A Business Cycle Model with Sticky Pricing and Endogenous Capital

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In this paper, we will study some business cycle models with sticky pricing and endogenous and firm-specific capital. We also manage to incorporate capital utilization into the models. As revealed by the simulation results, the cyclical behaviors of our business cycle models are quite normal compared with the literature and those of the actual economy except the simulated correlations between inflation and output. Such simulation result is mainly because in symmetric equilibriums, money in our models turns out to be superneutral.

Key Words: Business cycle, sticky pricing, endogenous and firm-specific capital, labor and capital utilization.
Subject Classification: E31,E32,E52,E58.

1. INTRODUCTION

In this paper, we will study some business cycle models with sticky pricing and endogenous capital.

As commented by King & Rebelo (1999), after decades of accumulated efforts since the 1930s, Kydland & Prescott (1982) and Long & Plosser (1983) first strikingly showed the promise of establishing the Real Business Cycle (RBC) models consistent with the actual economy on its key real variables' properties, including their persistences, volatilities and comovements with the other key real variables. Summary literature may also refer to Cooley & Prescott (1995). Following the RBC theoretic developments, the New Keynesian Economics (NKE) emerge, attempting to interpret the nominal aspect of the economy and provide as well an justification for monetary policy. Compared with the standard RBC framework, the NKE stresses one defining departure, i.e., price is sticky, rather than flexible as assumed by the RBC theory. As reviewed in Ball, Mankiw & Romer (1988), the nominal rigidities in Keynesian models in the 1970s were assumed rather than explained. Now after years of efforts, price stickiness, initially simply an assumption in view of its empirical relevance, is made to be part of agents' optimization outcomes by assuming that individual firms have market powers, i.e., they are price setters, but not price takers as assumed by the RBC theory. In the aggregate level, it

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is assumed according to the widely used Calvo pricing environment (Calvo, 1983), that at each period only a fraction, but not all of the firms will adjust their product prices due to the related adjustment costs. Some of the other early famous NKE literatures may refer to Fischer (1977), Taylor(1979,1980), Rotemberg (1982), Mankiw (1985). The subsequently important papers on sticky pricing may include McCallum (1994,1999a) and Mankiw & Reis (2001). All of the above mentioned pricing models are categorized as time dependent models due to the recently developed state dependent sticky pricing models, in which the number of firms adjusting prices is modeled to be endogenous, but not as exogenous as it is in the time dependent models. Papers may refer to Dotsey, King & Wolman (1999), Burstein (2002).

As is well known, capital dynamics is essentially important for the RBC models. But in the NKE literature, capital is generally assumed to be constant, which seems not very acceptable from the RBC theory perspective. So, in this paper we will study the business cycle models with sticky pricing and endogenous capital. In the modeling process we will try to make our model be as similar as possible to the standard RBC model. Also, as argued by Woodford (2003, Chp 5), we will set the capital here to be firm-specific.

There is another consideration why we think we may need to endogenize capital. A recent development in the RBC theory is, capital utilization matters for business cycles, although the capital itself may not. The literature may refer to Burnside & Eichenbaum (1996), Baxter & Farr (2001), King & Rebelo (1999), etc. So, we have to first endogenize capital if planning to investigate the role of capital utilization in business cycles.

Considering the input structure of a Cobb-Douglas production function with both capital and labor as input factors, we may also need to emphasize the role of labor utilization, i.e., the employment rate. So, in the next section 2, we will first start from the paper of Hansen (1985) to discuss how to introduce labor utilization and further capital utilization respectively into business cycle models, and treat them as the benchmark models for the two models to be defined in section 3 and 4 respectively for further comparisons in section 5.

The rest of the paper are organized as follows. In section 3, we construct a business cycle model with sticky pricing and endogenous and firm-specific capital. In section 4, we incorporate capital utilization into the model defined in section 3. In section 5, we discuss the related simulation results of the four models given in section 2, 3, and 4. Section 6 is the concluding remark.

2. THE BENCHMARK RBC MODELS : MODELS (1) AND (2)

2.1. Model (1)

We first make a review of the business cycle models due to Hansen (1985) for the sake of future simulation result comparisons.

Primarily due to Hansen (1985), in which a lottery probability is introduced into the households' labor decision, the RBC theory can also deal with labor market fluctuations nicely. Let's repeat Hansen's lottery theory of labor supply briefly as follows.

Each individual in the economy has to choose between working a fixed shift of h_t hours and not working at all. So, the choice for the household is, either work h_t hours, or, 0 hours regardless of how many hours such an individual ideally wants to choose flexibly, i.e., choose to work less or more than h_t hours. In this set up, the agents can be made better off by introducing lotteries to convexify their choice sets. By entering a lottery an agent can choose to work a fraction $b_t \in (0,1)$ of his days while remaining unemployed for the rest fraction $(1-b_t) \in (0,1)$ of his time.

Then, we can write the households' problem as

$$\max_{\{c_t, k^s_{t+1}, h^s_t, b^s_t\}} \{E_t \sum_{j=o}^{\infty} \beta^j [b_{t+j} \log(c^e_{t+j}) + (1-b_{t+j}) \log(c^u_{t+j}) + ab_{t+j} \log(1-h^u_{t+j})]\}$$

where, we use the fact $h^u_{t+j} = 0$, hence, $\log(1-h^u_{t+j}) = 0$.

s.t. for j=0,1,2,...

$$b_{t+j}c^e_{t+j} + (1-b_{t+j})c^u_{t+j} + k^s_{t+1+j} \leq w_{t+j}b_{t+j}h^s_{t+j} + (1+r_{t+j})k^s_{t+j}$$

where, the upper index e denotes "employed", u "unemployed", and s "supply".

Checking the first order conditions (FOCs) on consumption variables c^e_{t+j} and c^u_{t+j}, we notice that

$$c^e_{t+j} = c^u_{t+j}$$

So, by defining $c_{t+j} = c^e_{t+j} = c^u_{t+j}$, we can simplify the households' problem as

$$\max_{\{c_t, k^s_{t+1}, h^s_t\}} \{E_t \sum_{j=o}^{\infty} \beta^j [\log(c_{t+j}) + ab_{t+j} \log(1-h^s_{t+j})]\}$$

s.t. for j=0,1,2,...

$$c_{t+j} + k^s_{t+1+j} \leq w_{t+j}b_{t+j}h^s_{t+j} + (1+r_{t+j})k^s_{t+j}$$

Note that h_t is assumed by Hansen (1985) to be a constant h_o and the probability b_t is the only control variable for the households' labor decision.

For the representative firm, the problem can be written as

$$\max_{\{k^d_t, h^d_t, \mu_t, \nu_t\}} \{y_t - (r_t + \delta_t)k^d_t - w_t \nu_t h^d_t\}$$

where, the upper index d denotes "demand", ν_t is the aggregate employment rate, and

$$y_t = z_t k^{d\alpha}_t (v_t h^d_t)^{1-\alpha} \tag{1}$$

and, as usual, we assume that the productivity shock z_t evolves according to the law of motion :

$$z_{t+1} = \phi_z z_t + \epsilon^z_{t+1}$$

with $\phi_z \in (0,1)$, and $\epsilon^z_{t+1}\tilde{\ } N(0, \sigma^2_z)$.

In equilibrium, we have,

In the labor market, $h^d_t = h^s_t = h_t$;

In the capital market, $k^d_t = k^s_t = k_t$;

In the goods market, $c_t + [k_{t+1} - (1-\delta_t)k_t] = y_t$.

Also according to Proposition(1), we have $b_t = v_t$ to close the model, as implicitly applied in Hansen(1985).

Proposition 1. *The representative agent's lottery probability b_t of getting a job converges in probability to the economy's employment rate ν_t if the economy's population is large enough.*

Proof. See the Appendix. ∎

This lottery theory of labor supply is quite successful, and the macroeconomy acts just as if it were populated with a more elastic supply of labor, even if each individual agent may have no elasticity of labor supply since h_t can be assumed to be a constant.

The above RBC model is designated as model (1), the benchmark model for model (3), which is to be defined in section 3.

Now we start from model (1) to define model (2). Model (2) is simply model (1) plus a condition on capital utilization, and it is the benchmark model for model (4), which is to be defined in section 4.

The relationship among the four models are shown in the following graph:

$$\begin{tikzcd} Model(1) \arrow[r, "(capital\_utilization)"] \arrow[d, "(sticky\_pricing)"'] & Model(2) \arrow[d, "(sticky\_pricing)"] \\ Model(3) \arrow[r, "(capital\_utilization)"'] & Model(4) \end{tikzcd}$$

2.2. Model (2)

Generally, in the RBC literatures investigating capital utilizations, it is assumed that the depreciation rate δ_t takes a convex functional form of the capacity utilization rate μ_t. For example, in Baxter & Farr(2001), it is assumed that

$$\delta_t = \delta_o + \delta_1 \cdot \mu_t^{1+\zeta}/(1+\zeta) \tag{2}$$

where, the related parameters are assumed to be such that $\delta_1 > 0, \zeta > 0$.

Correspondingly, the Cobb-Douglas production function has to be rewritten as

$$y_t = z_t(\mu_t k_t^d)^\alpha (v_t h_t^d)^{1-\alpha} \tag{3}$$

Adding assumption (2) into model (1), and correspondingly replacing definition (1) with definition (3), we get model (2) based on model (1). Needless to say, once again we have to use Proposition(1) to close the model.

3. A BUSINESS CYCLE MODEL WITH STICKY PRICING AND ENDOGENOUS CAPITAL : MODEL (3)

Now we start from model (1) to define model (3), the business cycle model with sticky pricing and endogenous and firm-specific capital.

The economy is composed of monopolistically competitive firms of measure 1 and infinitely-lived households. Each firm specializes in producing one differentiated goods

$i \in [0,1]$ with the same degree of market power of pricing. Households have diversified preference of all of these products.

For modeling simplicity, we also assume that only the pricing of goods is sticky while the pricings of labor and capital, i.e., wage w_t and interest rate r_t are flexible.

In our modeling process, we use a two step approach to capture the firm's problem. The firm's problem is decomposed as two steps, one is on sale and the other on production. So, firstly we define and solve the firm's production problem, in which firms will minimize their production costs, hence generate their factor including capital and labor demand functions. Secondly, we will define and solve the firms' sale problem, in which the firms will optimize their sale prices to maximize profits. The advantage of such two step approach is, we can derive out and use the cost function consistent with our production function assumption in the firms' optimal pricing processes.

The model (3) is defined in sections 3.1, 3.2, and 3.3 subsequently.

3.1. The Household's Problem

Following Hansen(1985) that there is a lottery for the households to make labor decisions, the representative household's problem is

$$\max_{\{c_t, k^s_{t+1}, b_t\}} \{E_t \sum_{j=o}^{\infty} \beta^j [\log(c_{t+j}) + ab_{t+j}\log(1-h^s_{t+j})]\} \tag{4}$$

s.t. the nominal budget constraints per period for j=0,1,2,...

$$\begin{aligned} & \int_o^1 p(i)_{t+j}c(i)_{t+j}di + p_{t+j}\int_o^1 k(i)^s_{t+1+j}di \\ \leq \quad & p_{t+j}[\int_o^1 b_{t+j}w_{t+j}h(i)^s_{t+j}di + \int_o^1 (1+r_{t+j})k(i)^s_{t+j}di + \int_o^1 \Pi(i)_{t+j}di] \end{aligned} \tag{5}$$

plus the no Ponze-game condition

$$\lim_{T\to\infty} E_t \prod_{j=o}^{T}(1+r_{t+j})^{-1}\int_o^1 k(i)^s_{t+T}di = 0$$

where, probability b_{t+j}, wages w_{t+j} and capital returns r_{t+j} are assumed to be universal for any $i \in [0,1]$, and, $\Pi(i)_{t+j}$ is firm i's profit at period t+j.

Also, following Hansen (1985), we still assume that the working hours $h(i)^s_{t+j}$ for each firm $i \in [0,1]$ is a constant, i.e.,

$$h^s_{t+j} = \int_o^1 h(i)^s_{t+j}di = \int_o^1 h_o di = h_o$$

so, we have $l_{t+j} = 1 - h_o$.

The FOCs of the household's problem are

$$[\frac{c(i)_t}{c_t}]^{\frac{\theta_t - 1}{\theta_t}} = \lambda_t p(i)_t c(i)_t \tag{6}$$

$$a \log(1 - h_o) + \lambda_t p_t w_t h_o = 0 \tag{7}$$

$$E_t[\lambda_t p_t - \beta \lambda_{t+1} p(i)_{t+1}(1 + r_{t+1})] = 0 \tag{8}$$

plus its budget constraint (5), which now has to be binding so that the Lagrangian multiplier $\lambda_{t+j} \neq 0$.

Following Dixit & Stiglitz (1977), we here define the representative household's aggregate consumption c_t and price p_t as

$$c_t = [\int_o^1 c(i)_t^{\frac{\theta_t - 1}{\theta_t}} di]^{\frac{\theta_t}{\theta_t - 1}} \tag{9}$$

$$p_t = [\int_o^1 p(i)_t^{1-\theta_t} di]^{\frac{1}{1-\theta_t}} \tag{10}$$

Note also that by first deriving out $\lambda_t = [p_t c_t]^{-1}$ using equation (6) and definitions (9) and (10), its demand $c(i)_t$ for consumption goods $i \in [0, 1]$ can be derived as

$$c(i)_t = c_t[\frac{p(i)_t}{p_t}]^{-\theta_t} \tag{11}$$

which is functionally the same as what it appeared to be in Dixit & Stigilitz (1977).

It may be worth noting that originally in Dixit & Stiglitz(1977), they concluded that $-\theta_t < 0$ is approximately the related demand elasticity by neglecting the effect of each $p(i)_t$ on p_t, hence the indirect effect on $c(i)_t$. But, as is shown in Proposition(2), $-\theta_t$ is precisely the price elasticity of the related consumption goods $i \in [0, 1]$.

PROPOSITION 2. *In the above defined representative household's problem, for any consumption goods $i \in [0, 1]$, its consumption demand elasticity is not approximately but precisely $-\theta_t < 0$.*

Proof. See the Appendix. ∎

3.2. The Firm's Problem

As has been explained, here we will decompose the firms' problem in two steps. First, we will solve the production cost minimization problem, then, in the second step, we consider the firm's price optimization problem in a Calvo pricing environment.

Following the definition (1) on production technology, we assume that the production function for any firm specializing in producing goods $i \in [0, 1]$ is a Constant Return To Scale (CRTS)[2] Cobb-Douglas type, i.e.,

[2] The two-step approach is also able to incorporate straightforwardly the IRTS production technology into the model. Suppose that the production function is not necessarily CRTS, so, we write generally the production function to be

$$y(i)_{t+j} = z_{t+j}[k(i)_{t+j}^d]^\alpha [h(i)_{t+j}^d]^\gamma$$

$$y(i)_{t+j}= z_{t+j}k(i)_{t+j}^{\alpha}(v_{t+j}h_{t+j}^{d})^{1-\alpha} \tag{12}$$

where, the productivity term z_{t+j} is universal for any firm $i \in [0,1]$,

$$\log z_t= (1-\phi_z)\log z+\phi_z \log z_{t-1}+\epsilon_t^z \tag{13}$$

with its stochastic shock $\epsilon_t^z \sim i.i.d.N(0;\sigma_z^2)$.

Then, the firm $i \in [0,1]$ will have to consider the following real cost minimization problem,

$$\min_{\{k(i)_{t+1}^d, h(i)_t^d\}} \{m(i)_{t+j}\equiv (r_{t+j}+\delta)k(i)_{t+j}^d + w_{t+j}h(i)_{t+j}^d\} \tag{14}$$
$$s.t. \quad Z_{t+j}[k(i)_{t+j}^d]^{\alpha}[h(i)_{t+j}^d]^{1-\alpha} \leq y(i)_{t+j}$$

Note that the FOCs will be the same for both real and nominal cost minimization problems since the factor markets including the capital and labor markets are assumed to be universally priced for all firms.

Eliminating the Lagrangian multiplier, the FOCs on capital demand $k(i)_{t+j}^d$ and labor demand $h(i)_{t+j}^d$ are

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where, we don't necessarily ask $\alpha+\gamma=1$. Then, for firm $i \in [0,1]$, its cost minimization problem will become

$$\min_{\{k(i)_{t+1}^d, h(i)_t^d\}} \{m(i)_{t+j}\equiv (r_{t+j}+\delta)k(i)_{t+j}^d + w_{t+j}h(i)_{t+j}^d\}$$
$$s.t. \quad z_{t+j}[k(i)_{t+j}^d]^{\alpha}[h(i)_{t+j}^d]^{\gamma} \leq y(i)_{t+j}$$

Following the same algebra in the CRTS case, the real cost function $m(i)_{t+j}$ can be derived as

$$m(i)_{t+j} = \phi_c(r_{t+j}+\delta)^{\frac{\alpha}{\alpha+\gamma}} w_{t+j}^{\frac{\gamma}{\alpha+\gamma}} [\frac{y(i)_{t+j}}{z_{t+j}}]^{\frac{1}{\alpha+\gamma}}$$

It is well known that in a competitive market, the firms don't have profit maximizing production plans unless $\alpha+\gamma \leq 1$, i.e., production technology has to be decreasing return to scale or at most CRTS with zero profit. Now, we want to stress that when the firms have market powers, this conclusion doesn't necessarily hold any more. On the contrary, when the firms have market powers, the firms may have their maximum profits with appropriately defined IRTS production technology. Let's consider the following simple case to see the possibility.

First assume that the pricing is flexible, so that the firm's pricing problem is just one period problem. Also for convenience we assume that the firms are monopoly suppliers. Then, the firm's one period pricing problem can be defined as

$$\max_{\{p(i)_t\}} \{p(i)_t y(i)_t - p_t m(i)_t\}$$

where, $m(i)_{t+j}$ is still defined as the real marginal cost function. For simplicity, we assume that $y(i)_t = a\cdot p(i)_t^{-\theta}$, where, as usual, for the monopoly firm, we assume that $\theta > 1$ so that its price markup will be meaningful. Then, the above pricing problem can be simplified as $\max_{\{p(i)_t\}} \{a\cdot p(i)_t^{1-\theta} - b\cdot p(i)_t^{-\kappa\theta}\}$,where, $a > 0$, and $b > 0$ denotes $a \cdot p_t \cdot \frac{m(i)_t}{y(i)_t}$ and, $\kappa \in (0,1)$ for IRTS assumption. Then, the FOC will be $a(1-\theta)\cdot p^*(i)_t^{-\theta} + b\kappa\theta\cdot p^*(i)_t^{-\kappa\theta-1} = 0$. Using the FOC, the second order condition can be expressed as $p^*(i)_t^{-\theta-1}\{a(1-\theta)\cdot[(1-\kappa)\theta-1]\}$. It's easy to check that if $\theta \in (\frac{1}{1-\kappa},\infty)$, then the second order condition will be negative, i.e., the firm now will have a maximum profit under IRTS. Note that the lower bound $\frac{1}{1-\kappa} > 1$ since $\kappa \in (0,1)$ for IRTS assumption.

$$k(i)^d_{t+j}= [\frac{\alpha}{1-\alpha}]^{1-\alpha}[\frac{w_{t+j}}{r_{t+j}+\delta}]^{1-\alpha}[\frac{y(i)_{t+j}}{z_{t+j}}] \tag{15}$$

$$h(i)^d_{t+j}= [\frac{\alpha}{1-\alpha}]^{-\alpha}[\frac{w_{t+j}}{r_{t+j}+\delta}]^{-\alpha}[\frac{y(i)_{t+j}}{z_{t+j}}] \tag{16}$$

Plugging these two equations into the objective function (14), we get the real cost function $m(i)_{t+j}$ as

$$m(i)_{t+j} = \phi_c(r_{t+j}+\delta)^{\alpha} w^{1-\alpha}_{t+j}[\frac{y(i)_{t+j}}{z_{t+j}}] \tag{17}$$

where, $\phi_c = [(\frac{\alpha}{1-\alpha})^{1-\alpha} + (\frac{\alpha}{1-\alpha})^{-\alpha}]$.

Now is the second step to consider the firm's pricing problem.

For simplicity we adopt the Calvo assumptions on pricing environment, i.e., at each period firm specializing in goods $i \in [0,1]$ will with a constant probability $\varsigma \in (0,1)$ simply update its product price from p_{t-1} to $p(i)_t = \pi p_{t-1}$, and with the rest probability $(1-\varsigma) \in (0,1)$ adjust its product price $p(i)_t$ from p_{t-1} to p^*_t. Here, following the literature, for example, Kimball (1996), we assume that the steady state of the gross inflation rate $\pi_t \equiv \frac{p_t}{p_{t-1}}$ satisfies $\pi \geq 1$.

Then, the firm's price optimization problem will be

$$\max_{\{p(i)_t\}} \{E_t \sum_{j=o}^{\infty} (\varsigma\rho)^j [\pi^j p(i)_t y(i)_{t+j} - p_{t+j} m(i)_{t+j}]\} \tag{18}$$

where, $m(i)_{t+j}$ is the real cost function, as defined by equation (17), ρ is the non-stochastic nominal discount factor.

We will first in the next sub-section consider the market equilibrium conditions, then, go back solving problem (18) and give the results in Proposition (3).

3.3. Market Equilibriums

In equilibrium,

in the labor market,

$$h(i)_{t+j} = h(i)^s_{t+j} = h(i)^d_{t+j} \tag{19}$$

in the credit market,

$$k(i)_{t+j} = k(i)^s_{t+j} = k(i)^d_{t+j} \tag{20}$$

in the goods market, we may simply write the equilibrium condition as

$$y(i)_{t+j} = c(i)_{t+j} + I(i)_t \tag{21}$$

where, $I(i)_t$ represents goods i produced by firm i to supply all firms' investment demands in goods i to accumulate its capital aggregates, which may be viewed as an analogue of the household's consumption aggregate as defined in (9).

According to the Walrus' Law, using equation(5), $I(i)_{t+j}$ can be expressed as

$$I(i)_{t+j} = [\frac{p(i)_{t+j}}{p_{t+j}}]^{-1}(k(i)^s_{t+1+j} - (1-\delta)k(i)^s_{t+j}) \tag{22}$$

Note that in the expressions $k(i)^s_{t+j}$ and $k(i)^s_{t+1+j}$, the index i simply refers to the capital accumulated in firm i in period t+j, while from the goods perspective, these expressions actually represent composite aggregates of all goods. Following the definition (9) for consumption goods aggregate, we can analogously let I_{t+j} represent the aggregate of investment goods and as a result of goods market equilibrium it should satisfy

$$I_{t+j} = k(i)^s_{t+1+j} - (1-\delta)k(i)^s_{t+j}$$

then, we get

$$\frac{I(i)_{t+j}}{I_{t+j}} = [\frac{p(i)_{t+j}}{p_{t+j}}]^{-1} \tag{23}$$

Following Proposition(2), we assume analogously that the elasticity of investment demand for $I(i)_{t+j}$ is -1, i.e.,

$$\frac{d\ln(I(i)_{t+j})}{d\ln(p(i)_{t+j})} = -1 \tag{24}$$

With this assumption, we can get the following result on the firm's price optimization problem defined by (18).

Proposition 3. *For the firm $i \in [0,1]$, with its problem defined by (18), if the steady state π of the gross inflation rate $\pi_t \equiv \frac{p_t}{p_{t-1}}$ is sufficiently close to 1 such that $\varsigma\rho\pi \in (0,1)$, then, its optimizing price $p^*(i)_t$ will satisfy*

$$x(i)_t - \varsigma\rho\pi E_t x(i)_{t+1} = y(i)_t \tag{25}$$

where,

$$x(i)_t \equiv [(\theta_t - 1)c(i)_t + y(i)_t] + m(i)_t(\frac{p^*(i)_t}{p_t})^{-\theta_t} - \frac{m(i)_t}{y(i)_t}[(\theta_t - 1)c(i)_t + y(i)_t][\frac{p^*(i)_t}{p_t}]^{-1} \tag{26}$$

Proof. See the Appendix. ∎

Note that in the aggregate level, according to the Calvo pricing assumption and the Law of Large Number, for the aggregate price index p_t we have

$$p_t^{1-\theta_t} = \int_o^{\varsigma}(\pi p_{t-1})^{1-\theta_t}di + \int_{\varsigma}^{1-\varsigma} p_t^{*1-\theta_t}di = \varsigma(\pi p_{t-1})^{1-\theta_t} + (1-\varsigma)p^{*1-\theta_t}_t$$

so, we have

$$1 = \varsigma[\pi\frac{p_{t-1}}{p_t}]^{1-\theta_t} + (1-\varsigma)[\frac{p^*_t}{p_t}]^{1-\theta_t} \tag{27}$$

Then, in a symmetric equilibrium for firms, i.e., $\frac{p(i)_t^*}{p_t} = \frac{p_t^*}{p_t}$, we know that $\frac{p_t^*}{p_t}$ is a function of gross inflation rate π_t. By the definition of $x(i)_t$, we know that $x(i)_t$ is a function of inflation rate π_t. So, the equation (25) in Proposition (3) is an expression for the so-called New Philips Curve (NPC) for the above business cycle model.

As showed above, the firm's problem can be decomposed into two sub-problems, with the first sub-problem on cost minimization, and the second sub-problem on optimizing prices. This two step approach can be justified using backward induction. That is, the firm will first think of how to maximize the present value of its intertemporal nominal profits through optimizing its sale prices, while in this sale-in-advance price optimizing process, it has to evaluate its cost function, i.e., the most economic factor input combinations to implement the optimal price calculated out in the previous pricing decision.

Now, with the above given problems of households and firms, and the market equilibrium conditions, we have defined the competitive equilibrium of a business cycle model with price stickiness and endogenous capital.

4. INCORPORATING CAPITAL UTILIZATIONS INTO MODEL (3) : MODEL (4)

Now consider an extension of introducing capital utilization into the business cycle model defined in Sections 3.1, 3.2, and 3.3. And as has been explained, this model is designated as model (4) in coming simulations.

Let's first consider the firm's problem.

For the firm specializing in producing goods $i \in [0,1]$, its production problem, i.e., its cost minimization problem will become

$$\min_{\{k(i)_{t+1}^d, h(i)_t^d\}} \{m(i)_{t+j} \equiv (r_{t+j} + \delta(i)_{t+j})k(i)_{t+j}^d + w_{t+j}v(i)_{t+j}h(i)_{t+j}^d\}$$

$$s.t. \qquad z_{t+j}[\mu(i)_{t+j}k(i)_{t+j}^d]^\alpha[v(i)_{t+j}h(i)_{t+j}^d]^{1-\alpha} \leq y(i) \tag{28}$$

$$\delta(i)_{t+j} = \delta_o + \delta_1 \cdot \mu(i)_{t+j}^{1+\zeta}/(1+\zeta) \tag{29}$$

where, equation (28) and (29) are rewritten according to equations (12) and (2).

Note that here, in the labor market, it is the households that accept the fluctuations of employment rate, i.e., in equilibrium, the firms only have to pay those who get employed, while in the capital market, it is the firms that have to accept the fluctuations of capital utilizations.

Observing the FOCs of the Lagrangian equation of the problem, note first that for the optimal $\mu(i)_{t+j}$, we have

$$r_{t+j} + \delta_{t+j} = \delta_1 \cdot \mu(i)_{t+j}^{1+\zeta} \tag{30}$$

then, both $\delta(i)_{t+j}$ and $\mu(i)_{t+j}$ can be expressed as functions of r_{t+j} according to equation (30) and definition (29). So, the problem now is analogous to the case without capital utilization considerations. Referring to problem (14) and FOCs (15) and (16), we get the firm's factor demand functions as

$$k(i)^d_{t+j} = [\frac{\alpha}{1-\alpha}]^{1-\alpha}[\frac{w_{t+j}}{r_{t+j}+\delta(i)_{t+j}}]^{1-\alpha}[\frac{y(i)_{t+j}}{z_{t+j}\mu(i)^{\alpha}_{t+j}}] \tag{31}$$

$$v(i)_{t+j}h(i)^d_{t+j} = [\frac{\alpha}{1-\alpha}]^{-\alpha}[\frac{w_{t+j}}{r_{t+j}+\delta(i)_{t+j}}]^{-\alpha}[\frac{y(i)_{t+j}}{z_{t+j}\mu(i)^{\alpha}_{t+j}}] \tag{32}$$

Also referring to equation (17), the real cost function $m(i)_{t+j}$ can be expressed as

$$m(i)_{t+j} = \phi_c(r_{t+j}+\delta(i)_{t+j})^{\alpha}w^{1-\alpha}_{t+j}[\frac{y(i)_{t+j}}{z_{t+j}\mu(i)^{\alpha}_{t+j}}] \tag{33}$$

Then, referring to Proposition (3), the firms' optimal price $p^*(i)_t$ will satisfy the same functional form given the above re-defined $m(i)_t$ and $y(i)_t$, i.e.,

$$x(i)_t - \varsigma\rho E_t x(i)_{t+1} = y(i)_t$$

where, again

$$x(i)_t \equiv [(\theta_t - 1)c(i)_t + y(i)_t] + [\frac{p^*(i)_t}{p_t}]^{-\theta_t}m(i)_t - [\frac{p^*(i)_t}{p_t}]^{-1}m(i)_t[\frac{c(i)_t}{y(i)_t}(\theta_t - 1) + 1]$$

and, again we can replace $\frac{p^*(i)_t}{p_t}$ with the gross inflation rate $\pi_t \equiv \frac{p_t}{p_{t-1}}$ according to the aggregate price equation (27).

The household's problem remain the same since capital utilization is only directly associated with firms. So, the related FOCs are the functionally same as equations (6), (7) and (8), i.e.,

$$[\frac{c(i)_t}{c_t}]^{\frac{\theta_t-1}{\theta_t}} = \lambda_t p(i)_t c(i)_t \tag{34}$$

$$-a + \lambda_t p_t w_t = 0 \tag{35}$$

$$E_t[\lambda_t p_t - \beta\lambda_{t+1}p(i)_{t+1}(1+r_{t+1})] = 0 \tag{36}$$

With the above re-defined problems of households and firms and the market equilibrium conditions, we have extended model (3), which is defined in sections 3.1, 3.2 and 3.3, to model (4), which is simply model (3) plus capital utilization.

5. SIMULATION RESULTS OF THE FOUR BUSINESS CYCLE MODELS

First we report the calibration results of the related parameters for all models. The calibration results are summarized in **Table 2**.

Table 2

α	r	ς	π	θ	μ	δ	ζ	ϕ_z	σ_z	
0.36	0.015	0.86	1.0086	12	0.86	0.025	1.00	0.95	0.712*	0.468**

Note: * For model (1) and (3); ** For model (2) and (4), the less variance is compensated by the magnifying effect of capital utilization.

For parameters commonly used in four models, readers may refer to Hansen (1985), Cooley & Prescott (1995), Baxter & Farr(2001) and King & Rebelo (1999). For the parameter calibration results associated with the NPC, in particular, we set $\varsigma = 0.86$, i.e., 86% of the firms will not adjust their product prices, referring to the GMM estimation results by Eichenbaum & Fisher (2003). Also, according to the simulation results, the parameter θ ought to be quite larger than 1, so, the mark up will be quite close to 0, i.e., the monopoly degree of the macroeconomy is quite low. The calibrated θ is obtained as the value which makes the simulated variance of inflation be closest to that of the actual economy.

In **Table 3**, **4**, **5**, and **6**, we report the simulated results of the variances, persistences and covariances of the key variables of the models. The simulation is made for 80 periods from year 1980 to 2000 for the inflation considerations. In addition, we give in Appendix 1 all of the models' impulse responses due to productivity shock in four graphs for models (1), (2), (3) and (4) respectively.

Table 3 : Simulation Results of Model (1)

	std				$corr(x(t+j), y(t))$			
Output	1.75	0.27	0.47	0.71	1.00	0.71	0.47	0.27
Capital	0.53	0.69	0.66	0.56	0.38	0.09	-0.13	-0.29
Cap utilization	Na				Na			
Labor	1.30	0.13	0.35	0.63	0.98	0.74	0.53	0.35
Consumption	0.56	0.55	0.67	0.78	0.87	0.53	0.25	0.03
Investment	6.20	0.17	0.39	0.66	0.99	0.73	0.52	0.33
Capital return	0.07	0.07	0.30	0.59	0.96	0.74	0.55	0.38
Inflation	Na				Na			
		-3	-2	-1	$j = 0$	1	2	3

Table 4 : Simulation Results of Model (2)

	std				$corr(x(t+j), y(t))$			
Output	1.75	0.27	0.47	0.71	1.00	0.71	0.47	0.27
Capital	0.65	0.69	0.65	0.55	0.37	0.08	-0.13	-0.29
Cap utilization	0.91	0.03	0.26	0.56	0.93	0.74	0.56	0.40
Labor	1.29	0.18	0.40	0.66	0.99	0.73	0.51	0.32
Consumption	0.50	0.47	0.62	0.78	0.94	0.60	0.33	0.11
Investment	6.17	0.21	0.42	0.68	1.00	0.73	0.50	0.31
Capital return	0.04	0.03	0.26	0.56	0.93	0.74	0.56	0.40
Inflation	Na				Na			
		-3	-2	-1	$j = 0$	1	2	3

Table 5 : Simulation Results of Model (3)

	std				$corr(x(t+j),y(t))$			
Output	1.75	0.27	0.47	0.71	1.00	0.71	0.47	0.27
Capital	0.53	0.69	0.66	0.56	0.38	0.09	-0.13	-0.29
Cap utilization	Na				Na			
Labor	1.30	0.13	0.35	0.63	0.98	0.74	0.53	0.35
Consumption	0.56	0.55	0.67	0.78	0.87	0.53	0.25	0.03
Investment	6.20	0.17	0.39	0.66	0.99	0.73	0.52	0.33
Capital return	0.07	0.07	0.30	0.59	0.96	0.74	0.55	0.38
Inflation	0.53	-0.27	-0.47	-0.71	-1.00	-0.71	-0.47	-0.27
		-3	-2	-1	$j=0$	1	2	3

Table 6 : Simulation Results of Model (4)

	std				$corr(x(t+j),y(t))$			
Output	1.75	0.27	0.47	0.71	1.00	0.71	0.47	0.27
Capital	0.65	0.69	0.65	0.55	0.37	0.08	-0.13	-0.29
Cap utilization	0.91	0.03	0.26	0.56	0.93	0.74	0.56	0.40
Labor	1.29	0.18	0.40	0.66	0.99	0.73	0.51	0.32
Consumption	0.50	0.47	0.62	0.78	0.94	0.60	0.33	0.11
Investment	6.17	0.21	0.42	0.68	1.00	0.73	0.50	0.31
Capital return	0.04	0.03	0.26	0.56	0.93	0.74	0.56	0.40
Inflation	0.53	-0.27	-0.47	-0.71	-1.00	-0.71	-0.47	-0.27
		-3	-2	-1	$j=0$	1	2	3

For the corresponding statistics of the actual economy, these have been calculated by many papers, for example, Cooley & Hansen (1995). Comparing with the literature, the simulation results of our model (3) and (4) are quite normal, in particular, the variances of all of the endogenous variables are quite close to those of the actual economy. Essentially, this is primarily because in symmetric equilibrium, money (inflation) in this model turns out to be superneutral, i.e., in our model (3) and (4), which have monetary frictions, the equilibrium determination of all real variables is independent of the inflation rate. So, the models are able to achieve quite good fitness. Also, it is again demonstrated in model (4) that the capital utilization can magnify the response effects of the technological shock, so, we need less volatile exogenous technical shock to generate business fluctuations.

However, there remains a very big challenge, i.e., the simulated correlations between inflation and output is not good enough compared with those of the actual economy. In actual economy, inflation π_{t+j}, where $j \geq 0$, generally has a significant positive correlation with output y_t. For example, according to the estimations by Cooley & Hansen (1995), the correlations $corr(\pi_{t+j}, y_t)$ for $j = 0, 1, 2, 3, 4, 5$ are all distributed in the interval [0.34, 0.47]. But according to **Table 5** and **6**, the simulated correlations didn't show such positive correlations.

6. CONCLUDING REMARK

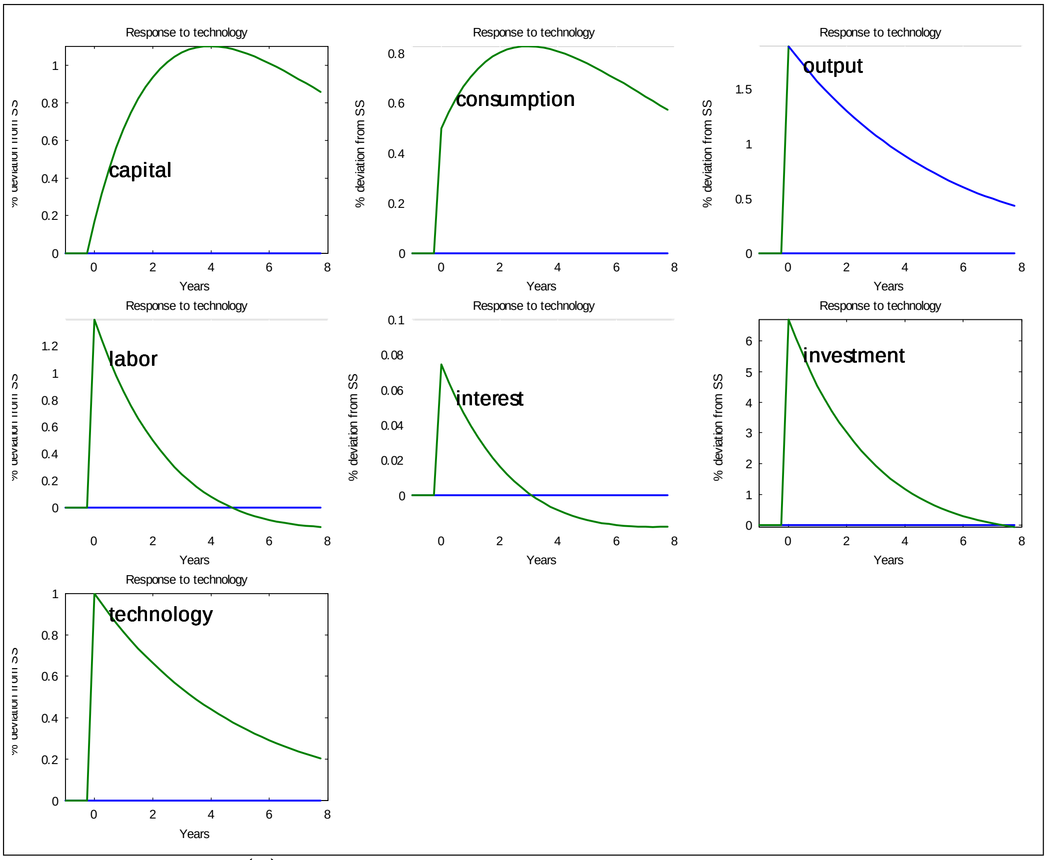
This paper is a quite preliminary study attempt on the quite challenging issue of nominal aspect dynamics of business cycle theory. And basically, it should be viewed as an exercise to try to understand the related literature in existence.

Theoretically, we manage to incorporate both sticky pricing and capital (further capital utilization) into business cycle models. Empirically, as revealed by the simulation results, the cyclical behaviors of our business cycle models with sticky pricing and endogenous capital are quite normal compared with the standard RBC literature. In particular, in all of the models, the variances of all of the endogenous variables are satisfactorily close to those of the actual economy. This is mainly because in symmetric equilibriums of our models (3) and (4), money turns out to be superneutral.

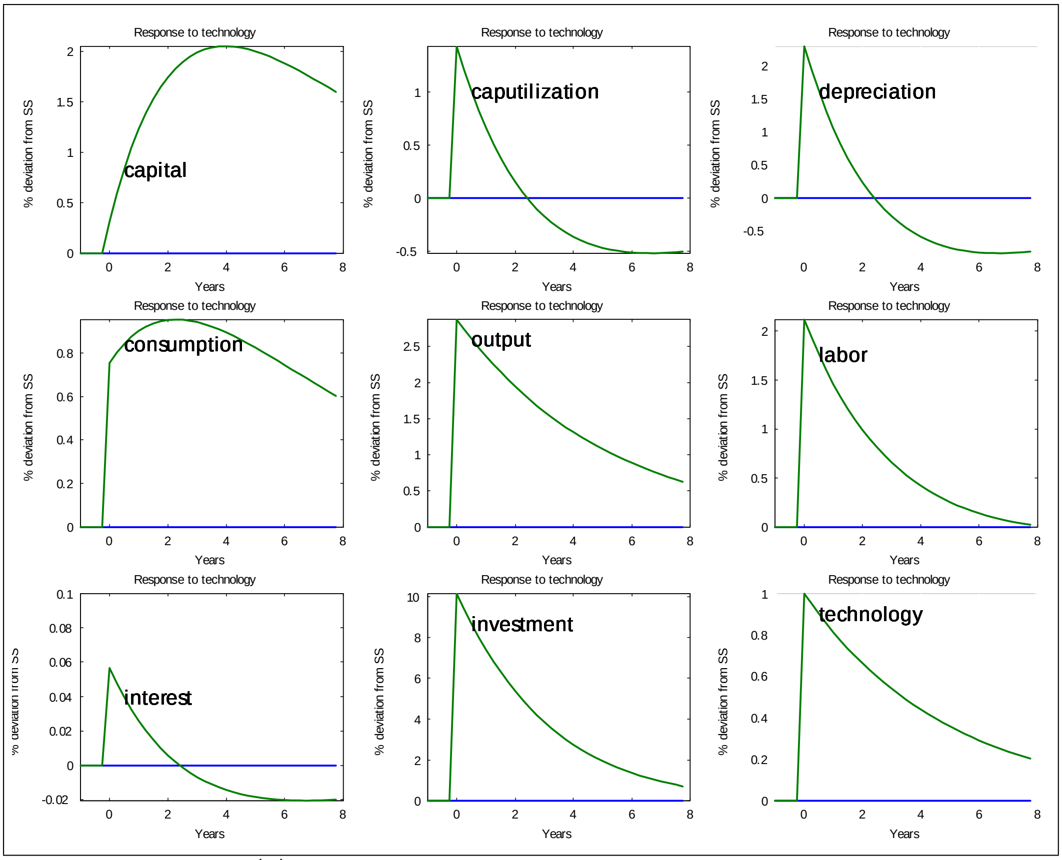
The problem of the paper is, the simulated correlations between inflation and output are not good. So, we need further working on this aspect.

7. APPENDIX 1

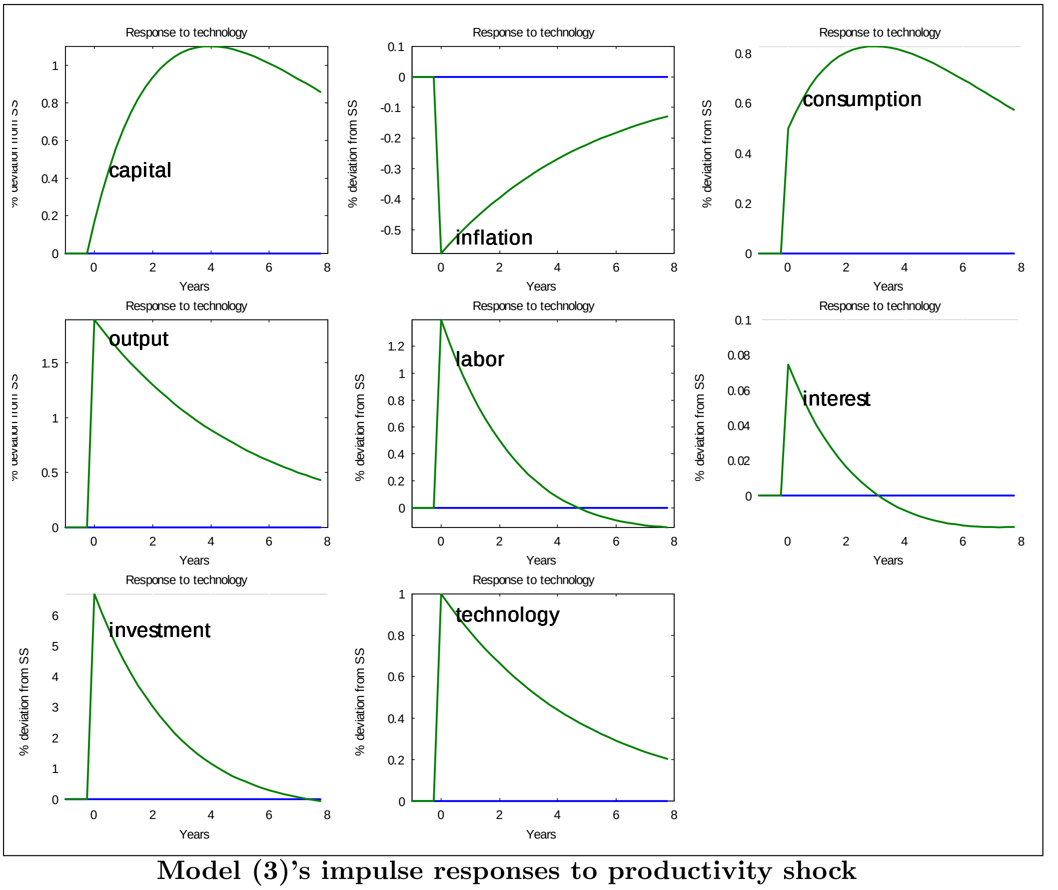
The impulse responses to productivity shock of Models (1), (2), (3) and (4) are given in the following graphs respectively.



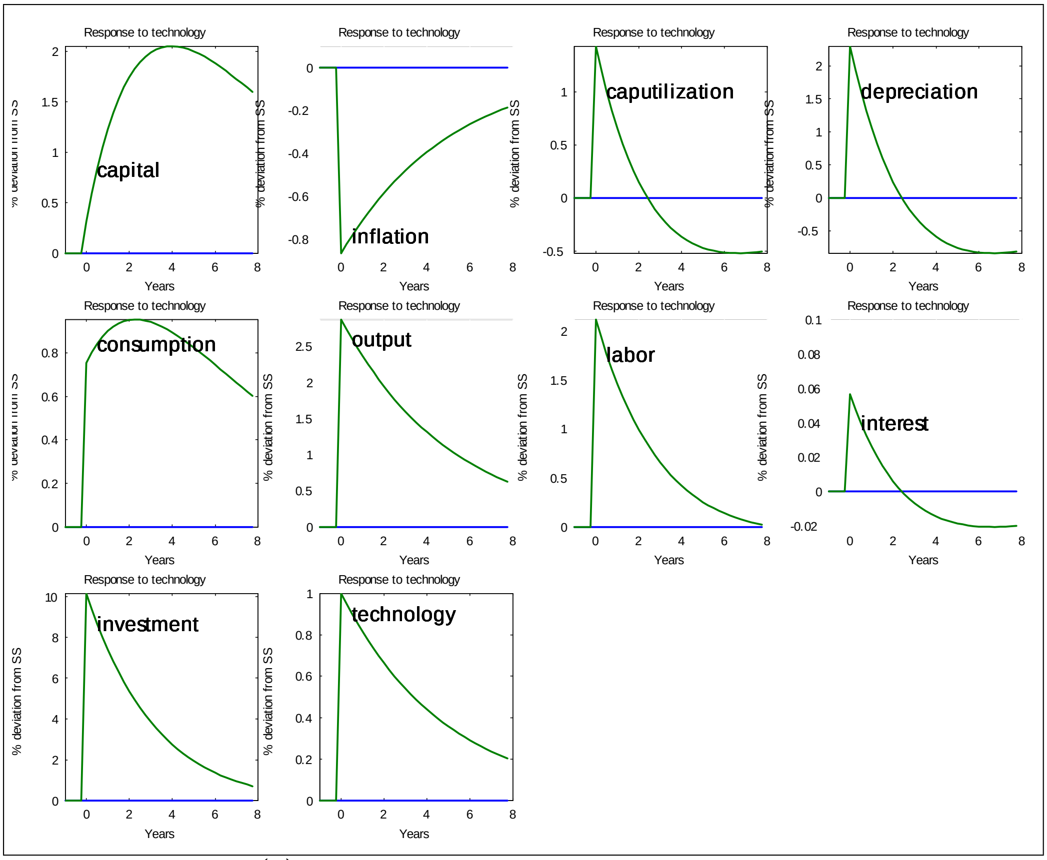
Model(1)'s impulse responses to productivity shock.



Model (2)'s impulse responses to productivity shock



Model (3)'s impulse responses to productivity shock



Model (4)'s impulse response to productivity shock

8. APPENDIX 2

Proof of Proposition(1):

Proof. In the aggregate level, in period t, let N_t denote the number of individuals who want to get a job. Then, we know that there will be N_t^e individuals who will get jobs, and N_t^u individuals who will get no jobs at period t, where, surely $N_t^e + N_t^u = N_t$. Given the representative agent assumption, i.e., given all of the individuals assumed to be identical, then according to the Chinkine's LLN, we get that the employment rate $\nu_t \equiv N_t^e / N_t * 100\%$ converges to p_t in probability since the economy's total population is assumed to be large enough. ∎

Proof of Proposition(2):

Proof.

- First taking log of equation (11) and taking derivative of $\log p(i)_t$ considering the indirect effects due to p_t and c_t ,

$$\frac{d\log c(i)_t}{d\log p(i)_t} = \frac{d\log c_t}{d\log p(i)_t} - \theta_t[1 - \frac{d\log p_t}{d\log p(i)_t}] \tag{37}$$

Then, taking log of equations (9) and (10), and rewriting them as :

$$\begin{aligned} \log c_t &= \log[\int_o^1 \exp(\log c(i)_t^{\frac{\theta_t - 1}{\theta_t}})di]^{\frac{\theta_t}{\theta_t - 1}} \\ \log p_t &= \log[\int_o^1 \exp(\log p(i)_t^{1-\theta_t})di]^{\frac{1}{1-\theta_t}} \end{aligned}$$

for these two equations, taking derivatives of $\log p(i)_t$,

$$\begin{aligned} \frac{d\log c_t}{d\log p(i)_t} &= [\frac{c(i)_t}{c_t}]^{\frac{\theta_t - 1}{\theta_t}}[\frac{d\log c(i)_t}{d\log p(i)_t}] \\ \frac{d\log p_t}{d\log p(i)_t} &= [\frac{p(i)_t}{p_t}]^{1-\theta_t} \end{aligned}$$

Plugging them into equation (37),

$$[1 - [\frac{c(i)_t}{c_t}]^{\frac{\theta_t - 1}{\theta_t}}]\frac{d\log c(i)_t}{d\log p(i)_t} = -\theta_t[1 - [\frac{p(i)_t}{p_t}]^{1-\theta_t}]$$

Notice that according to equation (11),

$$[\frac{c(i)_t}{c_t}]^{\frac{\theta_t - 1}{\theta_t}} = [\frac{p(i)_t}{p_t}]^{1-\theta_t}$$

so, if $[\frac{c(i)_t}{c_t}]^{\frac{\theta_t - 1}{\theta_t}} \neq 1$, or $[\frac{p(i)_t}{p_t}]^{1-\theta_t} \neq 1$, we must have

$$\frac{d\log c(i)_t}{d\log p(i)_t} = -\theta_t$$

So, the price elasticity of goods $c(i)_t$ is precisely $-\theta_t$.

Note that in the above derivation process we considered the indirect effects due to both p_t and c_t.

- For any two consumption goods $i_1 \neq i_2 \in [0, 1]$, as shown by Dixit & Stiglitz(1977), using equation (11), we have

$$\frac{c(i_1)_t}{c(i_2)_t} = [\frac{p(i_2)_t}{p(i_1)_t}]^{\theta_t}$$

so, $\theta_t > 0$ is precisely the elasticity of substitution between these two consumption goods $i_1 \neq i_2 \in [0, 1]$.

Proof of Proposition (3):

Proof.

- For the objective function $\max\limits_{\{p(i)_t\}}\{E_t \sum_{j=o}^{\infty}(\varsigma\rho)^j[\pi^j p(i)_t y(i)_{t+j} - p_{t+j}m(i)_{t+j}]\}$, its FOC of $p(i)_t$ can be written as

$$E_t\{d[p(i)_t y(i)_t - p_t m(i)_t]/dp(i)_t + \sum_{j=1}^{\infty}(\varsigma\rho\pi)^j y(i)_{t+j}\} = 0$$

$$\Rightarrow E_t\{[y(i)_t + p(i)_t\frac{dy(i)_t}{dp(i)_t} - \frac{dp_t}{dp(i)_t}m(i)_t - p_t\frac{dm(i)_t}{dp(i)_t}] + \sum_{j=1}^{\infty}(\varsigma\rho\pi)^j y(i)_{t+j}\} = 0 \qquad (*)$$

- For firm $i \in [0,1]$, we have $y(i)_t = c(i) + I(i)_t$

  According to our discussion and assumption made on the goods market equilibrium, i.e., the investment goods demand elasticity for goods i is -1 according to equation (24), $\frac{dI(i)_t}{dp(i)_t} = -\frac{I(i)_t}{p(i)_t}$; According to Lemma(2), $\frac{dc(i)_t}{dp(i)_t} = -\theta_t\frac{c(i)_t}{p(i)_t}$; so, $\frac{dy(i)_t}{dp(i)_t} = \frac{dc(i)_t}{dp(i)_t} + \frac{dI(i)_t}{dp(i)_t} = -\theta_t\frac{c(i)_t}{p(i)_t} - \frac{I(i)_t}{p(i)_t} = -(\frac{\theta_t c(i)_t + I(i)_t}{p(i)_t}) = -(\frac{(\theta_t-1)c(i)_t + y(i)_t}{p(i)_t})$.

- According to equation (17), $\frac{dm(i)_t}{dp(i)_t} = \frac{dm(i)_t}{dy(i)_t}\frac{dy(i)_t}{dp(i)_t} = [\frac{m(i)_t}{y(i)_t}][-\frac{(\theta_t-1)c(i)_t + y(i)_t}{p(i)_t}]$.

- According to definition (10), $\frac{dp_t}{dp(i)_t} = [\frac{p(i)_t}{p_t}]^{-\theta_t}$.

- Plugging these conditions into equation (*), we have

$$E_t\{-[(\theta_t-1)c(i)_t + y(i)_t] - (\frac{p^*(i)_t}{p_t})^{-\theta_t}m(i)_t -$$

$$(\frac{m(i)_t}{p(i)_t})(-[(\theta_t-1)c(i)_t + y(i)_t])[\frac{p^*(i)_t}{p_t}]^{-1} + \sum_{j=0}^{\infty}(\varsigma\rho\pi)^j y(i)_{t+j}\} = 0$$

$$\Rightarrow E_t\{\sum_{j=o}^{\infty}(\varsigma\rho\pi)^j y(i)_{t+j}\} = E_t x(i)_t \qquad (**)$$

  where, $x(i)_t \equiv [(\theta_t-1)c(i)_t + y(i)_t] + (\frac{p^*(i)_t}{p_t})^{-\theta_t}m(i)_t - \frac{m(i)_t}{y(i)_t}[(\theta_t-1)c(i)_t + y(i)_t][\frac{p^*(i)_t}{p_t}]^{-1}$,

  Since $\varsigma \in (0,1)$, $\rho \in (0,1)$, so, $\varsigma\rho \in (0,1)$, then, by assuming that the steady state of the gross inflation rate $\pi \geq 1$ is sufficiently close to 1 so that $\varsigma\rho\pi \in (0,1)$, multiplying both sides of equation (**) with $(1-\varsigma\rho F)$, where, F is the forward operator,

$$\Rightarrow \quad E_t\{\sum_{j=o}^{\infty}(1-\varsigma\rho\pi F)(\varsigma\rho\pi)^j y(i)_{t+j}\} = E_t(1-\varsigma\rho\pi F)x(i)_t = x(i)_t - \varsigma\rho\pi E_t x(i)_{t+1}$$

$$\Rightarrow \quad y(i)_t = E_t\{\sum_{j=o}^{\infty}(1-\varsigma\rho\pi F)(\varsigma\rho\pi F)^j y(i)_t\} = E_t\{\sum_{j=o}^{\infty}(1-\varsigma\rho\pi F)(\varsigma\rho\pi)^j y(i)_{t+j}\}$$

$$= \quad x(i)_t - \varsigma\rho\pi E_t x(i)_{t+1}$$

∎

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