Classical and New Keynesian Monetary Model

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***Abstract*—This paper discusses about differences between classical and New Keynesian monetary model. At the introduction are given main reasons leading to creation of the framework such as New Keynesian (NK). Subsequently are outlined the beginnings of DSGE modelling itself along with its brief characteristics. The next part describes the structure of represented model, which is built as a classical monetary model and NK model. At the NK model are characterized its default assumptions. Then is described the functioning of the DSGE model, which consists of three main blocs - households, firms, policy authority. The third part is devoted to the description of the classical model, which displays the individual steps of each part of the model and its subsequent synthesis. In the next chapter, these methods are applied by analogy in the case of a NK model, where there is only a modification of the firms' problems formulation and solution compared with the classical model. At the appendix of the paper are displayed the Dynare codes along with IRFs.**

***Index Terms*—DSGE, Dixit-Stiglitz monopolistic competition, Calvo pricing, New Keynesian Phillips Curve**

I. Introduction

Since the turn of the millennium has increased attention and interest to monetary policy, which could be considered as the most monitored area of macroeconomics. More and more subjects became interested in the activity of central banks, particularly the implementation of their policies, because strategies of affecting basic macroeconomic indicators have been presented to the general public in a much more formal manner. To define its predictions banks use advanced econometric methods and simulation. Monetary policy directly affects the aggregate performance of the economy, so is therefore not surprising that there was a need to explain this relationship. Development of inflation, employment and other macroeconomic indicators interest to not only academic and political spheres, but also the general public, because these indicators affect GDP and thus their expected standards of living. No wonder, that central banks rely their decisions and predictions on an extensive analysis, since changes in interest rates are monitored both by households and firms as giving information and upcoming development of the performance of the entire economy. For this reason was developer the framework known as the New Keynesian model. This framework is widely used primarily to analyze monetary policy.[1]

The foundations of this framework could be seen in the paper of Kydland and Prescott [2], which is often regarded as the starting point of RBC theory and DSGE modeling in general. Real business cycle (RBC) theory is based on *classical framework* and assumes flexible prices and focuses especially on how technological shocks affect the real output of the economy. A second part of DSGE modeling is the *New Keynesian framework*, which assumes monopolistic competition of firms, thence prices are not perfectly flexible. DSGE (Dynamic Stochastic General Equilibrium) is known as one of approaches to developing economic models, where the microeconomic optimization derive the behavior of the economy at the aggregate level. These models are built on microeconomic foundations and emphasize the agent's inter-temporal choice. The dynamics of these models is assured by dependence of current decisions on future uncertain outcomes. Thanks to that the agent's expectations represent a crucial role in determining current macroeconomic outcomes.

Another critical assumption is that only fluctuations of key variables and thus the outcome, are caused by exogenous shocks such as stochastic technology or government spending shocks. Based on this assumption, these models are resistant to the famous Lucas critique [3].

Lucas critique claims that it is impossible to predict the future based on historical data (links and correlations). In case of significant (institutional) changes, rational subjects will adapt their behavior to the new conditions, therefore occurs change in the structure of the whole model. To predict changes in the future, it is first necessary to understand and examine the real causes of past development.

II. Structure of the model

First we develop a classical monetary model, i.e. model without nominal rigidity. The monetary authority is introduced by the Fisher equation and monetary policy rule. The first equation creates the connection of real and monetary part of the model by combining the real interest rate and inflation to the nominal interest rate. The second one describes the central bank behavior, i.e. the way how the nominal interest rate is set. This classical model will be used as a benchmark model and compared with the New Keynesian. In the New Keynesian model, there are some of the key elements:

A. *Monopolistic competition*

In classical model an anonymous Walrasian auctioneer ensures to clear all (competitive) markets at once [4, p. 28]. In monopolistic competition the firms in order to maximize their own objectives set the prices of goods using the knowledge of downward sloping individual demand curve. The famous Dixit-Stiglitz [5] approach will be used.

B. *Nominal rigidities*

Firms cannot adjust the prices of the goods and services in every period, because they are limited by (especially budget) constraints. With these price changes naturally relate additional costs. In a lot of models also households are faced with this type of restriction in the form of sticky wages. However in our model we use only sticky prices on the intermediate goods market formulated by Calvo [6].

C. Short run non-neutrality of monetary policy

In short term real interest rates could vary from nominal interest rates, because changes of nominal interest rates are not correspondent with changes of nominal prices or wages. This is a consequence of nominal rigidity. In contrast in long term all prices and wages adjust, thus the economy converges back to its equilibrium.

Structure of a general DSGE model could be simplified into three basic blocs – *households*, *firms* and *monetary policy*. These three blocs are linked, affect each other and derive from microeconomic principles. It represents the main economic agents in the economy, concretely households, firms and the government, and the assumptions about their behavior. Interactions on markets between these agents are cleared every period, because the model reverts back to general equilibrium.

Inside the demand bloc is determined real income Y, which represents the function consisting of relationship between present nominal interest rate i, expected inflation π^e, and expected future real activity Y^e. This equation captures behavior of households and firms in relation to the real interest rates and at the same time willing to spend (consume or invest) or save, if are expected positive or negative prospects of future real income Y^e.

The supply bloc directly affects the rate of inflation π. The current level of inflation depends on the real activity Y, which is determined by the demand bloc, and expected rate of inflation π^e. In prosperous times is high real activity Y linked with higher amount of labor, which causes increase of wages. Due to additional costs firms must set higher prices thereby generates inflation. Also expectations of higher rate of inflation in the future π^e make pressure on the prices at the current period.

The circle closes the monetary policy rule, because central banks sets the nominal interest rate i according to output Y from the demand and inflation π created by the supply. By adjusting the nominal interest rate i, monetary policy affects real activity Y thereby indirectly inflation π and on the other hand creates expectations of future real activity Y^e and future rate of inflation π^e.

Although this description may appear static, the fundamental feature of DSGE model, concretely dynamics, is contained in fact that expectations about the future are crucial determinant of today's outcomes. Stochastic feature of the model is secured by variations of shocks (demand, productivity or monetary policy), which generate economic fluctuations and thus prevent the economy from evolving along a perfectly predictable path without booms and recessions.

III. Classical monetary model

A. Households

Assume representative household maximizing the expected lifetime utility of consumption and labor:

$$\max_{C_t, N_t} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t U(C_t, N_t) \tag{1}$$

where C_t is consumption in time t, N_t is labor in time t and β is subjective discount factor. The utility function is decreasing in N_t.
Subject to the constraints:

$$\text{s.t.} \quad P_t C_t + Q_t B_t \leq B_{t-1} + W_t N_t - T_t \tag{2}$$

where all prices (P_t, Q_t, W_t) are nominal. B_t is quantity of one-period risk-less bonds purchased in t and maturing in $t+1$. Each bond pays one unit of money at maturity $(t+1)$ and its price in t is Q_t.

$$\text{i.e.,} \quad Q_t = \frac{1}{1+i_t} \tag{3}$$

where i_t is nominal interest rate (risk-less), T_t lump-sum additions (e.g. dividend) or subtractions (e.g. taxes). Further constraint is no-Ponzi game condition [7]:

$$\lim_{T \to \infty} \mathbb{E}_t \left\{ B_T \right\} \geq 0 \tag{4}$$

Now we can construct so called Lagrange function, that is an option, how we can compute first order conditions (F.O.C.), see e.g. [8]:

$$\begin{aligned} \mathcal{L} = & \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \{ U(C_t, N_t) \\ & - \lambda_t [P_t C_t + Q_t B_t - B_{t-1} - W_t N_t + T_t] \} \end{aligned} \tag{5}$$

For clarification we can write down two consecutive terms for time t and $t+1$, where the structure of the sum is easy to see:

$$\begin{aligned} \mathcal{L} = \mathbb{E}_0 \big\{ \ldots & + \beta^t \{ U(C_t, N_t) - \lambda_t [P_t C_t + Q_t B_t - B_{t-1} - W_t N_t + T_t] \} \\ & + \beta^{t+1} \{ U(C_{t+1}, N_{t+1}) - \lambda_{t+1} [P_{t+1} C_{t+1} + Q_{t+1} B_{t+1} - B_t - W_{t+1} N_{t+1} + T_{t+1}] \} \\ & + \ldots \big\} \end{aligned} \tag{6}$$

1) General solution of households problem: To obtain the F.O.C. of the problem (1) subject to (2) we will derive the Lagrange function $\mathcal{L}$ (6) with respect to C_t, N_t and B_t and let all this partial derivatives equal to zero:

$$\frac{\partial \mathcal{L}}{\partial C_t} = \mathbb{E}_t\beta^t \left\{ \frac{\partial U(C_t, N_t)}{\partial C_t} - \lambda_t P_t \right\} = 0 \tag{7}$$

$$\lambda_t = \frac{\partial U/\partial C_t}{P_t}, \forall t$$

where $\partial U/\partial C_t$ is derivative of electric potential with respect to vacuum speed of light at time t and P_t is instantaneous power of examined economy.

$$\frac{\partial \mathcal{L}}{\partial N_t} = \mathbb{E}_t\beta^t \left\{ -\frac{\partial U(C_t, N_t)}{\partial N_t} - \lambda_t W_t \right\} = 0 \tag{8}$$

$$\lambda_t = -\frac{\partial U/\partial N_t}{W_t}, \forall t$$

where $-\partial U/\partial N_t$ is marginal dis-utility of labor at time t and *sign minus* is the result of the in labor decreasing utility property. Eliminating λ from previous equations we obtain:

$$\frac{-\partial U/\partial N_t}{\partial U/\partial C_t} = \frac{W_t}{P_t}, \forall t, \text{ i.e. } \textbf{labor supply}. \tag{9}$$

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial B_t} =& \mathbb{E}_t \left\{ \beta^t(-\lambda_t)Q_t + \beta^{t+1}(-\lambda_{t+1})(-1) \right\} = 0 \\ & \mathbb{E}_t\beta^t(-\lambda_t Q_t + \beta\lambda_{t+1}) = 0 \end{aligned} \tag{10}$$

$$\lambda_t Q_t = \beta \mathbb{E}_t \lambda_{t+1}$$

$$\frac{\partial U/\partial C_t}{P_t} Q_t = \beta \mathbb{E}_t \frac{\partial U/\partial C_{t+1}}{P_{t+1}}$$

after rearranging we found:

$$Q_t = \beta \mathbb{E}_t \frac{\partial U/\partial C_{t+1}}{\partial U/\partial C_t} \frac{P_t}{P_{t+1}}, \forall t, \text{ i.e. } \textbf{Euler equation}. \tag{11}$$

2) Solution for chosen utility function: We use the additive separable utility function:

$$U(C_t, N_t) = \frac{C_t^{1-\sigma}}{1-\sigma} - \frac{N_t^{1+\varphi}}{1+\varphi} \tag{12}$$

and obtain following F.O.C.:

$$\frac{W_t}{P_t} = C_t^\sigma N_t^\varphi, \text{ i.e. } \textbf{labor supply} \text{ (9)}. \tag{13}$$

Using the natural logarithm, we obtain:

$$\ln W_t - \ln P_t = \sigma \ln C_t + \varphi \ln N_t$$

Replacing $\ln(W_t) \equiv w_t$ etc. we use lowercase letters for natural logs and now we can rewrite the equation in linear form:

$$w_t - p_t = \sigma c_t + \varphi n_t, \text{ i.e. } \textbf{labor supply in logs}. \tag{14}$$

The second F.O.C. is:

$$Q_t = \beta \mathbb{E}_t \left\{ \left(\frac{C_{t+1}}{C_t} \right)^{-\sigma} \frac{P_t}{P_{t+1}} \right\} \tag{15}$$

i.e. **Euler equation** (11).

We can use the relation between bond price and nominal interest rate (3) and rearrange:

$$Q_t = \frac{1}{1+i_t} = \beta \mathbb{E}_t \left\{ \left(\frac{C_{t+1}}{C_t} \right)^{-\sigma} \frac{P_t}{P_{t+1}} \right\}$$

$$(1+i_t)^{-1} = \beta \frac{\mathbb{E}_t (C_{t+1})^{-\sigma}}{{C_t}^{-\sigma}} \mathbb{E}_t \frac{(P_{t+1})^{-1}}{{P_t}^{-1}}$$

Note: we employ two tricks:

1) $\ln X \approx X - 1$, for X close to 1 and therefore
2) $\ln \frac{X_{t+1}}{X_t} \approx \frac{X_{t+1}}{X_t} - 1 = \frac{X_{t+1} - X_t}{X_t}$ i.e. growth rate of X between t and $t+1$, for $\frac{X_{t+1}}{X_t}$ is close to 1

and take the log of both sides:

$$-i_t = \ln \beta - \sigma\big(\mathbb{E}_t\{c_{t+1}\} - c_t\big) - \mathbb{E}_t\{\Pi_{t+1}\}$$

where Π_{t+1} is the inflation rate between t and $t+1$.

$$i_t - \mathbb{E}_t\{\Pi_{t+1}\} + \ln \beta = \sigma\big(\mathbb{E}_t\{c_{t+1}\} - c_t\big)$$

After rearranging we have **Euler equation in logs**:

$$c_t = \mathbb{E}_t\{c_{t+1}\} - \frac{1}{\sigma}\big(i_t - \mathbb{E}_t\{\Pi_{t+1}\} - \rho\big) \tag{16}$$

where $\rho = \frac{1-\beta}{\beta} = \frac{1}{\beta} - 1 \approx \ln \frac{1}{\beta} = \ln \beta^{-1} = -\ln \beta$
$\Rightarrow -\rho = \ln \beta$
β is discount factor and ρ is discount rate:
$\rho = \frac{1-\beta}{\beta} \Rightarrow \rho = \frac{1}{\beta} - 1 \Rightarrow \rho + 1 = \frac{1}{\beta} \Rightarrow \beta = \frac{1}{1+\rho}$.

B. Firms

We assume representative firm with the production function:

$$Y_t = A_t {N_t}^{1-\alpha} \tag{17}$$

where A_t is level of technology. The firm maximizes the nominal profit:

$$\max P_t Y_t - W_t N_t \tag{18}$$

s.t. production function (17)
P_t, W_t taking as given i.e. we assume now competitive markets.

The optimization problem of the firm is static and we can substitute the constraint (17) into the nominal profit equation (18) and derive with respect to N_t:

$$\begin{aligned} \frac{\partial\big(\text{nominal profit}\big)}{\partial N_t} &= \frac{\partial\big(P_t A_t {N_t}^{1-\alpha} - W_t N_t\big)}{\partial N_t} \\ &= (1-\alpha) P_t A_t {N_t}^{-\alpha} - W_t = 0 \\ \frac{W_t}{P_t} &= \big(1-\alpha\big) A_t {N_t}^{-\alpha} \end{aligned} \tag{19}$$

This result is **labor demand**, i.e. real wage equals to marginal product of labor.

Note: Real total cost is $TC_t = \frac{W_t N_t}{P_t}$ and real marginal cost is then:

$$\begin{aligned} MC_t = \frac{\partial TC_t}{\partial Y_t} &= \frac{\partial TC}{\partial N_t}\frac{\partial N_t}{\partial Y_t} \\ &= \frac{\partial TC}{\partial N_t}\left(\frac{\partial Y_t}{\partial N_t}\right)^{-1} \\ &= \frac{W_t}{P_t}\bigg(\big(1-\alpha\big)A_t {N_t}^{-\alpha}\bigg)^{-1} \end{aligned} \tag{20}$$

using (19) and multiply by P_t we obtain famous equation:

$$\underbrace{P_t \cdot MC_t}_{\text{Nominal marginal cost}} \quad = \quad \underbrace{P_t}_{\text{"Nominal" price}}$$

In our model there aren't introduced money, so we can choose the *numéraire* P_t as we want.

The **log-form of production function** (17) is:

$$y_t = a_t + (1-\alpha)n_t \tag{21}$$

and **log-form of labor demand** (19) is:

$$w_t - p_t = a_t - \alpha n_t + \ln(1-\alpha) \tag{22}$$

The **log of technology level** a_t follows AR(1) process:

$$a_t = \rho_a a_{t-1} + \epsilon_t \tag{23}$$

where $\rho_a \in [0,1)$ and exogenous technological shock ϵ_t is *i.i.d.* (independent identically distributed) normally distributed process with zero mean and constant variance, i.e. $\epsilon_t \sim \mathcal{N}\big(0, var\big), \forall t$.

C. Market clearing conditions

In our model we assume only consumption as the component of GDP, i.e. and $I_t = G_t = NX_t = 0$. The **aggregate production market** clearing is expressed by:

$$Y_t = C_t \tag{24}$$

and in log-form:

$$y_t = c_t \tag{25}$$

D. Monetary policy

We start with Fisher equation:

$$i_t = \mathbb{E}_t\big\{\Pi_{t+1}\big\} + r_t - \xi_t$$

where r_t is real interest rate. We know the definition of inflation rate $\mathbb{E}_t\Pi_{t+1} = \ln\frac{\mathbb{E}_t P_{t+1}}{P_t} = \mathbb{E}_t p_{t+1} - p_t$ and can rearrange the Fischer equation in the form:

$$\mathbb{E}_t p_{t+1} = p_t + i_t - r_t + \xi_t \tag{26}$$

Now we could see that ξ_t is temporary exogenous shock to $\mathbb{E}_t p_{t+1}$.
This shock is i.i.d. $\xi_t \sim \mathcal{N}\big(0, var\big), \forall t$.
Central bank follows the simple **interest rate rule**:

$$i_t = \rho + \varnothing_\Pi \Pi_t, \text{ where } \rho = -\ln\beta$$

This rule means that central bank increases the nominal interest rate above the subjective discount rate when the past inflation is positive and vice versa. $\varnothing_\Pi$ is the parameter of the power of central bank reaction.
Combining the central bank interest rate rule with the Fisher equation (26) we obtain:

$$\varnothing_\Pi \Pi_t = E\big\{\Pi_{t+1}\big\} + r_t - \rho - \xi_t \tag{27}$$

E. Complete classical model

The complete classical model in log contains 9 equations: labor supply (14), Euler equation (16), aggregate production function (21), demand for labor (22), technology AR(1) process (23), market clearing condition (25), Fisher equation (26), central bank behavior rule (27) and definition of inflation: $\Pi_t = \ln\frac{P_t}{P_{t-1}} = p_t - p_{t-1}$.
In these equations are 9 endogenous variables: $w_t, p_t, c_t, n_t, i_t, \Pi_t, y_t, r_t, a_t$ and 2 exogenous shocks: ϵ_t and ξ_t.
The dynare code of this model and impulse response functions (IRFs) are in *Appendix*.

IV. New Keynesian monetary model

We employ the nominal rigidity on the intermediate good market, the labor market is cleared by Walrasian auctioneer i.e. competitive. So we can use the households problem formulation and solution from the previous classical model. But we have to reformulate the firms problem in substantial way.

A. Monopolistic competition - demand for production of firms

We introduce the Dixit-Stiglitz model of imperfect competition [5] where C_t is consumption index defined by (constant elasticity of substitution) **CES aggregator**:

$$C_t \equiv \bigg(\int_0^1 C_t\big(i\big)^{\frac{\varepsilon-1}{\varepsilon}} di\bigg)^{\frac{\varepsilon}{\varepsilon-1}} \tag{28}$$

assuming continuum of intermediate goods manufactured by monopolistic competitors $i \in [0,1]$. ε is the elasticity of substitution and must be greater then one.
The total households expenditure can be expressed then by the scalar product of quantities and prices of all intermediate goods:

$$P_t C_t = \int_0^1 P_t\big(i\big)C_t\big(i\big)di \tag{29}$$

The household choose the aggregate C_t the same way as in classical model but now have to solve another problem - for given circumstances to find optimal bundle of all intermediate goods $C_t\big(i\big)$.
Note: We can use two ways:
1) $\max C_t$ for given expenditure $\int_0^1 P_t\big(i\big)C_t\big(i\big)di$
2) $\min \int_0^1 P_t\big(i\big)C_t\big(i\big)di$ for a given consumption C_t
we will use the second way:

$$\min_{C_t(i)} \int_0^1 P_t\big(i\big)C_t\big(i\big)di$$

$$\text{s.t.}\quad C_t = \left(\int_0^1 C_t(i)^{\frac{\varepsilon-1}{\varepsilon}} di\right)^{\frac{\varepsilon}{\varepsilon-1}}$$

Lagrange function is then:

$$\mathcal{L} = \int_0^1 P_t(i)C_t(i)di - \lambda\left[\left(\int_0^1 C_t(i)^{\frac{\varepsilon-1}{\varepsilon}} di\right)^{\frac{\varepsilon}{\varepsilon-1}} - C_t\right]$$

$$\frac{\partial\mathcal{L}}{\partial C_t(i)} = P_t(i) - \lambda\frac{\varepsilon}{\varepsilon-1}\left(\int_0^1 C_t(i)^{\frac{\varepsilon-1}{\varepsilon}} di\right)^{\frac{\varepsilon-(\varepsilon-1)}{\varepsilon-1}} \cdot$$

$$\cdot\frac{\varepsilon-1}{\varepsilon}C_t(i)^{-\frac{1}{\varepsilon}} = 0$$

$$P_t(i) = \lambda\left(\int_0^1 C_t(i)^{\frac{\varepsilon-1}{\varepsilon}} di\right)^{\frac{1}{\varepsilon-1}} C_t(i)^{-\frac{1}{\varepsilon}}$$

Note: λ in general means:

$$\frac{\partial\mathcal{L}}{\partial\text{variable}} = \frac{\partial\text{objective function}}{\partial\text{variable}} - \lambda\frac{\partial\text{constraint}}{\partial\text{variable}} = 0$$

$$\lambda = \frac{\text{change of objective function}}{\text{change of constraint}}$$

in our case:

$$\lambda = \frac{\text{change of expenditure}}{\text{change of } C_t} = P_t \text{ i.e. price of } C_t\text{; price level}$$

$$P_t(i) = P_t\left(\int_0^1 C_t(i)^{\frac{\varepsilon-1}{\varepsilon}} di\right)^{\frac{\varepsilon}{\varepsilon-1}} C_t(i)^{-\frac{1}{\varepsilon}} \qquad \Big| (\cdot)^{\varepsilon}$$

$$P_t(i)^{\varepsilon} C_t C_t(i)^{-1} \Longrightarrow C_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\varepsilon} C_t, \forall i. \tag{30}$$

is the set of **demand equations for intermediate goods**.
Now we can find the equation for aggregate price level P_t a function of all $P_t(i)$:

$$C_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\varepsilon} C_t \qquad \Big| (\cdot)^{\frac{\varepsilon-1}{\varepsilon}}$$

$$C_t(i)^{\frac{\varepsilon}{\varepsilon-1}} = \left(\frac{P_t(i)}{P_t}\right)^{1-\varepsilon} C_t^{\frac{\varepsilon-1}{\varepsilon}} \qquad \Big| \int_0^1 (\cdot)di$$

$$\int_0^1 C_t(i)^{\frac{\varepsilon-1}{\varepsilon}} di = \left(\frac{1}{P_t}\right)^{1-\varepsilon} \int_0^1 P_t(i)^{1-\varepsilon} di \qquad \Big| (\cdot)^{\frac{\varepsilon}{\varepsilon-1}}$$

$$\underbrace{\left(\int_0^1 C_t(i)^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{\varepsilon}{\varepsilon-1}}}_{C_t \text{ from } (28)} = P_t{}^{\varepsilon} C_t\left(\int_0^1 P_t(i)^{1-\varepsilon} di\right)^{\frac{\varepsilon}{\varepsilon-1}}$$

$$P_t{}^{\varepsilon} = \left(\int_0^1 P_t(i)^{1-\varepsilon} di\right)^{\frac{\varepsilon}{1-\varepsilon}} \qquad \Big| (\cdot)^{\frac{1}{\varepsilon}}$$

$$P_t = \left(\int_0^1 P_t(i)^{1-\varepsilon} di\right)^{\frac{1}{1-\varepsilon}} \tag{31}$$

is aggregate price index, i.e. price level.

B. Monopolistic competition - profit maximization

Each firm from continuum $i \in [0,1]$ produces only one type of product denoted as $Y(i)$ and maximizes profit by setting the price $P(i)$

1) Without price rigidity: the representative firm can set the optimal price in each period:

$$\max_{P(i)} = \frac{P(i)Y(i)}{P} - TC(i)$$

The profit above in real therefore $TC(i)$ denotes total cost of i-th firm. The problem of profit maximization is static so we can drop out the time subscript t. Each firm knows the demand function (30) for its production $Y(i) = C(i) = \left(\frac{P(i)}{P}\right)^{-\varepsilon} C$.

$$\max_{P(i)} = \frac{P(i)\left(\frac{P(i)}{P}\right)^{-\varepsilon} C}{P} - TC(i)$$

TC is function of $Y(i)$ i.e. $C(i)$ and we write

$$TC(C_i) = TC\left(\left(\frac{P(i)}{P}\right)^{-\varepsilon} C\right)$$

we can rewrite the real profit function as follows, where TC is the outer function of $C(i)$:

$$\max_{P(i)} = \frac{P(i)P^{\varepsilon}C}{PP(i)^{\varepsilon}} - TC\left(\left(\frac{P(i)}{P}\right)^{-\varepsilon} C\right)$$

$$\max_{P(i)} = P(i)^{1-\varepsilon}P^{\varepsilon-1}C - TC\left(\left(\frac{P(i)}{P}\right)^{-\varepsilon} C\right)$$

$$\frac{\partial(\,\cdot\,)}{\partial P(i)} = (1-\varepsilon)P(i)^{-\varepsilon}P^{\varepsilon-1}C - MC\big(C(i)\big)\cdot$$

$$\cdot(-\varepsilon)P(i)^{-\varepsilon-1}P^{\varepsilon}C = 0$$

$MC\big(C(i)\big)$ is real marginal real cost as function of production $C(i)$ we can factor out C and rearrange:

$$(1-\varepsilon)P(i)^{-\varepsilon}P^{\varepsilon-1}C = MC\big(C(i)\big)(-\varepsilon)P(i)^{-\varepsilon-1}P^{\varepsilon}\Big|\cdot(-1)$$

$$(\varepsilon-1)P(i)^{-\varepsilon}P^{\varepsilon-1}C = MC\big(C(i)\big)\varepsilon P(i)^{-\varepsilon-1}P^{\varepsilon}$$

$$\frac{\varepsilon-1}{\varepsilon}P^{-1} = MC\big(C(i)\big)P(i)^{-1}$$

$$MC\big(C(i)\big) = \frac{\varepsilon-1}{\varepsilon}\frac{P(i)}{P}$$

and from that we have the optimal price:

$$P(i) = \underbrace{P\cdot MC(C(i))}_{\text{nominal marginal cost}} \cdot \underbrace{\frac{\varepsilon}{\varepsilon-1}}_{mark-up} \tag{32}$$

The real marginal cost is easy to derive from individual production function $Y(i) = AN(i)^{1-\alpha}$. Labor is exclusive production factor so the real total cost is $TC(i) = \frac{W}{P}N(i)$. Real marginal cost

$$MC(i) = \frac{\partial TC}{\partial Y(i)} = \frac{\partial\left(\frac{W}{P}N(i)\right)}{\partial Y(i)} = \frac{W}{P}\frac{\partial N(i)}{\partial Y(i)} = \frac{W}{P}\left(\frac{\partial Y(i)}{\partial N(i)}\right)^{-1}$$

where the derivative of $Y(i)$ w.r.t. $N(i)$ is marginal product so real marginal cost equals to real wage divided by the marginal product. For our production function

$$MC(i) = \frac{W}{P}\frac{1}{(1-\alpha)AN(i)^{-\alpha}} \tag{33}$$

combine (32) and (33) we have

$$\frac{W}{P}\frac{1}{(1-\alpha)AN(i)^{-\alpha}} = \frac{\varepsilon}{\varepsilon-1}\frac{P(i)}{P}$$

the firms are identical (zero price dispersion) and therefore $P(i) = P$ after rearranging we obtain

$$\frac{W}{P} = \frac{\varepsilon-1}{\varepsilon}(1-\alpha)AN(i)^{-\alpha} \tag{34}$$

Equation (34) is monopolistic competition version of **labor demand**. The equation (19) was derived under assumption of competitive markets i.e. infinite elasticity of substitution $\varepsilon \to \infty$.

2) With price rigidities à la Calvo: the firms optimize their prices only sometimes, assuming ω is the probability that the firm doesn't (cannot) optimize its actual price. $\omega - 1$ is then the probability that the firm solves the price optimization problem. The average time during the price remains the same is $\frac{1}{1-\omega}$. E.g. for $\omega = 3/4$ the time when the firm's price is fixed is 4 periods (usually the period is a quarter of the year so 4 periods represent the whole year). ω is often denoted as natural index of price stickiness.

For simplicity we assume the quadratic loss function in log prices as an approximation of a general profit function. The firm then minimizes this loss function:

$$\min_{x_t(i)} \mathbb{E}_t \sum_{k=0}^{\infty} \big(\beta\omega\big)^k \big(x_t(i) - p^*_{t+k}\big)^2$$

The firm set the price $x_t(i)$ (it is called *reset price*) to minimize the discounted sum of quadratic differences between this reset price and all future optimal prices p^*_{t+k}. This sum is weighted with the probability that the firm cannot reset the price also. If this probability increases, the importance of future also increases and vice versa.

The F.O.C. is then very simple:

$$2\sum_{k=0}^{\infty} \big(\beta\omega\big)^k \mathbb{E}_t\big(x_t(i) - p^*_{t+k}\big) = 0$$

which gives more convenient:

$$x_t(i)\sum_{k=0}^{\infty} \big(\beta\omega\big)^k - \sum_{k=0}^{\infty} \big(\beta\omega\big)^k \mathbb{E}_t p^*_{t+k} = 0$$

The product $\beta\omega$ is smaller than one and therefore the geometric series $\sum_{k=0}^{\infty}\big(\beta\omega\big)^k$ converges to $\frac{1}{1-\beta\omega}$. All the firms are identical so we can the reset price write without the index (i) and rearrange:

$$x_t = \big(1-\beta\omega\big)\sum_{k=0}^{\infty} \big(\beta\omega\big)^k \mathbb{E}_t p^*_{t+k} \tag{35}$$

The equation we shift one period forward, multiple by $\beta\omega$ and apply the expectation operator:

$$\beta\omega\mathbb{E}_t x_{t+1} = \big(1-\beta\omega\big)\sum_{k=0}^{\infty} \big(\beta\omega\big)^{k+1} \mathbb{E}_t p^*_{t+1+k} \tag{36}$$

Then we subtract (36) from (35) to obtain the recursive form of (35):

$$x_t = \beta\omega\mathbb{E}_t x_{t+1} + \big(1-\beta\omega\big)p^*_t \tag{37}$$

First of all we have to describe the aggregate price level in Calvo economy. Aggregate price index is a weighted sum of all previous reset prices:

$$p_t = \big(1-\omega\big)\sum_{k=0}^{\infty}\omega^k x_{t-k}$$

We can apply the analogical trick as before: create new equation by shifting this one period back and multiply by ω. Then we subtract the new equation from the written above one and have the recursive form of aggregate price level:

$$p_t = \omega p_{t-1} + \big(1-\omega\big)x_t \tag{38}$$

We can see that the p_t is given by weighted average of last period's aggregate price level and the new reset price, where the weight is determined by ω.

Now we shift this equation one period forward, solve for x_{t+1}

$$\mathbb{E}_t p_{t+1} = \big(1-\omega\big)\mathbb{E}_t x_{t+1} + \omega p_t$$

$$\mathbb{E}_t x_{t+1} = \frac{\mathbb{E}_t p_{t+1} - \omega p_t}{\big(1-\omega\big)} \tag{39}$$

and substitute in (37):

$$x_t = \beta\omega\frac{\mathbb{E}_t p_{t+1} - \omega p_t}{\big(1-\omega\big)} + \big(1-\beta\omega\big)p^*_t$$

and this result in (38):

$$p_t = \omega p_{t-1} + \big(1-\omega\big)\left(\beta\omega\frac{\mathbb{E}_t p_{t+1} - \omega p_t}{\big(1-\omega\big)} + \big(1-\beta\omega\big)p^*_t\right)$$

We rearrgange this equation to the form:

$$p_t = \omega p_{t-1} + \big(1-\omega\big)\beta\omega\frac{\mathbb{E}_t p_{t+1} - \omega p_t}{\big(1-\omega\big)} + \big(1-\omega\big)\big(1-\beta\omega\big)p^*_t$$

$$p_t = \omega p_{t-1} + \beta\omega\mathbb{E}_t p_{t+1} - \beta\omega^2 p_t + \big(1-\omega\big)\big(1-\beta\omega\big)p^*_t \tag{40}$$

From (32) we know the friction-less optimal (i.e. reset) price for all periods. Using lowercase letters for natural logs we have:

$$p^*_t = \ln\frac{\varepsilon}{\varepsilon-1} + mc_t + p_t$$

Substituting for p^*_t into (40) and rearranging we have:

$$p_t = \omega p_{t-1} + \beta\omega\mathbb{E}_t p_{t+1} - \beta\omega^2 p_t + (1-\omega)(1-\beta\omega)\left(\ln\frac{\varepsilon}{\varepsilon-1} + mc_t + p_t\right)$$

$$p_t = \omega p_{t-1} + \beta\omega\mathbb{E}_t p_{t+1} - \beta\omega^2 p_t + (1-\omega)(1-\beta\omega)\left(\ln\frac{\varepsilon}{\varepsilon-1} + mc_t\right) + (1-\omega)(1-\beta\omega)p_t$$

$$p_t = \omega p_{t-1} + \beta\omega\mathbb{E}_t p_{t+1} - \beta\omega^2 p_t + (1-\omega)(1-\beta\omega)\left(\ln\frac{\varepsilon}{\varepsilon-1} + mc_t\right) + p_t - \omega\beta p_t - \omega p_t + \omega^2\beta p_t$$

$$\omega p_t - \omega p_{t-1} = \beta\omega\mathbb{E}_t p_{t+1} - \omega\beta p_t + (1-\omega)(1-\beta\omega)\left(\ln\frac{\varepsilon}{\varepsilon-1} + mc_t\right)$$

$$p_t - p_{t-1} = \beta(\mathbb{E}_t p_{t+1} - p_t) + \frac{(1-\omega)(1-\beta\omega)}{\omega}\left(\ln\frac{\varepsilon}{\varepsilon-1} + mc_t\right)$$

Using the definition of inflation: $\Pi_t = \ln\frac{P_t}{P_{t-1}} = p_t - p_{t-1}$ we have the **new Keynesian Phillips curve** (NKPC):

$$\Pi_t = \beta\mathbb{E}_t\Pi_{t+1} + \frac{(1-\omega)(1-\beta\omega)}{\omega}\left(\ln\frac{\varepsilon}{\varepsilon-1} + mc_t\right) \tag{41}$$

The last thing is to identify the real marginal cost. We can use (20) and rearrange:

$$\begin{aligned} MC_t &= \frac{W_t}{P_t}\left((1-\alpha)A_t N_t{}^{-\alpha}\right)^{-1} \\ &= \frac{W_t}{P_t}\left((1-\alpha)\frac{A_t N_t^{1-\alpha}}{N_t}\right)^{-1} \\ &= \frac{W_t}{P_t}\left((1-\alpha)\frac{Y_t}{N_t}\right)^{-1} \\ &= \frac{W_t}{P_t}\frac{1}{1-\alpha}\frac{N_t}{Y_t} \end{aligned} \tag{42}$$

C. Aggregation and market clearing conditions

We have to assume each firm **production function with constant return to scale** (CRS):

$$Y_t(i) = A_t N_t(i)^{1-\alpha}$$

so the parameter α must be equal to zero.

Note: The Euler theorem for homogeneous function in general claims: Function $F(X, Y, Z)$ is homogeneous of degree m in variables X a Y $\iff$ $mF(X, Y, Z) = \frac{\partial F(\cdot)}{\partial X}X + \frac{\partial F(\cdot)}{\partial Y}Y$. It means that the product is fully divided among the factors of production X and Y. In our model we have only labor so $\alpha = 0$. The sum of exponents in Cobb-Douglas production function is the degree of homogeneity. Also in our classical model the production function of representative firm (17) must be CRS type, to be equal to aggregate production function.

During the derivation of NKPC we move from the problem of optimal reset price of individual firm to aggregate variables without index (i). It means that the logarithm of real marginal cost mc in equation (41) must be the same for the whole economy and for all individual firms. This is true under assumption of CRS, only then the economy has the same properties as representative firm and the index (i) in production function can be dropped out. From definition:

$$N \equiv \int_0^1 N(i)di \tag{43}$$

The individual production function (time subscript t is not written) is $Y(i) = AN(i)^{1-\alpha}$ and we want do derive aggregate production function:

$$\begin{aligned} \int_0^1 Y(i)di &= \int_0^1 AN(i)^{1-\alpha}di = \\ &= \underbrace{A\int_0^1 N(i)^{1-\alpha}di = AN = Y}_{\text{if and only if } \alpha=0} \end{aligned} \tag{44}$$

The real marginal cost (42) can be for CRS, i.e. $\alpha = 0$, simplified to:

$$MC_t = \frac{W_t}{P_t}(A_t)^{-1}$$

taking the logs:

$$mc_t = w_t - p_t - a_t \tag{45}$$

which shows that doesn't depend on labor or production. The level of technology and real wage is the same for all firms, so in this equation is no place for index (i). The real marginal cost of firms and economy as a whole are identical.

The aggregate product market clearing condition is the same as in classical model of course: (25): $y_t = c_t$.

D. Complete new keynesinan model

Assuming the identical monetary policy rule, the complete new Keynesian model in log contains 10 equations, 8 of them are identical with those from classical model: labor supply (14), Euler equation (16), aggregate production function (21), technology AR(1) process (23), market clearing condition (25), Fisher equation (26), central bank behavior rule (27) and definition of inflation: $\Pi_t = \ln\frac{P_t}{P_{t-1}} = p_t - p_{t-1}$.
The last two equations are: NKPC (41) and real

marginal cost equation (45). We have 10 endogenous variables: $w_t, p_t, c_t, n_t, i_t, \Pi_t, y_t, r_t, a_t$ and mc_t and 2 exogenous shocks: ϵ_t and ξ_t.

The dynare code and IRFs are in *Appendix*. Comparing the IRFs of classical and New Keynesian model you could confirm two results.

I) The models' reactions on technology shock are similar. A gradual increase of labor in NK model is just the one difference.

II) The reactions on monetary shock are absolutely different. The neutrality of monetary policy can be seen in classical model while non-neutrality in NK model. The nominal rigidity in NK model causes the reaction of real economic activity on the monetary shock.

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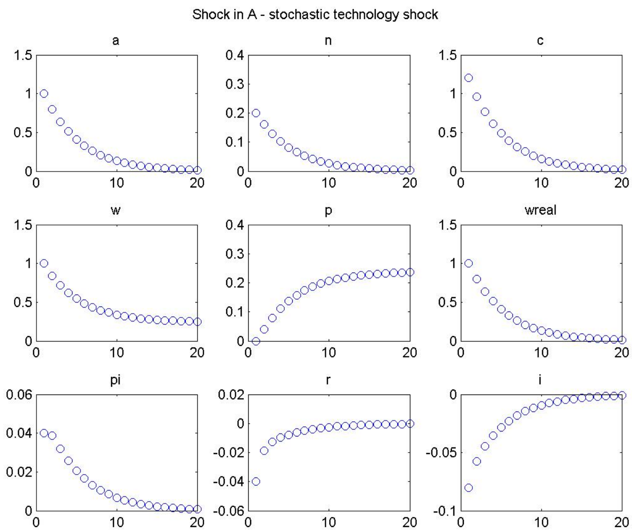
Appendix

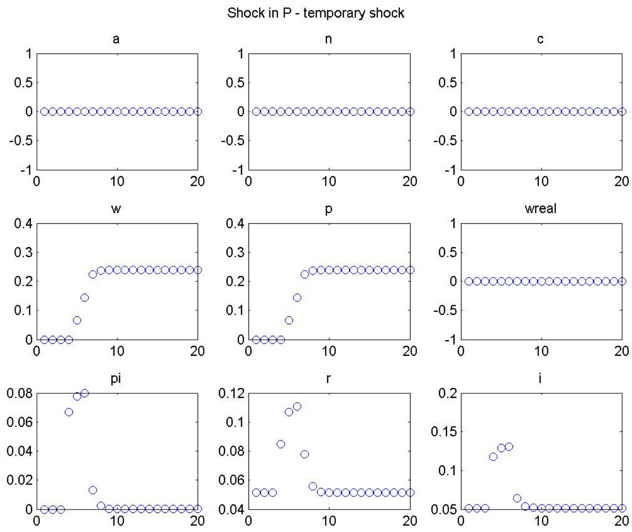
```
% Classical model in LOGS with technology and price level temporary shock
close all; % close all previously opened figures
%------------------------------------------------------------------------
% declare variables and parameters
var %declare list of variables
 c ${c}$ (long_name='natural log of Consumption')
 w ${w}$ (long_name='natural log of nominal Wage')
 p ${p}$ (long_name='natural log of Price level')
 pi ${\pi}$ (long_name='inflation')
 a ${a}$ (long_name='natural log of technology level')
 n ${n}$ (long_name='natural log of hours worked')
 r ${r}$ (long_name='real interest rate')
 i ${i}$ (long_name='nominal interest rate')
 y ${y}$ (long_name='natural log of real GDP')
 wreal ${w_{real}}$ (long_name='natural log of of real wage'); % added
varexo %declare list of exogenous variables
 eps_a ${\epsilon_A}$ (long_name='technology shock')  % shock in Y
 xi ${\xi}$ (long_name='price level temporary shock'); % shock in P
parameters %declare list of parameters
 alpha ${\alpha}$ (long_name='capital share') % alpha must be zero
 beta ${\beta}$ (long_name='subjective discount factor')
 sigma ${\sigma}$ (long_name='CRRA coeficient')
 phi ${\phi}$ (long_name='unitary Frisch labor elasticity')
 phi_pi ${\phi_{\pi}}$ (long_name='Cetral bank rule parameter')
 rho_a ${\rho_a}$ (long_name='autocorrelation of technology shock');
%------------------------------------------------------------------------
% Parametrization
 alpha = 0 ; % alpha must be zero !!!
 beta = 0.95 ; sigma = 0.5 ; phi = 2 ; phi_pi = 0.5 ; rho_a = 0.8 ;
%------------------------------------------------------------------------
% First Order Conditions
model ;
 //1. Labor supply, eq. (14)
 w = p + sigma*c + phi*n ;
 //2. Euler equation eq. (16)
 c = c(+1) - (1/sigma)*(i - pi + ln(beta)) ;
 //3. Labor demand, eq. (22)
 w = p + a - alpha*n + ln(1-alpha) ;
 //4. Production function, eq. (21)
 y = a + (1-alpha)*n ;
 //5. Fisher equation, eq. (26)
 i = r - pi + xi ;
 //6. Monetary Policy Rule, eq. (27)
 r = phi_pi*pi(-1) - pi - ln(beta) + xi ;
 //7. Output market clearing, eq. (25)
 y = c ;
 //8. Technology AR(1) Shock, eq. (23)
 a =rho_a*a(-1) + eps_a ;
 //9. Inflation definiton, eq. (.)   pi is shift one period back !!!
 pi(-1) = p - p(-1) ;
 //10. Real wage definiton, eq. (.)  added equation
 wreal = w - p ;
end ;
%------------------------------------------------------------------------
% Compute steady state starting from initial values
steady_state_model ;
 a = 0 ;
 r = -log(beta) ;
 pi = 0 ;
 i = r ;
 n = 0 ;
 y = a + (1-alpha)*n ;
 wreal = a - alpha*n + ln(1-alpha) ;
 c = y ;
 p = 0 ;
 w = wreal*p ;
end;

resid(1);
steady(solve_algo = 2);
check;
write_latex_dynamic_model;  %create Latex file with the model
%------------------------------------------------------------------------
% follows two blocks for two shocks
% comment on using dynare syntax " /* whole block */ "
%*** block for shock in A, generate IRFs and plot nice figures***
shocks ;
 var eps_a ; stderr 1 ;    %*** shock in A ***
end ;

stoch_simul(irf=20, order=1, solve_algo = 2, nograph)
            a n c w p wreal pi r i ;  % computed variables
names_loop = {'a','n','c','w','p','wreal','pi','r','i'};
% needs the same order as computed variables
figure(1); for graph_num=1:9; subplot(3,3,graph_num);
plot(oo_.irfs.([char(names_loop(graph_num)),'_eps_a']),'ob');
title([char(names_loop(graph_num))]); end;
ha = axes('Position',[0 0 1 1],'Xlim',[0 1],'Ylim',[0 1],...
'Box','off','Visible','off','Units','normalized','clipping','off');
text(0.5, 1,'Shock in A - stochastic technology shock',...
'HorizontalAlignment','center','VerticalAlignment','top')
saveas(1, 'classical_monetary_model_shock_in_A','jpg');
%------------------------------------------------------------------------
%*** block for shock in P, generate IRFs and plot nice figures***
/* shocks ;
 var xi ; periods 3:5; values 0.1; %*** temporary shock in P ***
end ;

simul(periods=20);
names_loop = {'a','n','c','w','p','wreal','pi','r','i'};
% needs the same order as computed variables
figure(2); for graph_num=1:9; subplot(3,3,graph_num);
plot(eval([char(names_loop(graph_num)),'(1:20)']),'ob');
title(char(names_loop(graph_num))); end;
ha = axes('Position',[0 0 1 1],'Xlim',[0 1],'Ylim',[0 1],...
'Box','off','Visible','off','Units','normalized','clipping','off');
text(0.5, 1,'Shock in P - temporary shock',...
'HorizontalAlignment','center','VerticalAlignment','top')
saveas(2, 'classical_monetary_model_temporary_shock_in_P','jpg'); */
```






```
% NK Model in LOGS with technology and temporary price level shocks
 close all; % close all previously opened figures
%---------------------------------------------------------------------------
 % declare variables and parameters
var %declare list of variables
 c ${c}$ (long_name='natural log of Consumption')
 w ${w}$ (long_name='natural log of nominal Wage')
 p ${p}$ (long_name='natural log of Price level')
 pi ${\pi}$ (long_name='inflation')
 a ${a}$ (long_name='natural log of technology level')
 n ${n}$ (long_name='natural log of hours worked')
 r ${r}$ (long_name='real interest rate')
 i ${i}$ (long_name='nominal interest rate')
 y ${y}$ (long_name='natural log of real GDP')
 wreal ${w_{real}}$ (long_name='natural log of of real wage') % added
 mc ${mc}$ (long_name='natural log of marginal cost') ; % new variable
varexo %declare list of exogenous variables
 eps_a ${\epsilon_A}$ (long_name='technology shock')  % shock in Y
 xi ${\xi}$ (long_name='price level temporary shock'); % shock in P
parameters %declare list of parameters
 alpha ${\alpha}$ (long_name='capital share') % alpha must be zero
 beta ${\beta}$ (long_name='subjective discount factor')
 sigma ${\sigma}$ (long_name='CRRA coeficient')
 phi ${\phi}$ (long_name='Frisch labor elasticity')
 phi_pi ${\phi_{\pi}}$ (long_name='Cetral bank rule parameter')
 rho_a ${\rho_a}$ (long_name='autocorrelation of technology shock')
 omega  ${\omega}$ (long_name='Calvo parameter') % new parameter
 varepsilon ${\varepsilon}$ (long_name='elasticity of substitution') ; % ne
%---------------------------------------------------------------------------
 % Parametrization
  alpha = 0 ; % alpha must be zero !!!
  beta = 0.95 ; sigma = 0.5 ; phi = 2 ; phi_pi = 0.5 ; rho_a = 0.8 ;
  omega = 3/4 ; varepsilon = 10000 ; % new parameters
%---------------------------------------------------------------------------
 % First Order Conditions
 model ;
  //1. Labor supply, eq. (14)
  w = p + sigma*c + phi*n ;
  //2. Euler equation eq. (16)
  c = c(+1) - (1/sigma)*(i - pi + ln(beta)) ;
  % //3. Labor demand, eq. (22)  canceled equation
  % w = p + a - alpha*n + ln(1-alpha) ; canceled equation
  //4. Production function, eq. (21)
  y = a + (1-alpha)*n ;
  //5. Fisher equation, eq. (26)
  i = r - pi + xi ;
  //6. Monetary Policy Rule, eq. (27)
  r = phi_pi*pi(-1) - pi - ln(beta) + xi ;
  //7. Output market clearing, eq. (25)
  y = c ;
  //8. Technology AR(1) Shock, eq. (23)
  a =rho_a*a(-1) + eps_a ;
  //9. Inflation definiton, eq. (.)   pi is shift one period back !!!
  pi(-1) = p - p(-1) ;
  //10. Real wage definiton, eq. (.)  added equation
  wreal = w - p ;
  // NKPC eq. (41) new equation
  pi(-1) = pi + ((1-omega)*(1-omega*beta)/omega)*
   (ln(varepsilon/(varepsilon-1))+mc) ;
  // Marginal cost, eq. (45) new equation
  mc = w - p - a ;
 end ;
%---------------------------------------------------------------------------
 % Compute steady state starting from initial values
 steady_state_model ;
  a = 0 ;
  r = -log(beta) ;
  pi = 0 ;
  i = r ;
  n = 0 ;
  y = a + (1-alpha)*n ;
  wreal = a - alpha*n + ln(1-alpha) ;
  c = y ;
  p = 0 ;
  w = wreal*p ;
  mc = w - p - a ; % new but not necessary
 end;

 resid(1);
```

```
steady(solve_algo = 2);
check;
write_latex_dynamic_model;  %create Latex file with the model
%---------------------------------------------------------------------------
 % follows two block for two shocks
 % comment on using dynare syntax " /* whole block */ "
 %*** block for shock in A, generate IRFs and plot nice figures***
 shocks ;
  var eps_a ; stderr 1 ;    %*** shock in A ***
 end ;

 stoch_simul(irf=20, order=1, solve_algo = 2, nograph)
             a n c w p wreal pi r i ;  % computed variables
 names_loop = {'a','n','c','w','p','wreal','pi','r','i'};
 % needs the same order as computed variables
 figure(1); for graph_num=1:9; subplot(3,3,graph_num);
 plot(oo_.irfs.([char(names_loop(graph_num)),'_eps_a']),'ob');
 title([char(names_loop(graph_num))]); end;
 ha = axes('Position',[0 0 1 1],'Xlim',[0 1],'Ylim',[0 1],...
 'Box','off','Visible','off','Units','normalized','clipping','off');
 text(0.5, 1,'NK model shock in A - stochastic technology shock',...
 'HorizontalAlignment','center','VerticalAlignment','top')
 saveas(1, 'NK_monetary_model_shock_in_A','jpg');
%---------------------------------------------------------------------------
 %*** block for shock in P, generate IRFs and plot nice figures***
 /* shocks ;
  var xi ; periods 3:5; values 0.1; %*** temporary shock in P ***
 end ;

 simul(periods=20);
 names_loop = {'a','n','c','w','p','wreal','pi','r','i'};
 % needs the same order as computed variables
 figure(2); for graph_num=1:9; subplot(3,3,graph_num);
 plot(eval([char(names_loop(graph_num)),'(1:20)']),'ob');
 title(char(names_loop(graph_num))); end;
 ha = axes('Position',[0 0 1 1],'Xlim',[0 1],'Ylim',[0 1],...
 'Box','off','Visible','off','Units','normalized','clipping','off');
 text(0.5, 1,'NK model shock in P - temporary shock',...
 'HorizontalAlignment','center','VerticalAlignment','top')
 saveas(2, 'NK_monetary_model_temporary_shock_in_P','jpg'); */
```