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Endogenous innovation under New Keynesian DSGE models

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Abstract

This paper constructs an endogenous growth model using the framework of New Keynesian dynamic stochastic general equilibrium models. We incorporate the Schumpeterian approach that generates seemingly sticky prices and reinterpret the Calvo mechanism from the perspective of Bertrand competition and successful entrepreneurs. Our results demonstrate that both positive productivity shocks and endogenous innovation have a negative effect on subsequent endogenous innovation. These self-destructive effects of endogenous innovation might account for the IT productivity paradox and productivity slowdown seen in advanced countries. Further, it is shown that there are both neutral and non-neutral properties of monetary policy shocks. They are neutral in terms of the growth effect, but non-neutral in terms of the level effect. In particular, expansionist monetary policies are desirable to facilitate endogenous innovation.

Keywords

Endogenous innovation, New Keynesian DSGE model, Calvo mechanism, Productivity shock, Monetary policy shock

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1. Introduction

The purpose of this paper is to incorporate an endogenous growth mechanism into a standard New Keynesian dynamic stochastic general equilibrium (DSGE) model and evaluate the effects of productivity shocks and monetary policy shocks on endogenous innovation, as well as other macroeconomic variables, including consumption, output, investment, interest rates, and factor prices. The standard endogenous growth literature (Segerstrom, Anant and Dinopoulos, 1990; Grossman and Helpman, 1991; Aghion-Howit, 1992) usually sticks to tractable models with closed-form solutions. Consequently, it does not necessarily pay sufficient attention to variables such as capital, investment, and monetary policy because the model becomes highly nonlinear once these variables are taken into account, making it impossible to derive closed-form solutions. This paper follows the Schumpeterian approach outlined in the endogenous growth literature, but differs in that the effects of technology and monetary policy shocks on endogenous innovation are evaluated in our model.

In contrast to the endogenous growth literature, real business cycle (RBC) models, starting with Kydland and Prescott (1982), resort to a linear approximation method and succeed in examining the business cycle properties that incorporate macroeconomic variables (see Cooley, 1995; Rebelo, 2005 for a review of this literature). However, their interest is primarily focused on business cycles generated by stochastic shocks in steady states, and less attention is paid to endogenous innovation and the resulting economic growth. The same approach is evident in the New Keynesian DSGE literature, which pays substantial attention to business cycles propagated by sticky prices and wages following the spirit of Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2003; 2007). The introduction of price and wage rigidities leads to significant improvement in replicating actual business fluctuations. However, the primary interest of these studies lies in business cycles in steady states, not in endogenous innovation.

In this respect, Phillips and Wrase (2006) provide an exception by incorporating Schumpeterian growth into a standard RBC model and examining how endogenous growth can generate realistic business cycles. However, because their model is primarily based on the RBC framework, market fictions such as price rigidities are not considered in their model. Consequently, the model is not sufficiently representative of the real-world business cycle. Thus, the difference between Phillips and Wrase (2006) and this paper lies in whether the Schumpeterian approach is applied to RBC or to New Keynesian models.

The introduction of an endogenous growth mechanism in this paper allows for an alternative interpretation of the Calvo mechanism (Calvo, 1983) widely adopted in the

New Keynesian models. Under this mechanism, a randomly selected proportion of firms are allowed to change their prices, while the remaining firms are not allowed to alter their prices. Although this mechanism is quite useful for generating sticky prices in the model, its micro-foundation has not been built, at least theoretically. Thus, it acts as a simplifying assumption rather than as the result of economic behavior.

This paper proposes an alternative interpretation of the Calvo mechanism by incorporating the Schumpeterian approach (Aghion and Howitt, 1998). Under this approach, all entrepreneurs undertake R&D activity, but only successful entrepreneurs are allowed to produce upgraded goods and set their prices. Unsuccessful entrepreneurs cannot produce competing goods at the equivalent price because they cannot obtain access to new technology. As a result, price rigidity prevails under Schumpeterian competition unless innovation takes place. This Schumpeterian competition provides the micro-foundation for the Calvo sticky price mechanism. In our model, price stickiness is not the result of various frictions in the economy. Rather, Schumpeterian competition brings about seemingly sticky prices without friction. The price-resetting probability in the Calvo mechanism corresponds to the innovation probability under Schumpeterian competition, which in turn is determined by R&D investment. We believe that this interpretation and model setting provides the micro-foundation for the Calvo mechanism.

In this paper, it is shown that monetary shocks have real effects without assuming any liquidity constraint on the part of consumers because they affect the amount of R&D investment, which in turn stochastically influences innovation. In particular, inflationary policies aimed at increasing the price level tend to face countervailing forces because at the same time they facilitate price-reducing innovation. Therefore, the policy effectiveness of inflation targeting is limited once endogenous innovation is incorporated into the model.

The rest of the paper is organized as follows. Section 2 describes our basic model and Section 3 presents a log-linearized system of equations. Section 4 presents a numerical evaluation of the effects of various shocks on innovation and other macroeconomic variables, and discusses policy implications primarily in terms of facilitating innovation. Section 5 concludes.

2. The model

In this section, we derive and present a standard linearized DSGE model by incorporating Schumpeterian entrepreneurs and endogenous innovation. Consider a discrete-time infinite-horizon economy populated by firms (Schumpeterian entrepreneurs and production firms) and infinitely lived households. Entrepreneurs undertake R&D activity, and once they succeed they produce differentiated intermediate goods. In this case, the previous production firm is replaced by the entrepreneur. Households consume and work.

The timing of information, shocks, and activities in this economy is as follows. Households begin period t with capital stock $(1-\delta)K_{t-1}$, where $0<\delta<1$ is the depreciation rate. They know the results of research undertaken by entrepreneurs in period $t-1$ and shock realizations at the beginning of the period. Factor and equity markets open and clear. Production firms (intermediate producers) rent capital and hire labor from households. Entrepreneurs also hire labor from households to undertake research. To finance this research, entrepreneurs issue equity shares in the current period. If they succeed in innovation, these shares are taken over in the next period as those of production firms. Following input and funding acquisitions, production and research takes place. Intermediate products are purchased and assembled by final goods firms. When these activities are complete, factor payments are made and the profits of production firms are distributed to shareholders. In addition, capital investment is made by the households to make new capital goods. The households carry over the capital in the next period. At the end of the period, research results and random shocks are revealed.

Now let us turn to decisions made by households, final goods firms, intermediate producers, capital producers, entrepreneurs, and the government.

2.1 Households

Households maximize a lifetime utility function given by

$$E_t \sum_{i=0}^{\infty} \beta^t \left[\frac{\left(C_t - hC_{t-1}\right)^{1-\sigma}}{1-\sigma} - \frac{A_t^{1-\sigma} L_t^{1+\eta}}{1+\eta} - \frac{A_t^{1-\sigma} N_t^{1+\xi}}{1+\xi} \right], \tag{1}$$

where E_t is the expectation operator conditional on all information available in period t, and $0<\beta<1$ is the discount factor. The utility is positively related to the consumption of goods relative to an external habit variable h, and negatively related to total hours of work required for the production of goods L_t and total hours of work required for R&D activity N_t. The total hours of work should be less than the upper limit $\bar{L}$ so that $L_t + N_t < \bar{L}$ holds. $A_t^{\sigma-1}$ is added here to ensure a balanced growth in the economy where A_t denotes total productivity, which is specified later.

The maximization is subject to the following sequence of budget constraints:

$$\begin{aligned} & P_t\left(C_t+I_I\right)+\frac{B_{t+1}}{R_t}=W_t\left(L_t+N_t\right)+Z_tU_tK_t-P_tK_t\left[\Psi_1\left(U_t-1\right)+\frac{\Psi_2}{2}\left(U_t-1\right)^2\right] \\ & +B_t+\Pi_t+\int_{i\in success} P^P_{i,t}Q^R_{i,t-1}di+\int_{i\in fail} P^P_{i,t}Q^P_{i,t-1}di-\int P^R_{i,t}Q^R_{i,t}di-\int P^P_{i,t}Q^P_{i,t}di, \end{aligned} \tag{2}$$

with the law of motion of capital

$$K_{t+1}=\left(1-\delta\right)K_t+I_t\left[1-\frac{\chi}{2}\left(\frac{I_t}{I_{t-1}}-1\right)^2\right], \tag{3}$$

where P_t is the general price level, I_t is the gross investment in capital, R_t is the nominal interest rate on bond holdings B_{t+1} between period t and period $t+1$, and W_t is the wage rate. Z_t is the return on capital, U_t denotes the rate of utilization of capital stock K_t, and the term in the bracket $\Psi_1\left(U_t-1\right)+\frac{\Psi_2}{2}\left(U_t-1\right)^2$ measures the cost of underutilization with Ψ_1 and $\Psi_2>0$. Thus, following Christian, Eichenbaum, and Evans (2005) and Smets and Wouters (2003), we incorporate the convex friction costs associated with variations in the use of the installed capacity. δ is the depreciation rate of capital.

The households own the stocks of equity shares of production firms and entrepreneurs from the previous period. After observing all relevant prices and the probabilities of successful innovation by the current entrepreneurs, households choose the amount of equity shares to hold until the next period, when the results of research are known by households. Thus, in terms of the budget constraint, $P^R_{i,t}$ and $Q^R_{i,t+1}$ are the price and quantity, respectively, of equity shares issued by entrepreneurs undertaking innovation in the i th sector. These shares are purchased by households, whose proceeds in turn are used by entrepreneurs to hire R&D labor N_t. This implies that $W_t N_t = \sum_i P_{i,t}^R Q_{i,t+1}^R$ holds in equilibrium. The dividends on equity shares held by the household in the previous period amount to successful entrepreneurs' profits Π_t in the current period. $P_{i,t}^P$ and $Q_{i,t+1}^P$ are the price and quantity, respectively, of equity shares issued by the production firm in the ith sector. Therefore, if the entrepreneur succeeds in innovation, the equity shares of the production firm in the corresponding sector will not pay dividends in the next period. However, if the entrepreneur fails in innovation, the production firm will pay dividends in the next period.

The law of motion of capital incorporates adjustment costs, denoted by the bracket on the right-hand side of (3), and δ is the depreciation rate of capital.

The first-order conditions associated with the household problem with respect to C_t, L_t, N_t, K_t, U_t, I_t, B_{t+1}, Q_{t+1}^R, and Q_{t+1}^P yield

$$\Gamma_t = \frac{\left(C_t - hC_{t-1}\right)^{-\sigma}}{P_t} - h\beta E_t \frac{\left(C_{t+1} - hC_t\right)^{-\sigma}}{P_t}, \tag{4}$$

$$A_t^{1-\sigma} L_t^{\varphi} = A_t^{1-\sigma} N_t^{\xi} = \Gamma_t W_t, \tag{5}$$

$$Q_t = \beta E_t \left\{ Q_{t+1}\left(1-\delta\right) + \Gamma_{t+1} Z_{t+1} U_{t+1} - \Gamma_{t+1} P_{t+1} \left[\Psi_1 \left(U_{t+1} - 1\right) + \frac{\Psi_2}{2}\left(U_{t+1} - 1\right)^2 \right] \right\}, \tag{6}$$

$$\frac{Z_t}{P_t} = \Psi_1 + \Psi_2 \left(U_{t+1} - 1\right)^2, \tag{7}$$

$$\Gamma_t P_t - Q_t \left[1 - \frac{\chi}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2 - \chi \frac{I_t}{I_{t-1}}\left(\frac{I_t}{I_{t-1}} - 1\right) \right] = \chi\beta E_t \left[Q_{t+1} \left(\frac{I_{t+1}}{I_t}\right)^2 \left(\frac{I_{t+1}}{I_t} - 1\right) \right] \tag{8}$$

$$\frac{\Gamma_t}{R_t} = \beta E_t \Gamma_{t+1} \tag{9}$$

$$E_t \left(1-\omega\right)\beta \left[\frac{\Gamma_{t+1}}{\Gamma_t} \frac{\Pi_{t+1} + P_{i,t+1}^P}{P_{i,t}^R} \right] = 1, \tag{10}$$

$$E_t \omega \beta \left[\frac{\Gamma_{t+1}}{\Gamma_t} \frac{\Pi_{t+1} + P^P_{i,t+1}}{P^P_{i,t}} \right] = 1, \tag{11}$$

where Γ_t denotes the Lagrange multiplier and Q_t corresponds to Tobin's Q, which measures the price of capital to be purchased from capital producers in this model.

2.2 Final goods firms

Firms in the final goods sector produces a homogenous good, Y_t, using intermediate goods, $Y_{i,t}$, $i \in [0,1]$, according to the Dixit–Stiglitz aggregate defined by

$$Y_t = \left[\int_0^1 Y_{i,t}^{(\varepsilon-1)/\varepsilon} di \right]^{\varepsilon/(\varepsilon-1)}, \tag{12}$$

where $\varepsilon > 1$ is the elasticity of substitution between intermediate goods. This production function exhibits constant returns to scale, diminishing marginal product, and constant elasticity of substitution. We assume that this sector is competitive, so that final goods firms take the price of the intermediate good $Y_{i,t}$ in period t, $P_{t,i}$, as given.

Cost minimization by final goods firms and households implies that demand for each good in period t can be written as

$$Y_{i,t} = \left(\frac{P_{i,t}}{P_t} \right)^{-\varepsilon} Y_t, \tag{13}$$

where $P_t \equiv \left(\int_0^1 P_{i,t}^{1-\varepsilon} \right)^{1/1-\varepsilon}$ denotes the aggregate price index in period t.

2.3 Intermediate goods producers

There is a continuum of monopolistically competitive firms owned by consumers, indexed by $i \in [0,1]$. Each intermediate producer faces the demand curve shown in (13) for its product and produces a differentiated good according to the following production function:

$$Y_{i,t} = S_t^a K_{i,t}^{1-\alpha} \left(A_{i,t} L_{i,t} \right)^{\alpha}, \tag{14}$$

where S_t^a is the exogenous productivity shock that takes place at the beginning of period t as follows:

$$\ln S_t^a = \left(1-\rho_a\right) \ln \bar{S}^a + \rho_a \ln S_{t-1}^a + \varepsilon_t^a, \tag{15}$$

where $\varepsilon_t^a \sim N\left(0, \sigma_a^2\right)$. $A_{i,t}$ denotes the productivity level for good i. Capital is freely mobile across firms. Firms rent capital from households in a competitive market in each period.

We assume that Schumpeterian entrepreneurs undertake R&D activity and when they succeed, they set a price that maximizes innovation rents. Thus, productivity evolves over time according to

$$A_{i,t}^{\alpha} = \begin{cases} \lambda A_{i,t-1}^{\alpha} & \textit{if succeeds in innovation,} \\ A_{i,t-1}^{\alpha} & \textit{otherwise,} \end{cases}$$

where $\lambda > 1$ is the magnitude of innovation in the intermediate good i. This specification follows the standard Schumpeterian model in the endogenous growth literature.

The factor demands for labor and capital and real marginal costs are determined by

$$\frac{W_t}{\alpha Y_{i,t} / L_{i,t}} = MC_{i,t}^{*\ell}, \tag{16}$$

$$\frac{Z_t}{(1-\alpha) Y_{i,t} / U_{i,t} K_{i,t}} = MC_{i,t}^{*\ell}, \tag{17}$$

$$MC_{i,t}^{*\ell} = \frac{1}{S_t^a A_{i,t}^{\ell}} \left(\frac{W_t}{\alpha} \right)^{\alpha} \left(\frac{Z_t}{1-\alpha} \right)^{1-\alpha}, \tag{18}$$

where * indicates the *real* marginal cost and $\ell = F, S$. The superscripts F and S emphasize the failure and success of innovation, respectively. Since the firm takes factor prices as given, the real marginal cost is constant at the firm level. Constant marginal cost is an outcome of constant returns to scale and perfect factor mobility.

2.4 Optimal price setting

Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2003, 2007) incorporate a number of frictions that appear to be necessary to replicate the empirical persistence of real macroeconomic data. In particular, sticky nominal prices that adjust in response to a Calvo mechanism play a critical role in creating sufficient inertia in inflation. Under this mechanism, a randomly selected proportion of firms are allowed to change their prices, while the remaining firms are not prohibited from altering their prices. Then, the selected firm maximizes the sum of expected future streams of profits. In this paper, only successful entrepreneurs can change their prices because they succeed in innovation with cost advantage over unsuccessful entrepreneurs. The innovation probability is determined as the result of R&D investment. Thus, the exogenous price-resetting probability in the Calvo mechanism corresponds to the endogenous innovation probability under Schumpeterian competition in our model.

Suppose an entrepreneur succeeds in innovating in relation to good i. The successful entrepreneur turns into a production firm at the beginning of period t, setting the price as follows:

$$\max_{P_{i,t}^S} E_t \sum_{j=0}^{\infty} (\beta\omega)^j V_{t,t+j} \left[\frac{P_{i,t}^S}{P_{t+j}} Y_{i,t+j} - \frac{MC_{i,t+j|t}^S}{P_{t+j}} Y_{i,t+j} \right], \tag{19}$$

subject to the sequence of demand constraints (13), where S denotes the success of innovation, $1-\omega$ is the probability of innovation in period t, which will be specified later, and $V_{t,t+j} \equiv \Gamma_{t+j} / \Gamma_t$ is the ratio of the marginal utility of consumption in period

$t+j$ to the marginal utility in period t, and $MC^S_{i,t+j|t}$ is the nominal marginal cost in period $t+j$ for the firm whose price was last set in period t. The firm takes as given the paths of $MC_{i,t+j|t}$, Y_{t+j}, and P_{t+j}. The first-order condition yields

$$P_t^S = (1+\mu)\frac{E_t\sum_{j=0}^{\infty}(\beta\omega)^j V_{t,t+j}\dfrac{MC^S_{i,t+j|t}}{P_{t+j}}Y_{i,t+j}}{E_t\sum_{j=0}^{\infty}(\beta\omega)^j V_{t,t+j}\dfrac{Y_{i,t+j}}{P_{t+j}}}, \qquad (20)$$

where $1+\mu=\dfrac{1}{1-1/\varepsilon}$ is the steady-state gross markup. Log-linearizing and rearranging this equation gives

$$\hat{P}_t^S = (1-\beta\omega)E_t\sum_{j=0}^{\infty}(\beta\omega)^j \hat{M}C^S_{i,t+j|t}, \qquad (21)$$

where a hat on a variable denotes the logarithmic deviation of the original variable with respect to its steady-state value. That is, $\hat{X}_t = \ln X_t - \ln X$. Thus, the firm sets the price that corresponds to a weighted average of its current and expected nominal marginal costs, with the weights being proportional to the probability of no innovation by rival entrepreneurs. To justify this pricing rule, we assume that the magnitude of innovation λ is sufficiently high such that $P^S_{i,t} < MC_{i,t+j|t-1}$ holds for $j \geq 0$. Hence, the optimal price blocks unsuccessful competitors from production.

2.5 Entrepreneurs

A Schumpeterian entrepreneur springs into existence in each intermediate good sector in each period. The entrepreneur issues equity shares $Q^R_{i,t+1}$ and uses the proceeds to hire labor. The result of R&D investment emerges at the end of the period, and can be exploited in the next period. Taking $P^R_{i,t}$, $Q^R_{i,t+1}$, W_t, and Z_t as fixed, the entrepreneur demands R&D labor in period t to maximize the expected gains from innovation as follows:

$$\left(1-\omega_t\right)E_t\beta V_{t,t+1}\left[\Pi_{i,t+1}+P^P_{i,t+1}\right]-W_tN_{i,t}, \tag{22}$$

subject to $W_tN_{i,t} \le P^R_{i,t}Q^R_{i,t+1}$, where $1-\omega_t$ denotes the probability that the entrepreneur innovates successfully in period t. We assume that the innovation probability is proportional to R&D investment as follows:

$$1-\omega_t = \kappa N_{i,t}, \tag{23}$$

where κ is sufficiently large to induce R&D investment. Then, constant returns imply that the size distribution of entrepreneurs is irrelevant. Hence, we can simply assume that only one entrepreneur exists for each intermediate good sector. As a result, the solution to the problem is to hire as many R&D labor hours as the entrepreneur can afford given the constraint of $W_tN_{i,t} \le P^R_{i,t}Q^R_{i,t+1}$. Hence, $P^R_{i,t}Q^R_{i,t+1} = W_tN_{i,t}$ holds for each entrepreneur in the intermediate goods sectors. Because of the symmetry condition, $N_{i,t}$ is the same across the sectors. Moreover, ω remain constant over time in the steady state. Thus, we have $\omega_{i,t} = \omega$, so that the aggregated endogenous productivity growth is given by

$$\hat{A}_t \equiv \int \hat{A}_{i,t}di = \left(1-\omega\right)\lambda. \tag{24}$$

In addition, the exogenous productivity shock generates the productivity growth rate. Thus, total productivity growth consists of an endogenous part ($\left(1-\omega\right)\lambda$) and an exogenous part (S^a_t).

2.6 The government

The monetary authority sets the nominal interest rate using the Taylor rule (Taylor, 1993)

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\ell_R} \left[\left(\frac{\pi_t}{\pi}\right)^{\ell_\pi} \left(\frac{Y_t}{Y}\right)^{\ell_y}\right]^{1-\ell_R} S_t^m, \tag{25}$$

where $\pi_t = p_t / p_{t-1}$, and R, π, and Y are the steady-state values of R_t, π_t, Y_t, respectively. S_t^m is the monetary shock represented by

$$\ln S_t^m = (1-\rho_m)\ln S^m + \rho_m \ln S_{t-1}^m + \varepsilon_t^m, \tag{26}$$

where $\varepsilon_t^m \sim N\left(0, \sigma_r^2\right)$.

We assume that the government cannot obtain funds through seigniorage. The government's budget constraint is therefore given by

$$\frac{B_{t+1}}{R_t} = B_t. \tag{27}$$

2.7 Market equilibrium

The final goods market is in equilibrium if production is equal to the sum of consumption and investment:

$$Y_t = C_t + I_t. \tag{28}$$

3. The log-linearized model

In this model, consumption, investment, capital, and output fluctuate around a stochastic growth path as a result of endogenous innovation. To make the steady state analysis, we need to detrend relevant variables so that all endogenous variables are stationary. Then, we log-linearize the system of equations and make simulation analysis.

3.1 Detrended model

The model in this paper allows for a balanced growth in output and consumption per household due to endogenous innovation. Accordingly, we transform the relevant variables as $y_t \equiv Y_t / A_t$, $c_t \equiv C_t / A_t$, $k_t \equiv K_t / A_t$, $i_t \equiv I_t / A_t$, $g_t \equiv G_t / A_t$, $p_t \equiv A_t^{1-\sigma} P_t$, $\gamma_t \equiv A_t^{2\sigma-1} \Gamma_t$, $q_t \equiv A_t^{\sigma} Q_t$, $z_t \equiv A_t^{1-\sigma} Z_t$, $w_t \equiv W_t / A_t^{\sigma}$, $p_t^P \equiv A_t^{1-\sigma} P_{i,t}^P$, $p_t^R \equiv A_t^{1-\sigma} P_{i,t}^R$, $mc_{i,t}^{\ell} = A_t^{1-\sigma} MC_{i,t}^{\ell}$, $\pi_t^* \equiv A_t^{1-\sigma} \Pi_t$, $b_t \equiv B_t / A_t^{\sigma}$, $tr_t \equiv Tr_t / A_t$, $\tau_t = T_t / A_t^{\sigma}$. We express all of the stationary endogenous variables in lowercase letters below.

3.2 Log-linearization

Before deriving the log-linearized system, we need to aggregate sector-specific variables over all of the intermediate sectors. We define these aggregated variables as $y_t \equiv \int y_{i,t} di$, $k_t \equiv \int k_{i,t} di$, $n_t \equiv \int n_{i,t} di$, $l_t \equiv \int l_{i,t} di$, $mc_t \equiv \int mc_{i,t}^{\ell} di$, and $A_t \equiv \int A_{i,t}^{\ell} di$. Using a property such as $\hat{y}_t = \sum_i \hat{y}_{i,t}$ and local approximation methods (Uhlig, 1995), we log-linearizing the above conditions. These transformed equations and corresponding steady state values are reported in Appendices A and B, respectively.

It should also be noted here that since the marginal costs are detrended, all of the transformed marginal costs are the same across intermediate goods sectors. Even if $A_t \neq A_{i,t}^{\ell}$, their expected growth rates should coincide such that $\hat{A}_t = E_t \hat{A}_{i,t}^{\ell}$ due to the same amount of R&D investment across entrepreneurs and the law of large numbers[1]. Hence, $\hat{m}c_t^S = \hat{m}c_{i,t}^F = \hat{m}c_t$ holds in the steady state.

The remaining condition is a New Keynesian Phillips curve. Detrending and quasi-differencing (21) gives

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[1] Note that producers have no incentive to make R&D investment because the next innovation damages current profits. Thus, only currently unsuccessful entrepreneurs make R&D investment.

$$\hat{p}_t^S = (1-\beta\omega)\,\hat{mc}_t + \beta\omega E\hat{p}_{t+1}^S. \tag{29}$$

In the intermediate goods sectors, $1-\omega$ entrepreneurs succeed in innovation and set the same price, while the remaining fraction ω of unsuccessful entrepreneurs do not change their price. Thus, the average price of the unsuccessful entrepreneurs is equivalent to the average price in the previous period such that

$$\hat{p}_t^F = \hat{p}_{t-1}. \tag{30}$$

Therefore, the aggregate price index in period t satisfies

$$\hat{p}_t = (1-\omega)\,\hat{p}_t^S + \omega\hat{p}_{t-1}, \tag{31}$$

which can also be transformed as

$$\hat{p}_t^S - \hat{p}_{t-1} = \frac{\hat{\pi}_t}{1-\omega}, \tag{32}$$

where

$$\hat{\pi}_t = \hat{p}_t - \hat{p}_{t-1}. \tag{33}$$

Substituting (32) into (29) yields

$$\hat{\pi}_t = \frac{(1-\omega)(1-\beta\omega)}{\omega}\left(\hat{mc}_t - \hat{p}_t\right) + \beta\hat{\pi}_{t+1}. \tag{34}$$

Both (33) and (34) are added in Appendix A. Therefore, the log-linearized equilibrium system consists of (A1)~(A19) with 19 endogenous variables.

4. Calibration and simulation

4.1 Calibration

In this section, we present a numerical analysis of the model. We calibrate the model by choosing values that are predominant in the literature wherever possible. Most of the model specification in this paper is similar to that used in New Keynesian models, except for R&D employment and equity prices. Hence, we refrain from estimating the model and characterizing business cycle properties in detail because these aspects have been studied extensively in the related literature. Instead, we conduct a numerical analysis primarily to evaluate the effects of exogenous shocks on endogenous innovation and, in turn, the effects of endogenous innovation on other macroeconomic variables.

The list of parameter values used in the calibration is shown in Table 1. Most of the parameter values are adopted from Costa (2016), but $1-\omega$ is relatively new to the literature. This value is chosen to yield an annual growth rate of roughly 2.5 percent. That is, $\omega = 0.975$. As for the marginal disutility with regard to the supply of R&D labor ξ, we set $\xi = 2.5$, a value that is slightly higher than the marginal disutility with regard to the supply of labor, $\eta = 1.5$. It should be noted that we also undertook sensitivity analyses with respect to these two parameters, but the results presented below remained unchanged and robust to various values of ω and η.

(Table 1)

4.2 Simulation

We now turn to a numerical analysis of the model. First, we calculate impulse response functions to two exogenous shocks: productivity shocks (ε_t^a) and monetary policy shocks (ε_t^m). The effects of these shocks on endogenous innovation can be evaluated by examining the changes in N_t, which primarily determine the probability of innovation and growth in the economy.

4.2.1 Effects of productivity shocks

The first experiment we consider is a one-time shock to productivity. Figure 1 shows the effect of such a shock on the relevant macroeconomic variables. It can be seen that this productivity shock causes the values of the marginal products of both labor and capital to rise. Thus, firms increase their demand for labor and capital, which in turn results in higher wages and rental prices. While an increase in household income leads to greater consumption and thus a greater output of final goods, it also increases the demand for leisure as a result of the income effect. The fall in labor supply accounts for the higher resistance of wages to a return to the steady state, whereas rental prices decrease to a point below the initial steady-state level. This result stands in sharp contrast to the learning-by-doing mechanism seen in the RBC literature (Cooper and Johri, 1997, 2002; Change, Gomes, and Schorfheide, 2002; Gunn and Johri, 2011; Hung and Wu, 2012). That mechanism suggests that a positive productivity shock increases both labor and capital investment, which in turn leads to a rise in intangible capital in the subsequent period through a learning-by-doing process. As a result, the shock is amplified, increasing both investment and labor supply. However, our model suggests that while investment increases, labor supply decreases in favor of leisure.

(Figure 1)

Thus, higher productivity leads to increases in output, consumption, investment, and input prices, while labor supply and wages fall below their initial levels. The latter pattern also applies to R&D labor. Consequently, productivity shocks slow endogenous innovation over the long term because the income effect dominates the substitution effect. This result might also provide a theoretical explanation for the productivity paradox relating to information technology (IT) (Loveman: 1988; Berndt, Morrison and Rosenblum: 1992; Morrison and Berndt: 1991) whereby the IT contribution is unrelated to the productivity growth found in empirical studies. IT obviously improves the productivity level; however, the positive productivity shocks enabled by IT innovation cause a decrease in R&D investment via the income effect, and as a result, the endogenous growth rate declines.

Moreover, these productivity shocks could be regarded as the result of endogenous innovation. Although this simulation rules out the effects of endogenous growth, when the next generation of innovation arrives, it has a positive effect on the productivity level. Hence, exogenous productivity shocks play exactly the same role as endogenous innovation in this model in terms of their effects on macroeconomic variables. Therefore, constant economic growth cannot be expected because the results of endogenous innovation have a negative effect on subsequent innovation. Thus, the economic growth rate is likely to decrease over time, which might also account for the productivity slowdown commonly observed in advanced countries after a period of high economic growth.

4.2.2 Effects of monetary policy shocks

Next, we examine the effects of monetary policy shocks. Figure 2 shows their effects on relevant macroeconomic variables. The expansionist monetary shock reduces the interest rate R, which raises the price of public bonds and reduces the demand for them. This fall in demand is offset by simultaneous rises in household consumption and savings (investment). Although capital income rises as a result of the increase in rental prices, net wealth declines as a result of the high price of bonds.

(Figure 2)

Consequently, households supply more labor as a result of the income effect, but a greater labor supply leads to a fall in wages. Hence, in contrast to the productivity shock, expansionist monetary shocks increase the R&D labor supply. This implies that more endogenous innovation is facilitated during these periods of greater labor supply. Note that endogenous innovation in our model leads to a fall in price levels. Low interest rate policies are usually adopted to boost inflation. However, countervailing forces take effect in opposition to inflationary pressures via endogenous innovation. As a result, the policy effectiveness of boosting inflation turns out to be limited.

Of course, R&D labor supply eventually returns to the initial state. However, the fact that there is more R&D investment and endogenous innovation is facilitated suggests that monetary policy shocks have a real effect in terms of productivity, but no effect on long-term growth. Therefore, while the neutrality of money was identified in terms of its effect on growth, the non-neutrality of money can also be ascertained in terms of a level effect. Hence, monetary effects can be either neutral or non-neutral, depending on which effect is examined.

Moreover, this monetary policy generates excessive fluctuations in consumption, output, and investment. Although their initial movements are positive, they eventually return to their initial levels. If the aim is simply to facilitate inflation, expansionist monetary policy is not particularly efficient. However, when more advanced productivity levels are targeted, regardless of business fluctuations, such a policy might be desirable.

4.3 Volatilities

To assess the contribution of the business fluctuation mechanism, we consider the model-implied volatilities (standard deviations) of the main variables of interest. Table 2 shows the standard deviations and relative volatilities of output, consumption, investment, capital, labor, R&D labor, interest rates, rental prices, and wages. The first column shows the volatilities when all of the productivity and monetary policy shocks are taken into account. The second column presents the case in which only productivity shocks occur, while the third column presents the case in which only monetary policy shocks occur. Standard deviations are expressed in percentage terms.

(Table 2)

The data show that investment is about five times more volatile than output, while consumption is less volatile than output. For example, Christensen and Dib (2008) reported that the standard deviations for output, investment, and consumption were 1.04, 5.61, and 0.72, respectively based on quarterly US data from 1979Q3 through 2004Q3. Although the standard deviations in our simulation analysis differ, the relative volatility of investment is quite close to that found in their model, i.e. investment is about five times more volatile than output. Moreover, consumption is also less volatile than output in our model. However, its relative volatility is much smaller in our model.

Productivity shocks generate greater volatility in output, consumption, and wages, whereas monetary shocks lead to more cyclical behavior by interest rates, rental prices, investment, capital, labor, and R&D labor. On one hand, monetary shocks have a much larger influence on interest rates through the Taylor rule. As a result, rental prices, investment, and capital tend to be more affected. On the other hand, productivity shocks have a greater effect than monetary shocks on output. Consequently, consumption is more likely to respond to productivity shocks.

4.4 Variance decomposition

Next, we consider the variance decompositions for output, consumption, investment, capital, labor, R&D labor, interest rates, rental prices, and wages. Table 3 shows the variance decompositions of the variables attributed to each of the two types of shocks.

(Table 3)

Obviously, productivity shocks account for the bulk of the variables, which is consistent with the RBC literature. However, our model allows for different implications from the RBC literature in that productivity shocks could be interpreted as the result of endogenous innovation. It follows that once endogenous innovation takes place at the beginning of a period, its effects surpass those of monetary policy shocks on fluctuations in macroeconomic variables, except for interest rates. Therefore, not only productivity shocks but also endogenous innovation accounts for most of the cycles.

Monetary policy shocks also have some impact on the fluctuations. In particular, interest rates are primarily influenced by monetary shocks via the Taylor rule. Moreover, about half of the fluctuations in both production and R&D labor hours are caused by monetary shocks. Because R&D labor determines the rate of endogenous innovation, monetary policy shocks affect productivity shocks as a result of endogenous innovation in the following period. Therefore, while productivity shocks play a significant role in generating business cycles in this model, monetary policy shocks have a significant effect on productivity shocks through the supply of R&D labor. As we have already seen, because positive productivity shocks have a negative impact on the supply of R&D labor, this implies that monetary policy shocks are no less important than productivity shocks in terms of facilitating endogenous innovation. Although monetary policy shocks have a modest influence on the overall business cycle, their indirect effects might be significant as a result of generating endogenous, rather than exogenous, productivity shocks in the next period. This highlights the significant role played by monetary policy in generating endogenous innovation directly and business cycles indirectly.

5. Conclusion

Although the basic feature of the model presented in this paper is a standard New Keynesian model, the introduction of an endogenous innovation mechanism provides three additional advantages compared with the related literature. First, the Calvo pricing mechanism can be reinterpreted as being generated by endogenous innovation, as opposed to a random “price-change signal.” The success of innovation gives rise to the same pricing mechanism as that developed by Calvo. Indeed, the specification of the pricing scheme in this paper is the same as that in the standard Calvo mechanism. However, using this new interpretation, our model is free from frictions in the economy that cause sticky prices. These seemingly sticky prices are only generated by Schumpeterian competition, with no arbitrary frictions.

Second, the slightly different interpretation of the Calvo mechanism in this paper has the consequence of generating endogenous innovation and growth, a result that has been disregarded in the New Keynesian literature. As a result, we can evaluate the effect of monetary policy on endogenous innovation, and in turn that of endogenous innovation on other macroeconomic variables.

Our results demonstrate both neutral and non-neutral properties of productivity and monetary policy shocks. They have neutral effects on the long-term growth rate by encouraging a return to the initial states through adjustment processes induced by these shocks. However, they have non-neutral effects on levels by changing the amount of R&D investment. Since the change in R&D investment changes the rate of endogenous innovation, it has a lasting effect on productivity levels. Therefore, as long as these shocks have a real effect on R&D investment, they have path-dependent effects on economic growth and cycles. In particular, it seems remarkable that positive productivity shocks and endogenous innovation both have a negative effect on subsequent endogenous innovation. This self-destructive effect of endogenous innovation might account for the IT productivity paradox and consequent productivity slowdown experienced in advanced countries. Appropriate monetary policies could be instrumental in further facilitating endogenous innovation. Thus, from this perspective, expansionist monetary policies are seen as desirable.

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Appendix A: The system of log-linearized equations

$$\hat{\gamma}_{t+1}+\hat{r}_t=\frac{\sigma}{(1-h)(1-h\beta)}\left[h\beta\left(\hat{c}_{t+1}-h\hat{c}_t\right)-\left(\hat{c}_t-h\hat{c}_{t-1}\right)\right]-\hat{p}_t, \tag{A1}$$

$$\varphi\hat{l}_t=\hat{\gamma}_t+\hat{w}_t, \tag{A2}$$

$$\xi\hat{n}_t=\hat{\gamma}_t+\hat{w}_t, \tag{A3}$$

$$\beta\hat{q}_t=(1-\delta)\hat{q}_{t+1}+\Psi_1\left(\hat{\gamma}_{t+1}+\hat{z}_{t+1}+\hat{u}_{t+1}\right)-\Psi_1\hat{u}_{t+1}, \tag{A4}$$

$$\Psi_1\left(\hat{z}_t-\hat{p}_t\right)=\Psi_2\hat{u}_t, \tag{A5}$$

$$\hat{\gamma}_t+\hat{p}_t-\hat{q}_t+\chi\left(\hat{i}_t-\hat{i}_{t-1}\right)=\chi\beta\left(\hat{i}_{t+1}-\hat{i}_t\right), \tag{A6}$$

$$\hat{p}_t^P-\hat{\gamma}_{t+1}=\hat{p}_t^R, \tag{A7}$$

$$\hat{p}_t^R=\hat{w}_t+\hat{n}_t, \tag{A8}$$

$$\hat{k}_{t+1}=(1-\delta)\hat{k}_t+\delta\hat{i}_t, \tag{A9}$$

$$\hat{y}_t=(1-\alpha)\left(\hat{u}_t+\hat{k}_t\right)+\alpha\hat{l}_t+\hat{s}_t^a, \tag{A10}$$

$$\hat{s}_t^a=\rho_a\hat{s}_{t-1}^a+\varepsilon_t^a, \tag{A11}$$

$$\hat{u}_t+\hat{k}_t=\hat{y}_t+\hat{m}c_t-\hat{z}_t, \tag{A12}$$

$$\hat{l}_t=\hat{y}_t+\hat{m}c_t-\hat{w}_t, \tag{A13}$$

$$\hat{m}c_t=\alpha\hat{w}_t+(1-\alpha)\hat{z}_t-\hat{s}_t^a, \tag{A14}$$

$$\hat{y}_t=\left(1-s_I\right)\hat{c}_t+s_I\hat{i}_t, \tag{A15}$$

$$\hat{r}_t=\ell_R\hat{r}_{t-1}+\left(1-\ell_R\right)\left(\ell_\pi\hat{\pi}_t+\ell_y\hat{y}_t\right)+\hat{s}_t^m, \tag{A16}$$

$$\hat{s}_t^m=\rho_m\hat{s}_{t-1}^m+\varepsilon_t^m. \tag{A17}$$

$$\hat{\pi}_t=\hat{p}_t-\hat{p}_{t-1}, \tag{A18}$$

$$\hat{\pi}_t = \frac{(1-\omega)(1-\beta\omega)}{\omega}(\hat{m}c_t - \hat{p}_t) + \beta\hat{\pi}_{t+1}. \tag{A19}$$

Appendix B: The steady-state equilibrium

$$P = 1, \tag{B1}$$

$$u = 1, \tag{B2}$$

$$r = \frac{1}{\beta}, \tag{B3}$$

$$z = \frac{1}{\beta} - (1-\delta), \tag{B4}$$

$$w = \left[\frac{(1-\beta\omega)(\varepsilon-1)}{\varepsilon}\right]^{\frac{1}{\alpha}} \left(\frac{(1-\alpha)\beta}{1-\beta(1-\delta)}\right)^{\frac{1-\alpha}{\alpha}} \alpha, \tag{B5}$$

$$mc = \left(\frac{w}{\alpha}\right)^{\alpha} \left(\frac{z}{1-\alpha}\right)^{1-\alpha}, \tag{B6}$$

$$s_I \equiv \frac{i}{y} = \frac{(1-\alpha)\beta(1-\beta\omega)}{1-\beta(1-\delta)} \frac{\varepsilon-1}{\varepsilon}\delta, \tag{B7}$$

$$s_C \equiv \frac{c}{y} = 1 - s_I, \tag{B8}$$

$$y = \Lambda s_C^{-\frac{\sigma}{\varphi+\sigma}}, \tag{B9}$$

$$\Lambda = \left[\frac{\alpha(1-h\beta)}{(1-h)^{\sigma}}\right]^{\frac{1}{\varphi+\sigma}} \left[\frac{(1-\beta\omega)(\varepsilon-1)}{\varepsilon}\right]^{\frac{1+(1-\alpha)\varphi}{\alpha(\varphi+\sigma)}} \left[\frac{(1-\alpha)\beta}{1-\beta(1-\delta)}\right]^{\frac{(1-\alpha)(1+\varphi)}{\alpha(\varphi+\sigma)}}, \tag{B10}$$

$$l = \alpha mc\, y/w, \tag{B11}$$

$$n = (\gamma w)^{\frac{1}{\xi}}, \tag{B12}$$

$$i = \delta k, \tag{B13}$$

$$\gamma = q = c^{-\sigma}(1-h)^{-\sigma}(1-h\beta). \tag{B14}$$

Table 1. Parameter Calibration

Parameters	Definition	Values
σ	Relative risk aversion	2
η	Marginal disutility with regard to supply of labor	1.5
ξ	Marginal disutility with regard to supply of R&D labor	2.5
α	Output elasticity of labor	0.6
β	Discount factor	0.985
δ	Depreciation rate	0.025
ε	Elasticity of substitution among intermediate goods	8
h	Habit persistence	0.8
Ψ_1	Sensitivity of cost of under-utilization installed capacity	$1/\beta-(1-\delta)$
Ψ_2	Sensitivity of cost of under-utilization installed capacity	1
ω	Probability of no innovation	0.975

Table 2. Standard Deviation and Relative Volatilities:

All, Productivity, and Monetary Shocks

Variables	All shocks	Productivity	Monetary
A. Standard deviations (%)			
Y	5.73	5.05	2.71
C	1.31	1.14	0.63
I	25.05	16.05	19.23
K	10.06	7.07	7.15
L	3.74	0.99	3.61
N	2.81	0.74	2.71
R	9.16	2.43	8.83
Z	6.56	3.11	5.77
W	6.14	5.3	3.11
B. Relative volatilities			
Y	1	1	1
C	0.23	0.23	0.23
I	4.37	3.18	7.10
K	1.76	1.40	2.64
L	0.65	0.20	1.33
N	0.49	0.15	1.00
R	1.60	0.48	3.26
Z	1.14	0.62	2.13
W	1.07	1.05	1.15

Table 3. Variance Decompositions

Variables	Variance	Percentage owing to:	
		Productivity	Monetary
Y	0.0033	77.71	22.29
C	0.0002	76.42	23.58
I	0.0627	41.04	58.96
K	0.0101	49.49	50.51
L	0.0014	7.02	92.98
N	0.0008	7.02	92.98
R	0.0084	7.04	92.96
Z	0.0043	22.53	77.47
W	0.0038	74.39	25.61

Figure 1. The economy's response to a positive productivity shock

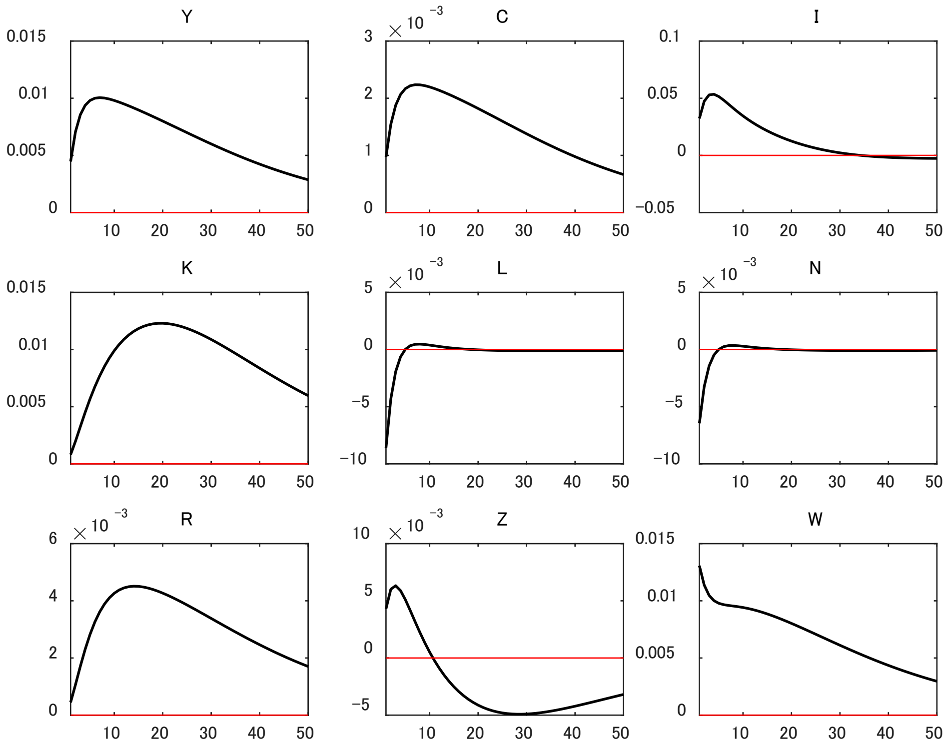

Figure 2. The economy's response to an expansionist monetary shock