1}\right)] \ , \end{aligned} \tag{5}$$

where $v_{0,t}$ and $z_{0,t}$ denote the value function of a typical adjusting firm ($j = 0$) and its one-period profit function, respectively.[7] The value function $v_{0,t}$ is in real term, so that choice variable, $p_{0,t}$, is the real price, i.e. the nominal price $P_{0,t}$ divided by the aggregate domestic price index $P_{H,t}$. The above expression says that an adjusting firm chooses the optimal price to maximize its expected present discounted values of current and future profits. In doing so, it has to take into account the possibility of price adjustment in future periods. There is an expected probability of $(1 - \alpha_{1,t+1})$ that it will choose not to adjust so that its expected

[7] Given the production function (1), CES demand function (2), real wage w_t and relative price $p_{j,t}$, the profit function is $z_{j,t} = (p_{j,t} - w_t/\tilde{\varepsilon}_{a,t})p_{j,t}^{-\varepsilon}\left(C_{H,t} + C_{H,t}^*\right)$ for any $j = 0, ..., J-1$.

value in the next period $(t+1)$ is $v_{1,t+1}$. With expected probability $\alpha_{1,t+1}$, it will optimally choose to adjust at time $t+1$ so that its value becomes $v_{0,t+1}$. The last term in the second line of (5) reflects the fact that if the firm decides to adjust in the next period, it must also pay the fixed adjustment cost — here, $\Xi_{1,t+1}$ is the expected fixed adjustment cost in the next period, conditional on adjustment. Since the fixed costs are in terms of labor unit, the expected cost is given by $w_{t+1}\Xi_{1,t+1}$, where w_{t+1} denotes the real wage. Households are assume to own the firms, so that future periods are discounted by the effective discount factor $\beta E_t \frac{\lambda_{t+1}}{\lambda_t}$, where λ_t is the shadow value of households' income and β is the subjective discount factor. Finally, since the fixed cost draw is random and each firm has the same production function and faces the same demand function, the maximization problem in (5) is identical for all adjusting firms. This means they would choose the same optimal price $p_{0,t}$.

For firms that choose not to adjust $(j = 1, ..., J-1)$ and hence simply apply prices from the previous period, the value functions can be expressed as

$$\begin{aligned} v_{j,t} \quad = \quad & z_{j,t} + \beta E_t \frac{\lambda_{t+1}}{\lambda_t}(1-\alpha_{j+1,t+1})v_{j+1,t+1} \\ & + \beta E_t \frac{\lambda_{t+1}}{\lambda_t}\alpha_{j+1,t+1}\left(v_{0,t+1} - w_{t+1}\Xi_{j+1,t+1}\right) \ . \end{aligned} \tag{6}$$

There is no max operator in (6) since the only decision made by non-adjusting firms is the input decision for production to meet demand. It has, however, a similar interpretation as equation (5). For example, the value function of $j = 2$ firms—firms that last adjusted their price 2 periods ago—depends on its current profit $z_{2,t}$ and its discounted next period's value function, which depends on whether a price adjustment occurs next period. There is an expected probability $\alpha_{3,t+1}$ that a $j = 2$ firm would optimally choose to adjust their prices, in which case it would become a $j = 0$ with value function $v_{0,t+1}$. The expected fixed adjustment cost in this scenario is $w_{t+1}\Xi_{3,t+1}$. On the other hand, with expected probability $(1-\alpha_{3,t+1})$, the firm would optimally choose not to adjust and keep the (nominal) price from the previous period. In this second scenario, it becomes a $j = 3$ firm in the next period with value function $v_{3,t+1}$. Given (6), we can solve the maximization problem in (5) recursively and obtain the optimal price expression.[8]

2.1.3 Probabilities of price adjustment and aggregate price index

To obtain the equilibrium expression for the probabilities of price adjustment, notice that firms only adjust their prices if there is a positive benefit of doing so, that is, the value of adjustment outweighs the fixed cost associated with adjustment. Given the continuous distribution of the fixed adjustment cost, there will be a mass of firms at the margin for each j that are indifferent between adjusting their prices or not. For these firms, there is a zero benefit to adjust, so that $(v_{0,t} - v_{j,t}) = w_t \bar{\epsilon}_{j,t}$, where $\bar{\epsilon}_{j,t}$ is the fixed cost at the margin for firms in "bin" j. Within each bin j, firms assigned a fixed cost smaller than $\bar{\epsilon}_{j,t}$ will optimally choose to adjust, while the non-adjusting firms are those receiving a fixed cost draw larger than $\bar{\epsilon}_{j,t}$. This means the proportion (or probability) of adjusting firms is given by

$$\alpha_{j,t} = G\left(\frac{v_{0,t} - v_{j,t}}{w_t}\right) \tag{7}$$

for each $j = 1, ..., J-1$. For $j = J$, we have $\alpha_{J,t} = 1$ since all firms will find it optimal to adjust after J periods. These probabilities of price adjustment also endogenously affect the aggregate fixed adjustment costs paid by adjustment firms. Specifically, the expected adjustment cost conditional on adjustment is given by

$$\Xi_{j,t} = \frac{1}{\alpha_{j,t}} \int_0^{G^{-1}(\alpha_{j,t})} x dG(x)$$

for $j = 1, ..., J$.

2.1.4 Price aggregation and the state-dependent pricing Phillips curve

Aggregating the prices of all varieties yields the domestic producer price index,

[8] See equation (14) in Dotsey, King and Wolman (1999) for the optimal price expression. The resulting expression is a generalization of that which obtains in the canonical time-dependent Calvo pricing model, see e.g. equation (5.9) in Goodfriend and King (1997). Under SDP, however, future probabilities of price adjustments are time-varying and serve to modify the stochastic discount factor.

$$P_{H,t} = \left[\int_0^1 P_{H,t}(i)^{1-\varepsilon}\right]^{\frac{1}{1-\varepsilon}} = \left[\sum_{j=0}^{J-1} \omega_{j,t} P_{j,t}^{1-\varepsilon}\right]^{\frac{1}{1-\varepsilon}}, \tag{8}$$

where $P_{j,t} \equiv p_{j,t} P_{H,t}$ is the nominal price for firms in bin j. For non-adjusting firms $j = 1, ..., J-1$, these prices are predetermined:

$$P_{j,t} = P_{j-1,t-1},$$

or in terms of relative prices,

$$p_{j,t} = \Pi_{H,t}^{-1} p_{j-1,t-1}.$$

$\Pi_{H,t} \equiv P_{H,t}/P_{H,t-1}$ is the domestic-price inflation.

As shown in Bakhshi, Khan and Rudolf (2007), the price index (8) can be combined with the adjusting firms' optimal reset price to produce a Phillips curve-like expression. When log-linearized around the steady state, this expression amounts to

$$\begin{aligned} \hat{\pi}_{H,t} \quad = \quad & E_t \sum_{j=1}^{J-1} \delta'_j \hat{\pi}_{H,t+j} + E_{tt} \sum_{j=0}^{J-1} \left[\psi'_j \widehat{mc}_{t+j} + \gamma_j \left(\hat{\omega}_{j,t+j} - \hat{\omega}_{0,t}\right)\right] \\ & + \eta_0 \, \hat{\Omega}_t + \sum_{j=1}^{\infty} \eta_j \hat{\Omega}_{t-j} + \sum_{j=1}^{\infty} \mu'_j \hat{\pi}_{H,t-1}, \end{aligned} \tag{9}$$

where all the hatted variables are in terms of deviations from their steady-state values. Here, $\hat{\pi}_{H,t}$ is domestic-price inflation and $\widehat{mc}_t$ is the real marginal cost. $\hat{\Omega}_t$ is a function of the distribution of firms according to the time since last price adjustments, $\{\hat{\omega}_{j,t}\}_{j=0}^{J-1}$, which summarize the aggregate frequency of price adjustments. The coefficients δ'_j, ψ'_j, γ_j, η_j, and μ'_j are all functions of the model's steady state and structural parameters.[9] As we shall see below, this state-dependent Phillips curve (SDPC) is a generalization of the canonical Phillips-curve expression under the Calvo time-dependent pricing model.

[9] See equations (11)-(13) in Bakhshi, Khan and Rudolf (2007) for the details of these coefficients.

2.1.5 The time-dependent pricing (TDP) model counterpart

To further highlight the role of the endogenous timing of price adjustments under SDP, it is useful to compare the model to its TDP model counterpart. In this alternative model, the adjustment probabilities $\alpha_{j,t}$ and fraction $\omega_{j,t}$ are held constant at their steady-state values under SDP. In terms of their near steady-state dynamics, this means $\hat{\alpha}_{j,t} = 0$ and $\hat{\omega}_{j,t} = 0$, implying $\hat{\Omega}_t = 0$. The SDPC in (9) becomes a time-dependent pricing Phillips curve (TDPC),

$$\hat{\pi}_{H,t} = E_t \sum_{j=1}^{J-1} \delta'_j \hat{\pi}_{H,t+j} + E_{tt} \sum_{j=0}^{J-1} \psi'_j \widehat{mc}_{t+j} \sum_{j=1}^{\infty} \mu'_j \hat{\pi}_{H,t-1}. \tag{10}$$

Put another way, the *extensive margin* (frequency) of price adjustments is held constant and plays no role in inflation dynamics — only the *intensive margin* (size) of price adjustments matters.

It is also informative to compare both the SDP model and its TDP model counterpart to the standard Calvo pricing model (Calvo-TDP). The Calvo-TDP model is a special case of the TDP model above when $J \to \infty$ and when steady-state probabilities α_j are identical across j.[10] Imposing this special case with $\alpha_j = (1 - \theta_H)$, we have the familiar (New Keynesian) Phillips curve expression

$$\hat{\pi}_{H,t} = \beta E_t \hat{\pi}_{H,t+1} + \lambda_H \widehat{mc}_t \ , \tag{11}$$

where $\lambda_H \equiv (1-\theta_H)(1-\theta_H\beta)/\theta_H$ is the Phillips curve slope and θ_H is the probability of price fixity (non-price adjustment). The Phillips curve (11) is the version used in the estimated DSGE model in Lie (2019).

[10]For any finite J and $\{\alpha_j\}_{j=1}^{J-1} = 0$ with $\alpha_J = 1$, we have the contracting model of Taylor (1980).

2.2 The rest of the model

The rest of the model is identical to that in Lie (2019). I therefore only present the log-linearized equilibrium equations of the model.[11] The notation $\hat{x}_t$ below denotes the *log* deviation of any variable x_t from its steady state or trend, except for inflation and interest-rate variables, which are in *level* deviation from their respective steady-state values.

Aggregate consumption $\hat{c}_t$ follows the following dynamics:

$$\begin{aligned}(\hat{c}_t - h\hat{c}_{t-1}) \quad &= \quad E_t(\hat{c}_{t+1} - h\hat{c}_t) - \sigma^{-1}(1-h)(\hat{\imath}_t - E_t\hat{\pi}_{t+1}) \\ &\quad +\sigma^{-1}(1-h)(\hat{\varepsilon}_{g,t} - E_t\hat{\varepsilon}_{g,t+1}) - \kappa_0\sigma^{-1}(1-h)(\hat{\imath}_t - E_t\hat{\imath}_{t+1}) \ .\end{aligned} \tag{12}$$

This expression is derived from households' optimal intertemporal consumption and labor choices. The consumption decision each period is subject to a degree of internal habit formation h and to an exogenous preference shock $\hat{\varepsilon}_{g,t}$, which follows a first-order autoregressive process $\hat{\varepsilon}_{g,t} = \rho_g\hat{\varepsilon}_{g,t-1} + \eta_{g,t}$, with $\eta_{g,t} \sim$ i.i.d. $N(0, \sigma_g^2)$. The variables $\hat{\imath}_t$ and $\hat{\pi}_t$ denote the nominal interest rate and consumer price index (CPI) inflation, respective. This otherwise-standard "IS-curve" equation has an additional term involving current and expected future interest rates (the second term in the second line of (12)), due to a cash-in-advance (CIA) constraint assumption in which households have to purchase a ν^h fraction of consumption goods using cash or money. Here, κ_0 is a reduced-form parameter that is a positive function of structural parameter ν^h; when $\nu^h = 0$, we obtain a standard IS-curve equation under the cashless-purchase assumption.[12] Movements in the nominal interest rate thus have additional dynamic effects on consumption fluctuations when a money-holding friction is present.[13]

The aggregate resource constraint in the domestic economy is given by

$$\hat{y}_t = (1-\tau)\hat{c}_t + \kappa\eta(2-\phi)\hat{S}_t + \kappa\eta\hat{\Psi}_{F,t} + \kappa\hat{y}_t^* \ . \tag{13}$$

[11] A more detailed description of the model can be found in the associated online appendix of the paper in https://www.dropbox.com/s/ijcrclhfymguxvk/Appendix_Lie_ITadj_Indo_Oct2018.pdf?dl=0

[12] That is, $\kappa_0 \equiv \nu^h\bar{R}^{-1}/\left(1+\nu^h(1-\bar{R}^{-1})\right)$, where $\bar{R}$ is the long-run steady-state gross nominal interest rate.

[13] In an estimated DSGE model for Indonesia, Zams (2017) finds that the Bayesian posterior mean estimate of ν^h is 0.42, which is non-trivial. The marginal log-likelihood of the model with a money-holding (CIA) friction is found to be larger than that in the cashless model, suggesting that the former fits the data better.

Output $\hat{y}_t$ is absorbed by demands from the domestic households and the foreign economy. The former is equal to $(1-\tau)\hat{c}_t$ where τ represents the share of foreign-produced goods in the aggregate consumption basket, while the latter depends positively on the terms of trade (ratio of import prices to export prices), $\hat{S}_t$, foreign aggregate demand or output, $\hat{y}_t^*$, and the law of one price (LOP) gap, $\hat{\Psi}_{F,t}$, representing the deviation of the law of one price for the import goods at the retail level.[14] The structural parameter η is the elasticity of substitution between domestic and imported goods.

The terms of trade and LOP gap evolve according to

$$\Delta\hat{S}_t = \hat{\pi}_{F,t} - \hat{\pi}_{H,t} \ , \tag{14}$$

$$\Delta\hat{\Psi}_{F,t} = \hat{e}_t^c + \hat{\pi}_t^* - \hat{\pi}_{F,t} \ , \tag{15}$$

where $\hat{\pi}_t^*$, $\hat{\pi}_{F,t}$, and $\hat{e}_t^c$ denote CPI-inflation in the foreign economy, import-price inflation in the domestic economy, and nominal exchange-rate growth (depreciation), respectively. CPI inflation $\hat{\pi}_t$ is linked to producer-price inflation $\hat{\pi}_{H,t}$ through

$$\hat{\pi}_t = \hat{\pi}_{H,t} + \tau\left(\hat{S}_t - \hat{S}_{t-1}\right) \ . \tag{16}$$

The real exchange rate, $\hat{q}_t$, relates to the LOP gap and the terms of trade through

$$\hat{q}_t = \hat{\Psi}_{F,t} + (1-\tau)\hat{S}_t. \tag{17}$$

The real marginal cost $\widehat{mc}_t$, which enters the domestic-price Phillips curve in (9), follows

$$\begin{aligned} \widehat{mc}_t \quad = \quad & \varphi\hat{y}_t - (1+\varphi)\hat{\varepsilon}_{a,t} + \tau\hat{S}_t + \sigma(1-h)^{-1}\left(\hat{c}_t - h\hat{c}_{t-1}\right) \\ & + \kappa_0\hat{\imath}_t \ , \end{aligned} \tag{18}$$

where $\hat{\varepsilon}_{a,t} = \rho_a\hat{\varepsilon}_{a,t-1} + \eta_{a,t}$ is the exogenous technology, with $\eta_{a,t} \sim$ i.i.d. $N(0,\sigma_a^2)$.

Importers in the model purchase foreign varieties to be sold in the domestic market. The

[14] More formally, $\hat{\Psi}_{F,t}$ is the ratio of aggregate domestic-currency price of import goods at the dock and its aggregate price at the retail level.

law of one price (LOP) is assumed to hold at the dock for each of these varieties. These importers, however, have some monopoly power in the domestic market, and hence, charge a positive mark-up, i.e. there is a deviation from the LOP at the retail level. They are subject to the Calvo, time-dependent pricing mechanism, with θ_F as the probability of non-optimal price reset. There is a past price indexation mechanism: when importers are not allowed to adjust prices optimally, they index their prices to a mixture of past import-price inflation and current inflation target, with relative weights given by δ_F and $1-\delta_F$, respectively. These assumptions lead to a Phillips curve equation for the import sector,

$$\begin{aligned}\hat{\pi}_{F,t} - \delta_F \left(\hat{\pi}_{F,t-1} - \hat{g}_t^{\overline{\pi}}\right) &= \beta E_t \left[\hat{\pi}_{F,t+1} - \delta_F \left(\hat{\pi}_{F,t} - \hat{g}_{t+1}^{\overline{\pi}}\right)\right] \\ &\quad + \frac{(1-\theta_F)(1-\theta_F\beta)}{\theta_F}\widehat{\Psi}_{F,t} \\ &\quad + \hat{\varepsilon}_{cp,t} \ ,\end{aligned} \tag{19}$$

where the LOP gap becomes the relevant marginal-cost measure. $\hat{\varepsilon}_{cp,t}$ is the import cost-push shock, assumed to follow $\hat{\varepsilon}_{cp,t} = \rho_{cp}\hat{\varepsilon}_{cp,t-1} + \eta_{cp,t}$, with $\eta_{cp,t} \sim$ i.i.d. $N(0, \sigma_{cp}^2)$. $\hat{g}_t^{\overline{\pi}} \equiv \log(\overline{\Pi}_t) - \log(\overline{\Pi}_{t-1})$ is the growth rate of the inflation target.

The equilibrium in the foreign exchange or asset market is given by the interest-parity condition,

$$(\hat{\imath}_t - E_t\hat{\pi}_{t+1}) - \left(\hat{\imath}_t^* - E_t\hat{\pi}_{t+1}^*\right) = E_t\Delta\hat{q}_{t+1} - \chi\hat{a}_t - \chi E_t\hat{\phi}_{t+1} \ , \tag{20}$$

where $\hat{\imath}_t^*$ and $\hat{a}_t$ denote the foreign nominal interest rate and net foreign asset position (as a fraction of steady-state output), respectively. The relative risk-premium shock, $\tilde{\phi}_t$, evolves according to $\hat{\phi}_t = \rho_\phi\hat{\phi}_{t-1} + \eta_{\phi,t}$, with $\eta_{\phi,t} \sim$ i.i.d. $N(0, \sigma_\phi^2)$ and χ is a parameter governing the impact of the shock on the relative holding of foreign asset. The equation describing the net foreign asset position is given by

$$\hat{c}_t + \hat{a}_t = \beta^{-1}\hat{a}_{t-1} - \tau\left(\hat{S}_t + \widehat{\Psi}_{F,t}\right) + \hat{y}_t \ . \tag{21}$$

The paths of the foreign variables—$\hat{\pi}_t^*$, $\hat{y}_t^*$, and $\hat{\imath}_t^*$—are assumed to be exogenously given by a vector autoregression of order two (VAR(2)), following Justiniano and Preston (2010).

The monetary policy rule The central bank in the model is assumed to conduct monetary policy according to a Taylor-type rule

$$\hat{\imath}_t = \rho_i \hat{\imath}_{t-1} + (1-\rho_i)\left[\psi_\pi \hat{\pi}_t + \psi_y \hat{y}_t + \psi_{\Delta_y} \Delta \hat{y}_t + \psi_e \hat{e}_t^c\right] - \tilde{\varepsilon}_{M,t} \ , \tag{22}$$

where $\tilde{\varepsilon}_{M,t} \sim$ i.i.d. $N(0, \sigma_M^2)$ is the unanticipated monetary-policy shock. The inflation target—in terms of level deviation from the constant long-run target, $\widehat{\overline{\pi}}_t \equiv \overline{\pi}_t - \overline{\pi}$—evolves according to

$$\widehat{\overline{\pi}}_t = \rho_{\overline{\pi}} \widehat{\overline{\pi}}_{t-1} + \tilde{\varepsilon}_{\overline{\pi},t} \ . \tag{23}$$

2.3 Calibration and computation

I compute the rational expectations equilibrium based on the linearized model equations above. Table 1 presents the calibration of the model, which is based on the posterior mean estimates in Lie (2019). While it is possible to estimate the structural parameters of the DSGE-SDP model using a Bayesian approach—see Bhattacharyya (2019) for such an estimation using Indonesian data—it is not the current focus of the paper and hence, is better left for future research.

In terms of the distribution of fixed adjustment costs, I assume a generalized Uniform distribution with CDF

$$F(x) = \bar{\kappa} + (1-\bar{\kappa})\left[\frac{(x/K) - \kappa_1}{\kappa_2 - \kappa_1}\right] \ , \tag{24}$$

where κ_1 is the left parameter and κ_2 is the right parameter of the Uniform distribution,. It is generalized in a sense that the distribution (24) allows for a fraction $\bar{\kappa} \in [0, 1)$ of firms to receive a zero fixed adjustment cost and permits any value for the largest possible cost, K. These parameters are calibrated as follows. First, I set $\kappa_1 = 0$ and $\kappa_2 = 1$, implying a Standard Uniform distribution. Next, $\bar{\kappa}$ and K are jointly calibrated so that the largest period of price fixity is $J = 9$ and the implied average duration of price fixity is 2.4 quarters in the steady state. This duration is consistent with that in the Calvo model with probability of price fixity $\theta_H = 0.59$, which is the posterior mean estimate reported in Lie (2019).[15] This procedure results in $\bar{\kappa} = 0.33$ and $K = 0.049$. Figure 1 plots the steady-state

[15] The average steady-state duration of price fixity under the SDP model can be calculated as

probabilities (α_j) and the implied distribution of firms (ω_j) as a function of j (time since the last price adjustment) based on the calibration. Here, the steady-state hazard function—α_j as a function of j—is increasing because firms' values (v_j) are decreasing with j for non-zero steady-state inflation.

3 Variance decompositions and impulse response function

In this section, I investigate the implications of the extensive margin of price adjustment by looking at the model's conditional variance decompositions and impulse response functions. These are two typical analyses conducted within a DSGE model, especially in the context of policy analysis. They provide important inputs for policymakers. The former is useful in assessing which sources of fluctuations (exogenous shocks) are important for business cycle fluctuations, while the latter can be used to evaluate the pass through of shocks to each economic variable. Impulse response analysis is also typically used to evaluate the effectiveness of a given monetary policy framework (rule) in smoothing out the business cycle and whether alternative monetary policy frameworks are warranted.

As a point of comparison, I also compute the solutions to the two time-dependent pricing model counterparts: TDP-Calvo model and TDP model. Recall that the TDP-Calvo model is the model estimated in Lie (2019) in which the domestic firms adjust their prices in a Calvo manner and the domestic-price Phillips curve is represented by (11). The TDP model is the time-dependent pricing counterpart of our SDP model, but with adjustment probabilities $\alpha_{j,t}$ and fractions $\omega_{j,t}$ held constant at their steady-state values. The TDP-Calvo model is solved assuming that the probability of price fixity is $\theta_H = 0.59$, which implies that the three models—SDP, TDP, and TDP-Calvo—share the same average duration of price fixity (2.4 quarters) at the steady state.

$\sum_{j=1}^{J} j\alpha_j \prod_{i=1}^{j-1}(1-\alpha_i)$. Under the Calvo model, the duration is $(1-\theta_H)^{-1}$.

3.1 Conditional variance decompositions at various horizons

Table 2 first reports the conditional variance decompositions of CPI inflation, output (Gross Domestic Product (GDP) per capita), and the nominal interest rate (BI rate) under the TDP-Calvo model. Overall, the findings are as those in Lie (2019).[16] Inflation fluctuations at all considered horizons are dominated by technology and monetary-policy shocks. For example, at 1-year (4-quarter) horizon, these two shocks are responsible for over 78% of inflation variations. Likewise, preference and risk-premium shocks explain a significant fraction of fluctuations in the nominal interest rate, with inflation-target shocks also play an important role, especially at longer horizons. Output fluctuations are largely explained by technology and monetary-policy shocks, with the latter play a less prominent role in the medium to long run, as expected. Minor variations aside, these variance decompositions results are largely the same as those obtained under the TDP model, reported in Table 3. This is unsurprising, as the two models share the same *constant*, average duration of price fixity, both inside and outside the steady state.

Under the SDP model, however, the duration of price fixity is time-varying, due to the endogenous nature of the timing of price adjustments. This has a potentially important implication on the role of various shocks in the fluctuations of various variables. As shown in Table 4, this is indeed the case, especially for output. Here, technology shocks are overwhelmingly responsible for output variations. These shocks explain at least 90% of the fluctuations for all considered horizons. Monetary policy shocks—which are shown to explain a large portion of output fluctuations in the short run in the TDP model—now account for only 7% of output fluctuations at 1-quarter horizon and less than 4% at longer horizons. The other shocks also now appear to be less important, e.g. preference shocks explain less than 1% of the variations in output, irrespective of the horizon.

Inflation variations are also affected by the incorporation of SDP assumption into the model, although to a lesser degree than output. Technology and monetary-policy shocks are still the dominant driver of variations in inflation. There appears to be a non-trivial increase

[16] Note that the decompositions in Table 2 are not identical to those in Lie (2019) since the decompositions in this paper are based on the structural parameters' posterior mean estimates, while that paper reports the posterior mean (forecast error) variance decompositions. The general conclusions, however, are identical.

in the contribution of technology shocks, at the expense of import cost-push shocks' contribution. The contribution of the other shocks appear to be largely unaffected. If anything, inflation-target shocks' contribution is somewhat smaller—but still non-trivial, especially at longer horizons—than that under the TDP model. On the nominal interest rate, the endogenous timing of price adjustments under SDP does not appear to alter its variance decompositions much: its variations are still largely explained by preference, risk-premium, and inflation-target shocks and the numbers look very similar to those under the TDP model in Table 3.

At this point, it is important to recognize that the decompositions in Table 4 are obtained based on the shock variances estimated from a DSGE model with Calvo pricing. In a more proper comparison, one ideally also estimates the variances of these shocks under the SDP assumption, prior to computing the decompositions. Notwithstanding, the disparity between the variance decompositions in Tables 2-3 and Table 4 demonstrates that variations in the extensive margin of price adjustments may non-trivially alter the conclusion regarding the importance of each shock for the fluctuations of key macroeconomic variables in Indonesia. What is the mechanism behind the disparity? To answer this question, I turn to impulse response function analysis.

3.2 Impulse responses

Here, I focus on analyzing the impulse responses to technology, preference, and monetary-policy shocks. The responses to these three shocks are enough for us to understand the decomposition results above and the role of the extensive adjustment margin.

Technology shocks Figure 2 plots the responses of selective variables to a 1% technology shock for the SDP, TDP, and TDP-Calvo models. On impact, the temporarily-higher technology (productivity) level increases output and reduces inflation in all three models. Despite this qualitative similarity, the magnitudes under the SDP model are markedly different than those in the two time-dependent pricing models. Under SDP, output jumps on impact by about 53% higher—0.76% compared to 0.5% deviation from the steady state—than under the TDP model. This higher increase in output occurs for the first three periods

— in subsequent periods, the responses are similar across the different models. Inflation, on the other hand, decreases by more on impact under SDP.

The dynamics of the fraction of price adjusting firms, $\hat{\omega}_{0,t}$, provide an explanation of the mechanism behind this quantitative disparity. A positive technology shock reduces the marginal cost of production. All else equal, this leads to those firms who are adjusting their prices to optimally reduce their prices. This *intensive margin* of price adjustment is the sole source of variations in domestic-price inflation in the TDP and TDP-Calvo models. Under the SDP model, however, the variation in the *extensive margin* of price adjustments also play a role. Here, in response to the shock, more firms decide to adjust their prices, i.e. there is an increase in the fraction of adjusting firms relative to the steady state. This additional margin causes domestic-price inflation (not shown), and hence CPI inflation, to decrease by more under SDP. Since more firms decide to decrease their prices, aggregate demand goes up by more, providing an explanation for the higher increase in output under SDP. The allocation under the SDP model is therefore closer to the efficient allocation, i.e. the allocation under the flexible-price equilibrium, compared to that under the TDP model. Alternatively, defining output gap as the deviation of output from its flexible-price equilibrium level, we can say that the output gap is less negative under SDP in response to a given positive technology shock.

On the movements of the nominal interest rate, given the policy rule (22), the central bank faces a tradeoff when responding to inflation, output, and exchange rate fluctuations.[17] Lower inflation and an exchange rate appreciation would lead the central bank to reduce the nominal rate, while higher output would warrant a rate hike. The calibrated policy parameters imply that this tradeoff is resolved in favor of inflation and exchange rate movements, causing the rate to slightly decrease by 0.06% per annum on impact in the SDP model. Although the nominal decreases by more in the TDP and TDP-Calvo models, the differences are quantitatively minor. This suggests that the extensive margin of price adjustment plays a minor role in driving nominal interest rate fluctuations, at least when the economy is hit by a productivity shock. Real interest rate movements, on the other hand, appear to be

[17] The exchange rate in the model is defined as the home currency price of foreign currency, e.g. IDR/USD. Hence, an increase (decrease) in the exchange rate means a home currency depreciation (appreciation).

markedly affected by the variations in the extensive margin, owing to the latter's influence on inflation expectations.

The impulse responses above indicate that the variation in the extensive margin of price adjustments causes inflation and output to be more responsive to productivity shocks, which provides an explanation as to why the contributions of technology shocks to inflation and output fluctuations increase once we incorporate a state-dependent pricing assumption (see Tables 2-4). The responses of the nominal interest rate—minor quantitative disparities across the three models—are also consistent with the fact that variance decompositions of the nominal interest rate are largely unchanged.

Preference shocks Turning now to demand shocks, Figure 3 compares the impulse responses to a 1% consumption preference shock in the SDP model and TDP model. The responses under the TDP-Calvo model are not included since they are largely the same as those under the TDP model.

On impact, the positive preference shock increases aggregate demand in both models, leading to higher output and inflation. However, the variation in the extensive margin of price adjustment under SDP alters the response size. Here, in response to higher aggregate demand, more firms decide to adjust (increase) their prices, i.e. there is an increase in the fraction of adjusting firms $\hat{\omega}_{0,t}$. As a consequence, the domestic price index increases by more under SDP, which explains the higher increase in CPI inflation on impact. Since there are more firms increasing the prices of their products, however, aggregate demand increases by less under SDP. This explains the higher decrease in output under TDP. In response to the increase in inflation and output, the central bank engages in a contractionary measure by increasing the nominal interest rate on impact. The movements in the rate, however, are largely the same across the two models. There is an exchange rate appreciation on impact, due largely to the associated increase in the nominal interest rate. It then depreciates as the nominal rate gradually decreases back to the steady state.

These responses are again consistent with the previous variance decomposition results. For example, it provides an explanation as to why the contribution of preference shocks to output variability is smaller under SDP for all horizons. It is also consistent with the result that the fluctuations of the nominal interest rate do not appear to be affected by the variation in the extensive margin of price adjustment.

Monetary-policy shocks Figure 4 now plots the impulse responses when the economy is subjected to a 1% monetary policy shock. This expansionary shock leads to a period of higher inflation and output level, as is familiar. Once again, the variation in the extensive margin affects the response size. An expansionary monetary policy shock stimulates the aggregate demand, which then leads to an increase in the fraction of adjusting firms. This causes inflation to increase by more under SDP: it increases by 6% per annum on impact compared to less than 5% under TDP. Output increases by less on impact instead, owing to a lower increase in the aggregate demand as the price level increases at a faster rate under SDP. Hence, similar to preference shocks, monetary policy shocks in general cause *less* output variations and *more* inflation variations, once variations in the extensive margin of price adjustment are taken into account. All else equal, this also means that a given expansionary monetary policy measure would be found to be less effective in stimulating output and consumption when the model features state-dependent pricing. This has an important implication for DSGE-based policy analysis, as I further show in the next section.

4 State-dependent pricing and COVID-19 impact and policy analysis

In this section, I show that state-dependent pricing may crucially affect DSGE model-based analysis of the economic consequences of the COVID-19 pandemic and the impact and effectiveness of the associated policy responses. The pandemic, which started as a localized health crisis, has wreaked havoc on the global economy. In response to the pandemic, many countries around the world—including Indonesia—have imposed (and are still imposing) various restrictions on social and business interactions, disrupting the supply chain and effectively shutting down large parts of the economy. This has led to various layoffs, firm exits, and scores of people voluntarily reducing their labor supply because of the risk of infection. Such aggregate supply disruptions in turn bring about aggregate demand effects as people cut back on their consumption, both voluntarily and involuntary. Evidently, the supply shocks associated with the COVID-19 pandemic have triggered even larger demand shocks, causing a contraction in output and employment and a likely decrease in the inflation rate.[18]

Motivated by the pandemic, there is a growing number of recent papers analyzing its impact and how should policymakers respond. There are generally two modelling approaches taken by researchers when dealing with macroeconomic issues surrounding COVID-19. The first approach builds on the classic SIR (*Susceptible-Infected-Removed*) epidemiological model, first proposed by Kermack and McKendrick (1927). To analyze the macroeconomic implications and policy tradeoffs, this model is then merged with a standard macroeconomic model, e.g. a real business cycle model. This approach, for example, is considered in Alvarez, Argente and Lippi (2020), Atkeson (2020), Boissay et al. (2020), Eichenbaum, Rebelo and Trabandt (2020), and Jones, Philippon and Venkateswaran (2020). In the second approach, the COVID-19 pandemic is not specifically modelled, but is instead treated as an exogenous shock within a general equilibrium model. Faria-e Castro (2020), for example, models the pandemic as a large negative shock to the utility of consumption in the contact-intensive service sector in a DSGE model. Using a standard New Keynesian model, Fornaro and Wolf (2020) treat the pandemic as a negative shock to the productivity growth rate. McKibbin and Fernando (2020*a*,*b*) consider various global macroeconomic scenarios and implications of the pandemic by translating it into shocks to the labor supply, equity risk premium, cost of production, and consumer spending.

4.1 Modelling the COVID-19 pandemic

This paper takes a pragmatic approach by treating the COVID-19 pandemic as an exogenous shock (or set of shocks) to the economy. Specifically, I model the pandemic as a combination of labor supply and preference (consumer spending) shocks.[19] Although the model presented

[18] As shown in Guerrieri et al. (2020), a Keynesian supply shock such as the COVID19 pandemic can theoretically lead to changes in the aggregate demand larger then the supply shock itself, leading to output contraction.

[19] Given the temporary nature of the shocks in the model, it is implicitly assumed that the economic effect of the COVID-19 pandemic is temporary, i.e. there is no permanent effect on the long-run growth rate of the economy. This assumption is unlikely to be true, however, given that the pandemic appears to have such a devastating supply-side effect, e.g. a destruction of human and organization capitals and disruption to the global supply chain.

in Section 2 does not have a labor supply shock, it could be included easily by modifying the household preference to include such a shock ($\tilde{\varepsilon}_{s,t}$):

$$u(C_t, N_t) = \tilde{\varepsilon}_{g,t} \left(\frac{(C_t - H_t)^{1-\sigma}}{1-\sigma} - \tilde{\varepsilon}_{s,t} \frac{N_t^{1+\varphi}}{1+\varphi} \right). \tag{25}$$

Here, $\tilde{\varepsilon}_{g,t}$, C_t, $H_t \equiv hC_{t-1}$, and N_t denote the preference (spending) shock, aggregate consumption, external consumption habit, and aggregate labor, respectively. This utility function is identical to the function in the original model, except for the addition of the labor supply shock, $\tilde{\varepsilon}_{s,t}$, which is assumed to follow an AR(1) process

$$\log(\tilde{\varepsilon}_{s,t}) = \rho_s \log(\tilde{\varepsilon}_{s,t-1}) + \eta_{s,t}$$

with $\eta_{s,t} \sim$ i.i.d. $N(0, \sigma_s^2)$. The additional labor supply shock modifies the marginal disutility of labor, which impacts on the labor supply decision and hence, the marginal cost of production. In particular, the log-linearized real marginal cost equation in (18) now becomes

$$\begin{aligned} \widehat{mc}_t \;\; = \;\; & \hat{\varepsilon}_{s,t} + \varphi \hat{y}_t - (1+\varphi)\hat{\varepsilon}_{a,t} + \tau \hat{S}_t + \sigma(1-h)^{-1}(\hat{c}_t - h\hat{c}_{t-1}) \\ & + \kappa_0 \hat{\imath}_t \ , \end{aligned} \tag{26}$$

with the only change being the addition of $\hat{\varepsilon}_{s,t} \equiv \log(\tilde{\varepsilon}_{s,t})$. The rest of the model equations are unaffected by the inclusion of this labor supply shock.

How do labor supply shocks affect the economy? Figure 5 plots the impulse responses to a negative 1% labor supply shock, with the persistence parameter calibrated to $\rho_s = 0.7$. As we can see, the shock behaves like a classic supply shock: it leads to a contraction in output and employment and higher inflation. It also causes the exchange rate to depreciate (not shown) as expected inflation rises. Despite the output contraction, the rise in inflation prompts the central bank to raise the policy rate on impact. These dynamics closely mirror the supply-side effect of the COVID-19 pandemic.

4.1.1 Calibrating the pandemic shocks

Ideally, the size and nature of these pandemic shocks are identified or estimated from actual data, perhaps using a Bayesian technique if a DSGE model is involved. While such an exercise is an important undertaking, especially given the ongoing nature of and devastating economic costs from the COVID-19 pandemic, this paper takes an alternate route by calibrating the size of these shocks.[20] I leave the estimation exercise for future research.

The calibration is as follows. I assume that the economy's starting state is at period 0, which corresponds to the fourth quarter of 2019 (2019.Q4). Actual 2019.Q4 data on CPI inflation (3% average from October-December 2019) and BI 7-day repo rate (5% on December 2019) are used to calibrate the starting points for CPI inflation and the nominal interest rate. Assuming that the long-run inflation target is 3%—consistent with BI's mid-point target for 2020—it implies a 2% starting real interest rate. At periods 1-4 (2020.Q1-2020.Q4), I assume the CPI inflation rates are equal to 3%, 2.5%, 2%, and 2%, respectively, which implies that the average inflation rate for the year would be 2.4%. Note that the period-1's rate is equal to the actual average inflation rate in Indonesia in 2020.Q1.

Next, output is assumed to be at the steady state in period 0, so that $\hat{y}_t = 0$. In subsequent period, from periods 1-4, I set $\hat{y}_t = -2\%, -4\%, -4\%, -2\%$, respectively. The calibration of $\hat{y}_t = -2\%$ for period 1 is consistent with a 2% reduction in Indonesia's GDP growth from 2019.Q4 to 2020.Q1 (the growth rate decreased from 4.97% to 2.97%, based on official statistics from Bank Indonesia). Across these periods, output on average would then be 3% lower relative to the steady state (period 0's value). This 3% "GDP-growth cost" is lower than the roughly 5.4% cost predicted by the IMF in its June 2020 report regarding the impact of the pandemic on Indonesia's GDP growth rate in 2020.[21] Notwithstanding this lower cost, it still represents a significant output cost.

With these assumptions in place, I then search for a sequence of labor supply shocks $\{\eta_{s,t}\}$ and preference shocks $\{\eta_{g,t}\}$ that imply the above inflation and output patterns in periods

[20] Such an estimation exercise would warrant a separate paper.

[21] This cost can be inferred from the revision in the IMF's projection of Indonesia's 2020 GDP growth rate between its October 2019 report and June 2020 report. In the former report, just before the pandemic, the projected growth rate was 5.1%. It was revised down to -0.3% in the June 2020 report, which implies a 5.4% projected cost to the GDP growth rate.

1-4. This exercise is conducted under the SDP model, assuming that no other shocks hit the economy during these and subsequent periods. In calibrating these shocks, the central bank is thus assumed to follow its normal monetary policy conduct, represented by the Taylor-type rule in (22). The resulting sequence of shocks are given in the following table:

Period (Quarter)	1 (2020.Q1)	2 (2020.Q2)	3 (2020.Q3)	4 (2020.Q4)
Labor supply ($\eta_{s,t}$)	-6.11%	-7.82%	-3.61%	2.37%
Preference ($\eta_{g,t}$)	-0.91%	-1.03%	-0.25%	0.67%

Despite the somewhat ad-hoc nature of the calibration, the above sequence constitutes a realistic representation of the nature of the pandemic shocks. For example, the two shocks hit the hardest in period 2 (2020.Q2), coinciding with what happened in Indonesia during the second quarter of 2020 when many parts of the country were under large-scale restrictions on social and economic interactions (PSBB). The negative shocks in periods 1-3 are quite large, e.g. a -1.03% preference shock in period 2 is equal to an almost 3-standard deviation shock, given the estimated σ_g in Table 1. It also implies a recovery in period 4 (2020.Q4): there is a positive labor supply shock and a positive preference (spending) shock in that period, perhaps in response to a successful development of a COVID-19 vaccine, a discovery of an effective treatment, or successful virus containment efforts.

To obtain a fuller picture of the impact of these pandemic shocks, Figure 6 plots the impulse responses under the SDP model and the corresponding TDP model. Recall that the calibration of output levels and CPI inflation rates in periods 0-4 is with respect to the SDP model, and hence, their responses under SDP are as calibrated. Despite this, the dynamics of inflation and output in these first five periods look to be almost the same under TDP. This is because of the contrasting responses in the fraction of adjusting firms (the extensive margin) to the two shocks. Since inflation goes up under a negative labor supply shock, more firms decide to adjust their prices relative to in the starting point (see Figure 5) . A negative preference shock, however, causes a decrease in the fraction of adjusting firms. In spite of the large size of the shocks, these two contrasting responses are responsible for the relatively small decrease in the fraction of adjusting firms seen in Figure 6, hence explaining the similarity of inflation and output fluctuations across the two models. The pandemic shocks lead to exchange rate depreciations in periods 1-3, which are partly responsible for the temporary improvements in the current account (not shown).[22]

In terms of the central bank response to the shocks based on the Taylor-type rule (22), the nominal interest rate decreases from 5% to 3.3% in period 1, 1.6% in period 2, and 1.4% in period 3. While they may not coincide perfectly with the actual BI 7-day repo rates, the decreasing pattern does fit the actual course of the rates in the first half of 2020, and likely, the direction of the rate in third quarter of 2020. From period 4 onwards, the rates are gradually increased again as the economy slowly recovers from the effect of the pandemic shocks. A full economic recovery is not achieved, however, even after 4 years. Output does seem to be fully back at its previous level prior to the pandemic by period (quarter) 15, but inflation is still below its 3% target. The real interest rate is also still below its normal (natural) rate of 2%.

4.2 Further monetary policy response to the pandemic shocks

I now show that analysis of the effectiveness of a given monetary policy expansion in response to the pandemic shocks is contingent upon the assumption of the price adjustment process. For this purpose, the monetary expansion is represented by a 1% monetary policy shock $\tilde{\varepsilon}_{M,t}$ in each of periods 2-4. The central bank is still assumed to follow the policy rule (22) throughout all periods. Hence, this exercise abstracts from other possible (unconventional) policy measures such as quantitative easing.[23] It also assumes away the possible coordinated fiscal and monetary policy response, given that the fiscal authority in the model is assumed to be passive (Leeper (1991)).

The results from this exercise are depicted in Figure 7 for both the SDP and TDP models. As expected, such a monetary expansion leads to larger exchange rate depreciations. These

[22] In this exercise, the foreign economy is implicitly assumed to be at the steady state, and hence, not affected by the COVID-19 pandemic. It is possible for the current account to deteriorate when this assumption is relaxed.

[23] As of this writing, Bank Indonesia has indeed committed to purchase around 574 trillion rupiah of sovereign bonds directly from the Indonesian government to help finance its fiscal response to the pandemic. To analyze the effect of such a measure, the model in this paper would need to be extended to include both short-term and long-term government bonds — see e.g. the model in Hohberger, Priftis and Vogel (2019).

depreciations appear to be of equal magnitude throughout all periods, irrespective of the pricing process assumption. The monetary expansion also mitigates the output contractions in both models. Quantitatively, however, the expansion would appear to be more effective when the analysis is conducted using the TDP model. Here, output only decreases by about 2.5% in period 2, compared to an almost 4% decrease in the same period when the monetary policy shocks are absent (Figure 6). Under SDP, the mitigating effect is less than 1%: instead of a 4% decrease, output decreases by 3.2% relative to the steady state. At the peak of the monetary expansion effect in period 4, output under TDP is almost back at its starting level. When the analysis is conducted using the SDP model, however, the analyst would find that output in period 4 (2020.Q4) would still be 1.5% *lower* relative to the starting value prior to the pandemic.

This disparity, again, can be explained by the dynamics of the extensive margin of price adjustments under SDP. Here, the further monetary stimuli cause a significant increase in the fraction of price-adjusting firms. In fact, at its peak in period 4, 20% more firms relative to that in period 0 decide to adjust (increase) their prices. This variation in the extensive margin leads to higher inflation rates under SDP and weakens the stimulating effect of the monetary expansion implied by the model. Assuming that the SDP model is closer to the true data generating process, an analyst using the TDP model to conduct the analysis might erroneously conclude that the current stimulus measures are enough, while in fact, further expansionary measures are potentially warranted.[24]

5 Conclusion

This paper studies the implications of state-dependent pricing in a small open-economy dynamic stochastic general equilibrium (DSGE) model for Indonesia. I show that variations in the timing and frequency of price adjustment inherent in a state-dependent pricing assumption could have important implications for DSGE model-based policy analysis in Indonesia. This extensive margin effect produces disparities in the conditional variance decompositions

[24] In a recent paper, Bhattacharyya (2019) compares the Bayesian estimation of the TDP model and SDP model in this paper based on Indonesian data from 2005.Q3-2017.Q1. He finds that the SDP model fits the data better, as evidenced by the higher marginal likelihood.

and the impulse responses to various shocks responsible for business cycle fluctuations. An investigation into the impact of COVID-19 pandemic shocks indicates that such variations non-trivially affect the analysis on the appropriate degree of monetary policy response to the shocks. The broader implication is clear. For modelling and analyzing the Indonesian economy, in which the inflation rates have historically been moderate-to-high and highly variable, state-dependent pricing is an essential model feature.

The findings in this paper imply that variations in the extensive margin may also impact upon forecasts generated by a DSGE model. Future research should look into whether the model's forecasting performance crucially depends on this model feature. It is also of interest to fully estimate the structural parameters of the model. While a calibration exercise is good enough for some purposes, including that of this paper, a (Bayesian) estimation of a DSGE model opens up various new possibilities for policy analysis. One could, for example, perform a more thorough analysis of the economic impact of the COVID-19 pandemic and the effectiveness of various alternative policy measures.

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Table 1: Calibration

Description	Parameter	Value
Inv. elas. of intertemporal substitution	σ	0.53
Subjective discount rate	β	0.99
Habit formation	h	0.03
Inverse Frisch elas. of labor supply	φ	2.02
Elas. of subs. domestic and imported goods	η	1.27
Frac. of consumption held in money	ν^h	0.38
Consumption share of foreign-produced goods	τ	0.20
Risk-premium shock parameter	χ	0.01
Index. to past inflation, importers	δ_F	0.21
Prob. of optimal price reset, importers	θ_F	0.41
Taylor rule, interest rate smoothing	ρ_i	0.75
Taylor rule, inflation	ψ_π	1.60
Taylor rule, output	ψ_y	0.12
Taylor rule, output growth	ψ_{Δ_y}	0.91
Taylor rule, nominal exchange rate	ψ_e	0.33
Autoregr. technology shock	ρ_a	0.59
Autoregr. preference shock	ρ_g	0.90
Autoregr. import cost-push shock	ρ_{cp}	0.93
Autoregr. risk-premium shock	ρ_ϕ	0.97
Autoregr. inflation-target shock	$\rho_{\bar{\pi}_*}$	0.995
Std. technology shock	σ_a	2.81
Std. preference shock	σ_g	0.39
Std. cosh-push shock	σ_{cp}	6.13
Std. MP shock	σ_M	0.78
Std. risk-premium shock	σ_ϕ	0.35
Std. foreign output shock	σ_{y^*}	0.62
Std. foreign inflation shock	σ_{π^*}	0.66
Std. foreign interest-rate shock	σ_{i^*}	0.11
Std. inflation-target shock	$\sigma_{\bar{\pi}^*}$	0.12
Long-run steady-state inflation target (% per year)	$400(\bar{\Pi} - 1)$	4

Notes: *(1)* The parameter values above are based on the posterior mean estimates in Lie (2019) for the model with a cash-in-advance (CIA) constraint; *(2)* for the calibration of the distribution of the fixed adjustment costs, see the main text.

Table 2: Conditional variance decompositions under TDP-Calvo

Horizon (quarters ahead)	Preference	Risk-premium	Technology	Import cost-push	Monetary policy	Inflation target	Foreign shocks
Inflation							
1	5.11	0	43.93	13.13	37.11	0.48	0.25
2	5.95	0.03	39.57	13.31	39.81	0.97	0.36
4	5.96	0.58	40.22	12.69	38.23	1.90	0.42
10	5.77	2.04	39.21	11.98	36.10	4.38	0.52
20	5.57	2.77	37.32	11.46	34.36	7.95	0.57
40	5.25	2.79	34.90	10.84	32.14	13.52	0.56
Nominal int. rate							
1	51.37	25.50	4.25	0.01	0.11	15.90	2.86
2	46.47	30.38	2.42	1.88	0.06	16.23	2.55
4	40.33	35.07	1.31	3.74	0.04	17.27	2.24
10	33.71	37.69	0.70	3.54	0.04	22.40	1.94
20	28.48	35.47	0.51	2.67	0.03	31.12	1.71
40	22.79	28.97	0.40	2.56	0.03	43.85	1.41
Output							
1	4.46	3.18	60.76	0.72	30.61	0.01	0.26
2	2.44	1.72	76.87	1.64	17.17	0.01	0.17
4	1.81	1.39	81.53	2.62	12.51	0	0.14
10	1.75	1.58	80.12	4.66	11.75	0	0.14
20	1.72	1.60	78.75	6.24	11.55	0	0.14
40	1.71	1.66	78.05	6.99	11.44	0	0.14

Notes: *(1)* Entries above are the conditional variance decompositions (in percentages) for the time-dependent pricing (TDP) model with a Calvo-pricing assumption; *(2)* the Calvo probability of price fixity for the domestic-goods sector θ_H is set to 0.59, equal to the posterior mean estimate in Lie (2018) —- all other parameter values are as in Table 1; *(3)* foreign shocks include foreign-output, foreign-inflation, and foreign interest-rate shocks.

Table 3: Conditional variance decompositions under TDP

Horizon (quarters ahead)	Preference	Risk-premium	Technology	Import cost-push	Monetary policy	Inflation target	Foreign shocks
Inflation							
1	5.51	0	41.29	13.41	38.93	0.59	0.28
2	6.19	0.13	37.20	13.95	41.10	1.05	0.38
4	6.33	0.65	37.22	13.40	39.95	1.99	0.45
10	6.08	2.30	36.34	12.6	37.56	4.55	0.56
20	5.87	3.08	34.51	12.02	35.66	8.24	0.61
40	5.51	3.08	32.20	11.35	33.28	13.98	0.60
Nominal int. rate							
1	50.90	26.73	3.54	0.03	0.13	15.73	2.93
2	46.06	31.23	2.08	2.00	0.08	15.95	2.60
4	39.93	35.80	1.13	3.87	0.06	16.94	2.28
10	33.31	38.46	0.60	3.64	0.04	21.98	1.97
20	28.20	36.23	0.44	2.75	0.04	30.60	1.75
40	22.63	29.67	0.34	2.64	0.03	43.24	1.44
Output							
1	4.35	3.28	60.33	0.72	31.07	0	0.26
2	2.56	1.96	74.64	1.84	18.82	0	0.18
4	1.90	1.49	79.77	3.11	13.58	0	0.14
10	1.85	1.50	78.10	5.72	12.68	0	0.15
20	1.82	1.48	76.57	7.56	12.43	0	0.14
40	1.81	1.59	75.83	8.32	12.31	0	0.14

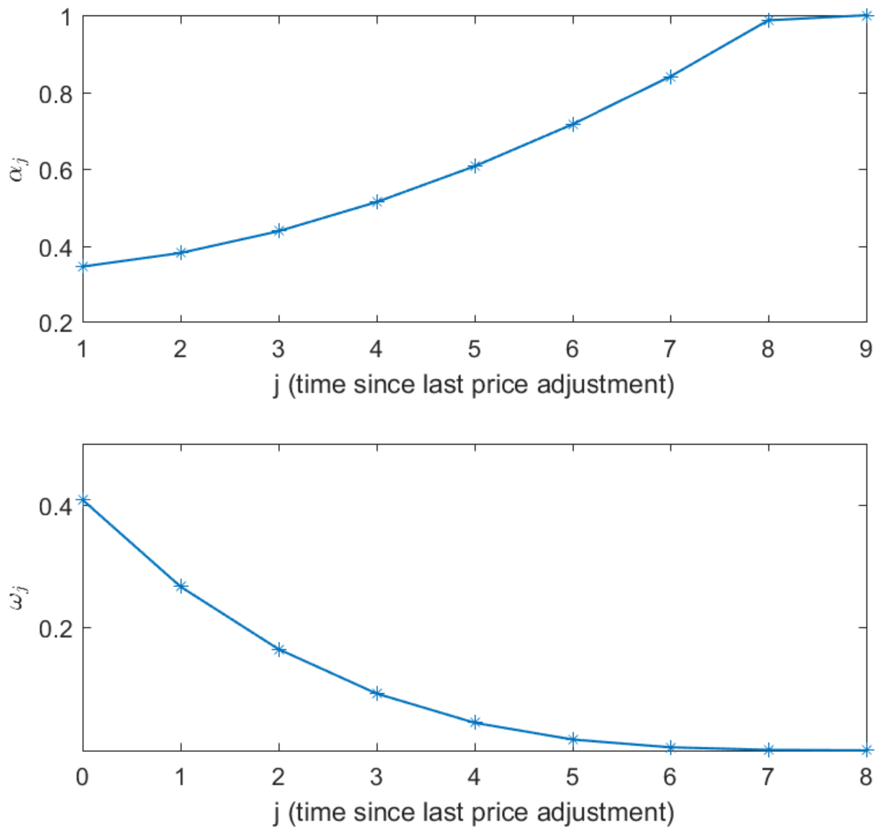
Notes: *(1)* Entries above are the conditional variance decompositions (in percentages) for the time-dependent pricing (TDP) model, based on the calibrated parameter values in Table 1; *(2)* foreign shocks include foreign-output, foreign-inflation, and foreign interest-rate shocks.

Table 4: Conditional variance decompositions under SDP

Horizon (quarters ahead)	Preference	Risk-premium	Technology	Import cost-push	Monetary policy	Inflation target	Foreign shocks
Inflation							
1	5.64	0.43	49.74	7.79	35.79	0.34	0.27
2	5.94	0.56	47.20	8.48	36.84	0.65	0.33
4	5.71	1.24	48.39	8.13	34.96	1.22	0.36
10	5.57	2.29	47.35	7.83	33.65	2.86	0.43
20	5.45	2.80	45.82	7.61	32.57	5.28	0.47
40	5.24	2.81	43.81	7.37	31.13	9.18	0.47
Nominal int. rate							
1	51.46	27.17	2.22	0.02	0.17	15.96	3.00
2	45.75	32.24	1.15	2.02	0.09	16.09	2.66
4	39.29	36.79	0.62	3.96	0.05	16.98	2.31
10	32.94	38.99	0.33	3.72	0.04	21.99	1.99
20	27.92	36.64	0.24	2.80	0.04	30.60	1.76
40	22.42	29.99	0.19	2.68	0.03	43.24	1.45
Output							
1	0.66	0.26	91.54	0.52	6.97	0	0.05
2	0.41	0.21	94.30	1.08	3.96	0	0.04
4	0.45	0.33	93.95	1.99	3.23	0	0.04
10	0.46	0.37	91.89	4.13	3.11	0	0.05
20	0.46	0.37	90.48	5.58	3.06	0	0.05
40	0.46	0.46	89.80	6.19	3.04	0	0.05

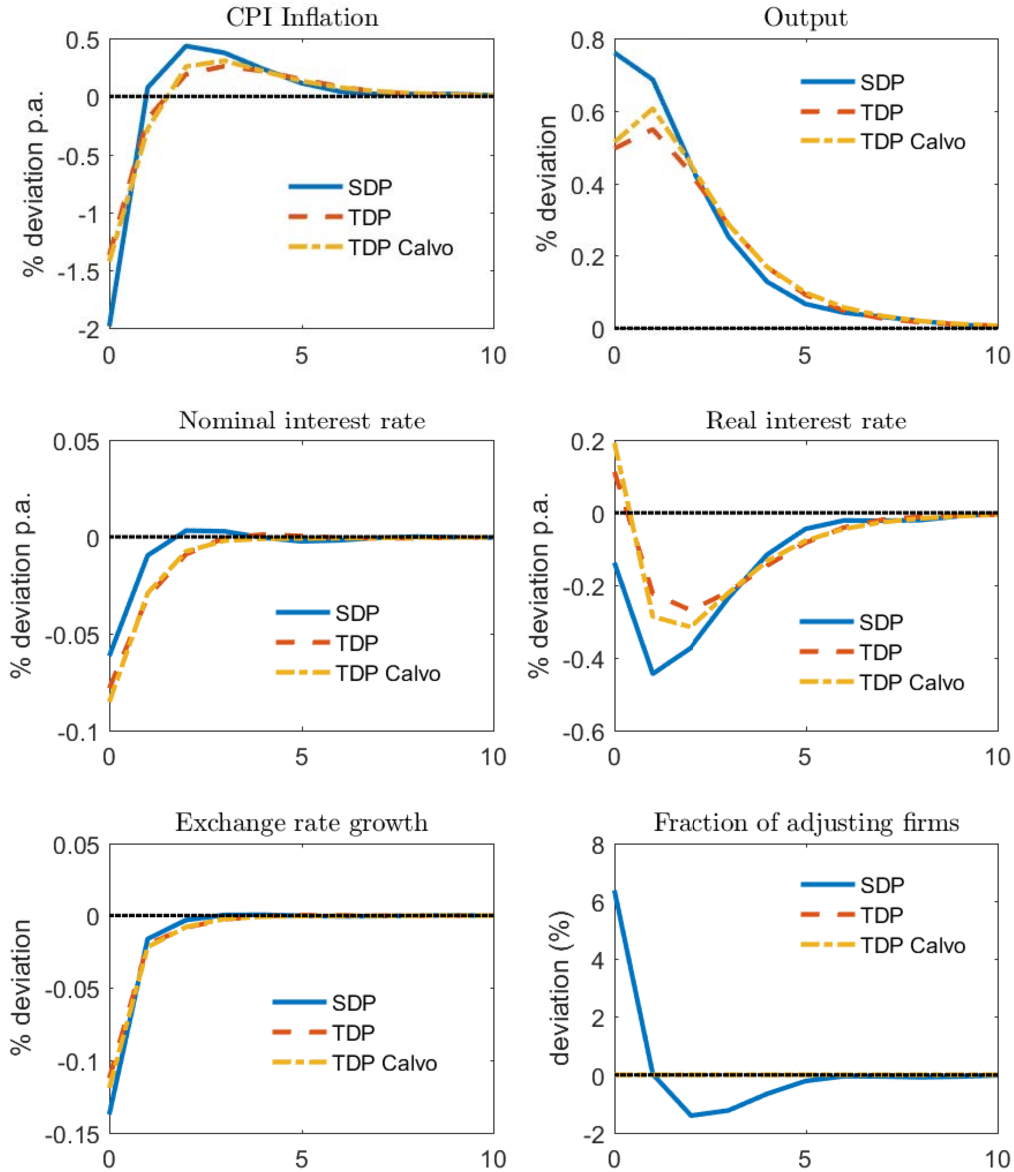
Notes: *(1)* Entries above are the conditional variance decompositions (in percentages) for the state-dependent pricing (SDP) model, based on the calibrated parameter values in Table 1; *(2)* foreign shocks include foreign-output, foreign-inflation, and foreign interest-rate shocks.

Figure 1: Steady-state probabilities and distribution of price adjustment



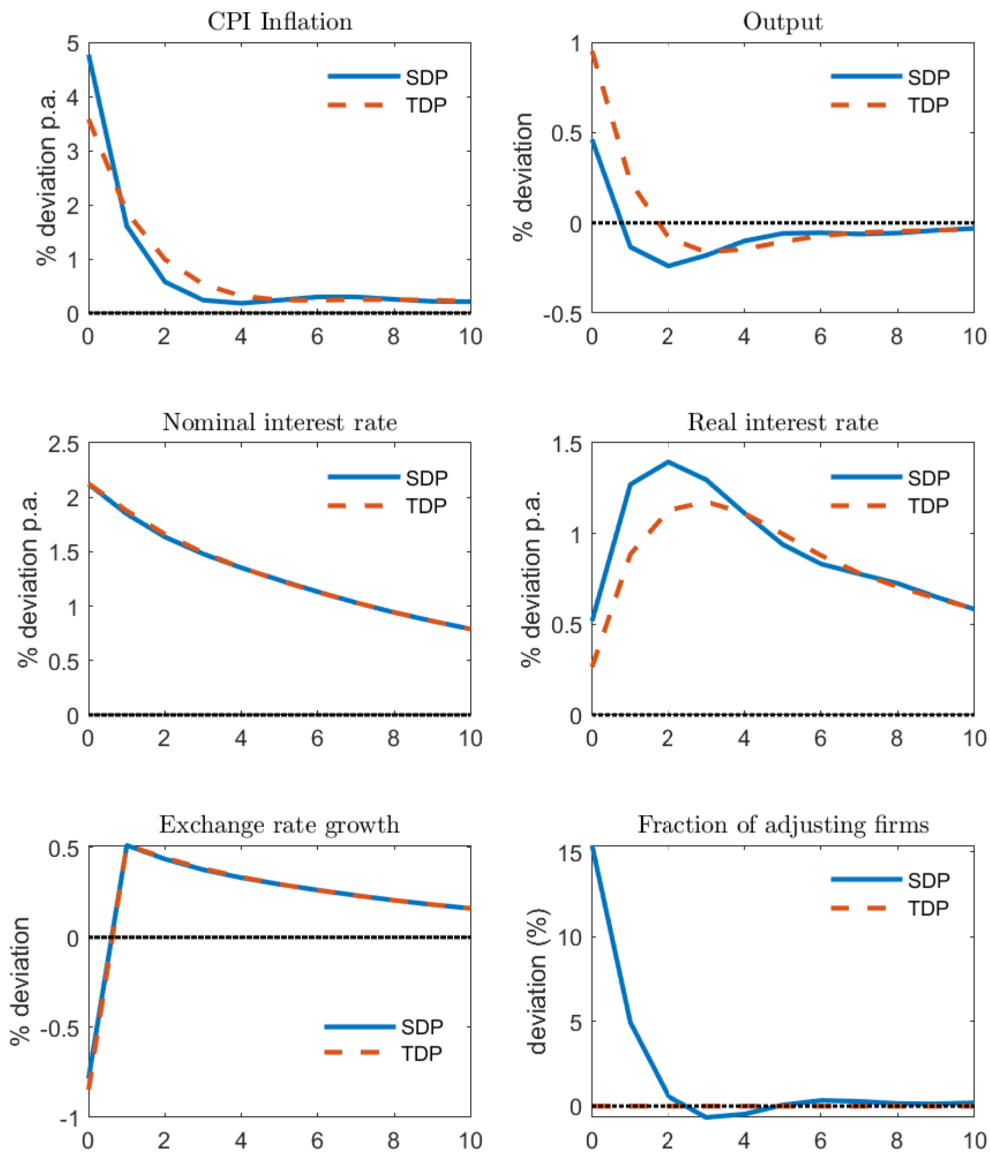
Notes: *(1)* the longest period of price fixity is $J = 9$; *(2)* the steady-state inflation rate is assumed to be 4% per year, equal to the long-run inflation target; *(3)* the horizontal (j) axis is in quarters.

Figure 2: Impulse responses to a technology shock



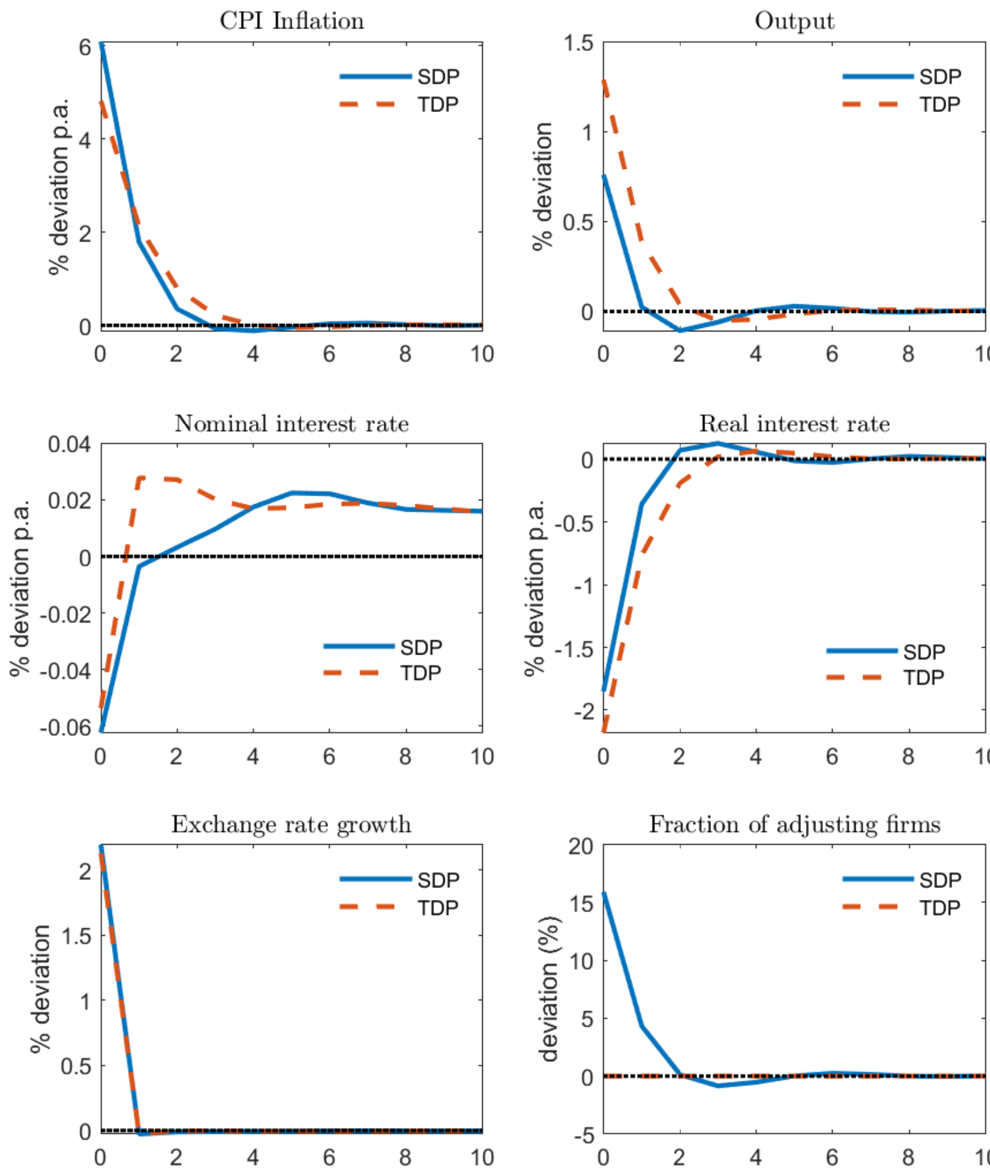
Notes: *(1)* The figure plots the impulse responses to a 1% technology shock $\eta_{a,t}$ under the SDP model (solid line), TDP model (dashed line), and TDP-Calvo model (dash-dotted line); *(2)* all three models are subject to the same exogenous technology process $\hat{\varepsilon}_{a,t} = \rho_a \hat{\varepsilon}_{a,t-1} + \eta_{a,t}$ (with $\rho_a = 0.59$) and are calibrated to have the same average duration of price fixity at the steady state; *(3)* all other parameter values are set as in Table 1.

Figure 3: Impulse responses to a preference shock



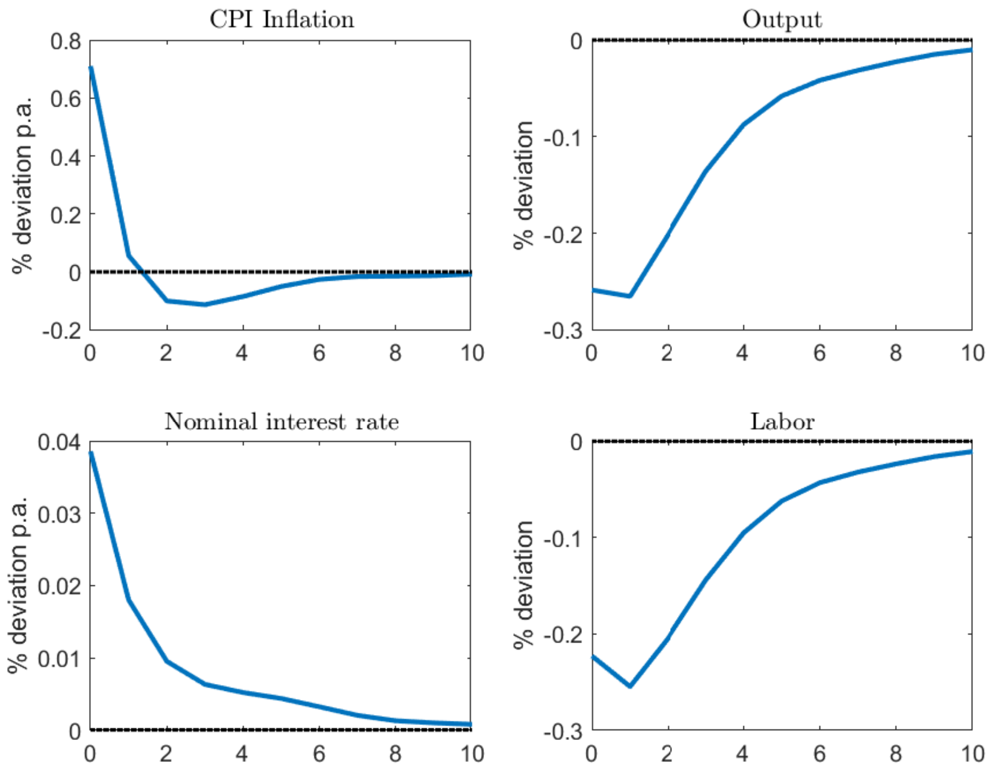
Notes: *(1)* The figure plots the impulse responses to a 1% preference shock $\eta_{g,t}$ under the SDP model (solid line) and TDP model (dashed line); *(2)* all three models are subject to the same exogenous preference process $\hat{\varepsilon}_{g,t} = \rho_g \hat{\varepsilon}_{g,t-1} + \eta_{g,t}$ (with $\rho_g = 0.9$) and are calibrated to have the same average duration of price fixity at the steady state; *(3)* all other parameter values are set as in Table 1.

Figure 4: Impulse responses to a monetary-policy shock



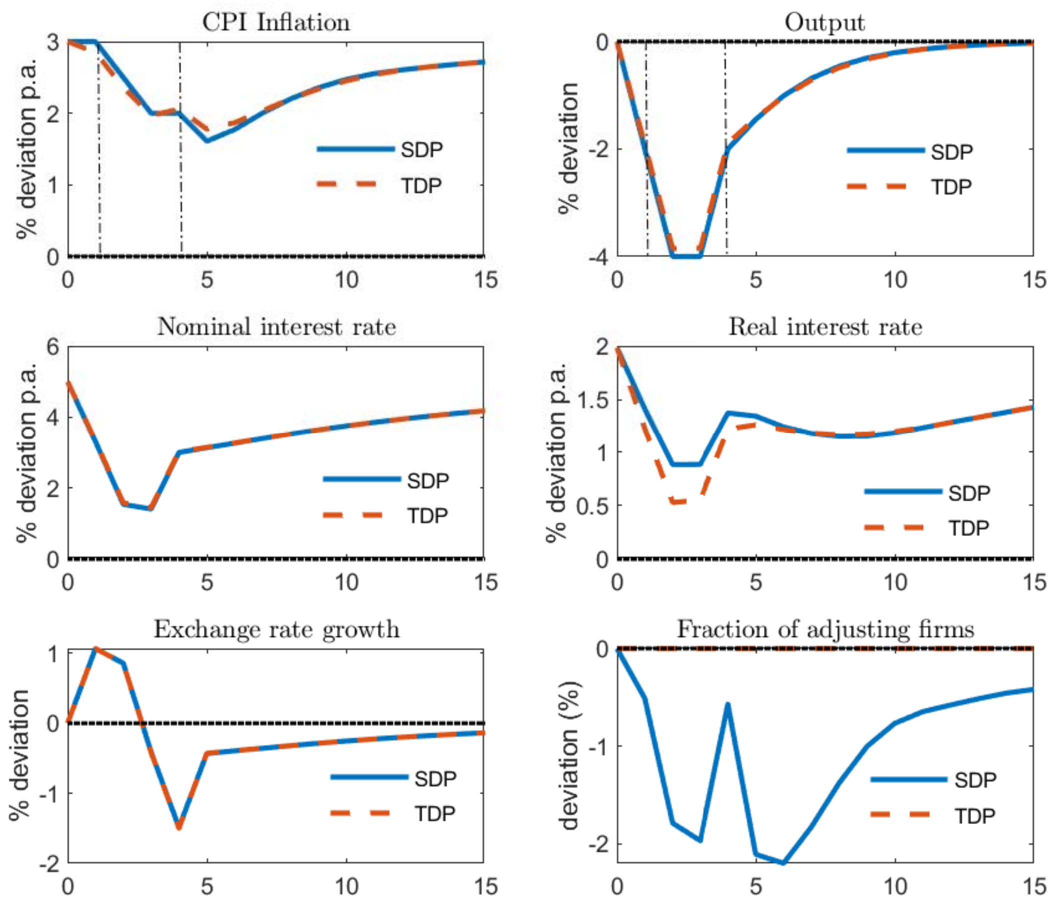
Notes: *(1)* The figure plots the impulse responses to a 1% (expansionary) monetary-policy shock $\tilde{\varepsilon}_{M,t}$ under the SDP model (solid line) and TDP model (dashed line); *(2)* all three models are subject to the same i.i.d. monetary-policy shock $\tilde{\varepsilon}_{M,t}$ and are calibrated to have the same average duration of price fixity at the steady state; *(3)* all other parameter values are set as in Table 1.

Figure 5: Impulse responses to a labor supply shock in the SDP model



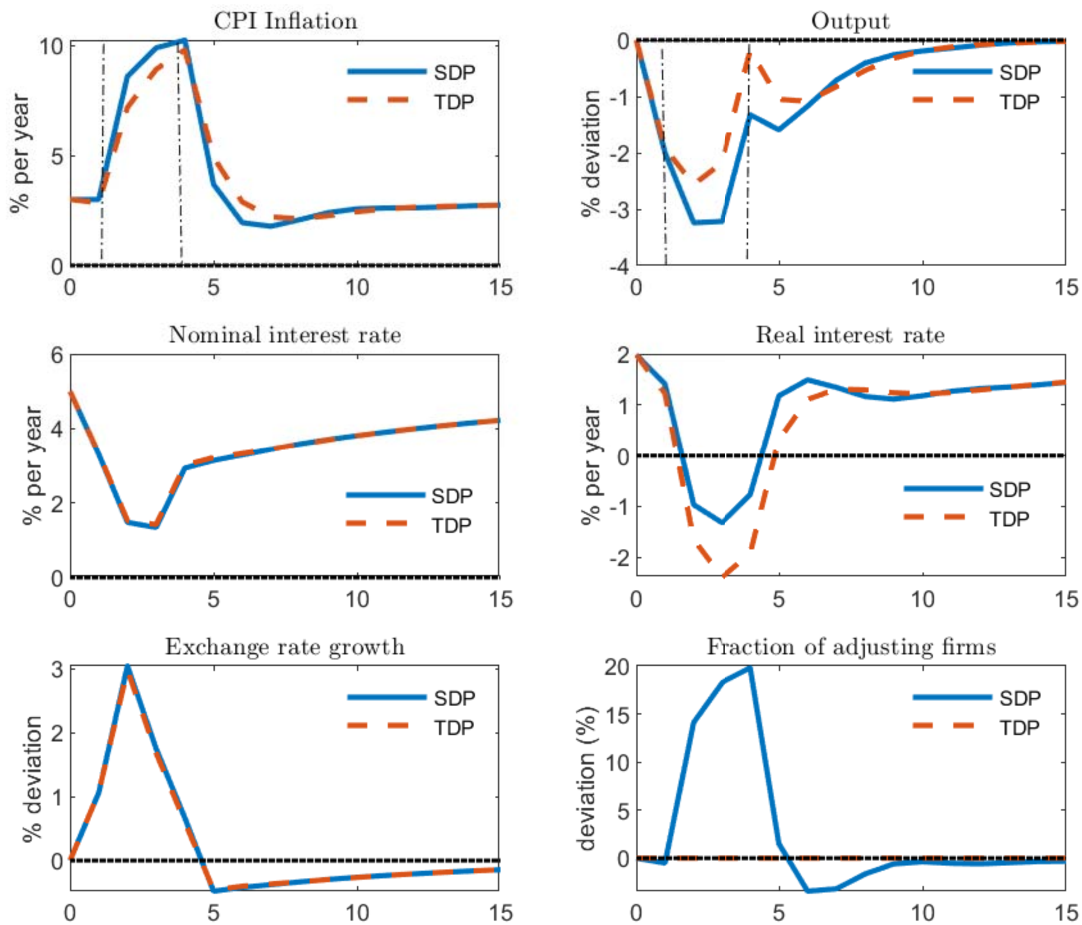
Notes: *(1)* The figure plots the impulse responses to a negative 1% labor supply shock $\eta_{s,t}$ under the SDP model; *(2)* the exogenous labor supply process follows $\hat{\varepsilon}_{s,t} = \rho_s \hat{\varepsilon}_{s,t-1} + \eta_{s,t}$, with $\rho_s = 0.7$; *(3)* all other parameter values are set as in Table 1.

Figure 6: Impact of COVID-19 pandemic shocks under SDP vs. TDP



Notes: *(1)* COVID-19 pandemic shocks are modelled as a combination of labor supply shocks and preference (spending) shocks; *(2)* the calibration of the timing and size of these shocks is described in the main text in Section 4.1.1; *(3)* the central bank is assumed to follow its normal conduct of monetary policy, represented by the Taylor-type rule in equation (22); *(4)* periods 0, 1, 2,... represent quarters and refer to 2019.Q4, 2020.Q1, 2020.Q2,..., respectively.

Figure 7: Monetary policy expansion and COVID-19 pandemic shocks under SDP vs. TDP



Notes: *(1)* Monetary expansion is modelled as a 1% monetary-policy shock $\tilde{\varepsilon}_{M,t}$, each in periods 2-4; *(2)* the central bank is still assumed to conduct policy according to the Taylor-type rule in equation (22); *(3)* COVID-19 pandemic shocks are modelled as a combination of labor supply shocks and preference (spending) shocks, with their timing and size described in Section 4.1.1; *(4)* periods 0, 1, 2,... represent quarters and refer to 2019.Q4, 2020.Q1, 2020.Q2,..., respectively; *(5)* plots for CPI inflation and nominal and real interest rates are now in level (% per year).