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**Embodied Technology and Monetary Shocks; Lumps, Bumps,
and Humps**

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Abstract

VAR analysis of monetary shocks suggest that an unanticipated, positive money shocks cause a drop in nominal interest rates, and increases in output, consumption, prices, and wages. Further, impulse responses indicate a "hump shaped" pattern with the maximum effect felt 1-2 years after the initial shock. Limited participation models can replicate the contemporaneous correlations of money shocks, but have difficulty with the longer run dynamics. This paper integrates a limited participation framework in a vintage capital model in an attempt to strengthen the monetary transmission mechanism.

1. Introduction

The literature on monetary policy shocks documents that a positive money shock leads to a persistent fall in the nominal interest rate and a persistent rise in real output. Furthermore, the dynamics following the shock resemble a "hump shaped" pattern. For example, Christiano, Eichenbaum, and Evans (1997) use a VAR analysis and document the following stylized facts for a positive shock to money.:

- Output follows a hump shaped pattern with the peak occurring 2 years following the shock.
- Hump shaped response of inflation with the peak response 2.5 years following the shock.
- Hump shaped response to consumption with the peak response 1.5-2 years following the shock.
- Interest rates remain low for a year following the shock.
- Real wages, productivity and profits rise following the shock.

These observations are at odds with standard economic theory. In standard cash-in-advance models, the typical result of an unexpected monetary injection

is a fall in output and employment and a rise in nominal interest rates. This is because these models only capture the anticipated inflation effect of a monetary innovation. In the Cooley and Hansen (1989) framework, for example, a monetary innovation raises expectations of inflation. This increase in the inflation tax on wages lowers the cost of leisure relative to consumption. Therefore, labor supply is reduced and output subsequently falls. In Stockman (1981), the inflation tax lowers the price of consumption relative to capital causing a decline in investment. Again, the end result is that output falls.

The argument behind the failure of these models is that they can only capture the *anticipated inflation effect* of a monetary shock. Assuming that households believe that higher current money growth will be followed by higher future money growth results in expectations of higher future prices and causes borrowers and lenders to add an inflation premium to nominal interest rates. This anticipated inflation effect raises nominal interest rates and depresses economic activity. An additional effect of monetary shocks is referred to as a *liquidity effect*: extra money in the economy pushes down real interest rates which increases economic activity. The evidence supports the view that, at least in the short run, the liquidity effect of a money shock dominates the anticipated effect.

Modifications to the standard cash in advance models, referred to collectively as limited participation models, have been proposed by such authors as Lucas (1990), Fuerst (1990), and Christiano and Eichenbaum (1999) to generate the liquidity effect of a money shock. Limited participation models assume that financial institutions are in continuous contact with firms who borrow to finance either investment or labor expenditures. Households save through deposits held by the financial intermediary, but cannot continuously adjust their savings decision. The central bank conducts open market operations directly with these financial institutions. In this framework, unexpected monetary injections create "excess liquidity" in the financial market. Consequentially, firms are forced to absorb a disproportionately large share of the added money which puts downward pressure on real interest rates and increases economic activity. While limited participation models improve contemporaneous money/output correlations, they still fail to generate the amount of persistence seen in the data. Specifically, the liquidity effect of a monetary shock only exists during the period of the shock. I argue that this lack of persistence is not due to inadequacy of the monetary transmission mechanism, but can be accounted for by the lack of a strong propagation mechanism in the neoclassical view of capital accumulation.

Limited participation models are extensions of the standard neoclassical framework and therefore inherit the neoclassical view of capital accumulation in which changes in the capital stock take place smoothly over time. This view is clearly contradicted in the data. Doms and Dunne (1993) use a 12,000 plant study and find that, over a 15 year period, 25% of a plant's investment expenditures is concentrated in a single year - 50% is concentrated in a contiguous 3 year period. In this paper I construct a model where capital accumulation is "lumpy", occurring all at once when old plants are replaced with new ones.

Previous studies suggest that investment specific technological change is a potentially important source of growth. Bahk and Gort (1993) find that a one year change in the age of capital is associated with a 2.5 to 3.5 % rise in output. Greenwood, Hercowitz and Krusell (1994) argue that 60% of post war growth can be attributed to investment specific technological progress. Additionally, there is evidence showing that the production of capital goods is becoming more efficient over time. Gordon (1990) documents that the relative price of capital in terms of consumption has declined in the U.S. economy. These observations suggest that new technology is embodied in new capital goods.

Some of the earliest work on vintage capital was pioneered by Robert Solow. In Solow (1962), capital had a fixed lifetime and the amount of labor in a plant

was fixed over its lifetime. Here, I allow the firm to efficiently allocate labor over plants. A result of this is that older plants will employ less labor than plants with newer technology. This is consistent with the observation that older plants are smaller than newer firms. Greenwood, Cooley, and Yorukoglu (1997) construct a non-monetary vintage capital economy to examine the implications of changes in the tax treatment of capital. Among their findings is that the dynamics of capital accumulation are strikingly different from the standard models. Particularly, the dynamics of capital accumulation are more "sluggish" than in standard models. In this paper I use a monetary vintage capital framework to examine the implications of vintage capital for the real effects of monetary shocks. Real effects of money enter through the limited participation framework used by previous authors. I show that a limited participation setup with vintage capital can produce much more persistent effects of money shocks.

The remainder of the paper is as follows: In section two, the economic environment is outlined. The highlight of this section is the firm's investment decision. In standard models, the firm's investment decision can be reversed in the next period. Therefore, the first order condition for capital accumulation only involves a one period forecast of the state of the world. Here, investment decisions are irreversible for the lifetime of the capital. Therefore, the forecast must be made

over the lifetime of capital. In section three, the model's general equilibrium is explicitly defined. Section four describes the model's balanced growth path. In section five, the model is calibrated to match salient features of the US economy. Sections six and seven analyze the results of the model by exploring the impact of monetary shocks on the model's steady state and the transitional dynamics.

2. The Economic Environment

There exists a representative firm which operates a continuum of manufacturing plants distributed over the unit interval. Plants are indexed by the age of the capital. Capital has a lifetime of N periods after which it is scrapped. Therefore, every period an age N plant is retired and must be replaced with a new plant. The firm must decide how to allocate labor across plants as well as how much capital to install in a new plant. Once the capital is installed, it is in place until it is retired in N periods. Capital goods become more productive over time, so as a plant ages its capital becomes less productive relative to new capital. There is no physical depreciation. Agents in the economy allocate time over labor and leisure and income over cash and deposits. There is a financial intermediary that holds deposits for consumers and loans money to the firm. The role of government is to adjust the money supply via open market operations conducted directly with

the financial intermediary.

2.1. Production

There exists a representative firm that operates a continuum of manufacturing plants. Capital has a life of N years, after which it is unusable. Therefore, manufacturing plants are identified by the age of the capital employed. With a uniform distribution, the measure of plants of age i equals $1/N$. The firm must decide the size of a new plant as well as how to allocate labor over the various plants. Consider a representative age i plant. It has at its disposal k_i efficiency units of capital and employs l_i units of labor. It produces output according to the following technology

$$y_i = k_i^\alpha l_i^\omega \quad \alpha + \omega \leq 1 \quad (2.1)$$

where y_i is output. Output can be converted to consumption goods on a one to one basis. However, as in Greenwood, Hercowitz, and Huffman (1994), the economy becomes more efficient over time at producing capital goods. Let q_t represent the time t state of technology for producing capital goods. Technology for capital goods production grows at the exogenous rate of γ_q . Let i_t represent new investment and k_{1t+1} represent capital to be placed in a new plant. New

capital formation is governed by the following process.

$$k_{1t+1} = q_t i_t \tag{2.2}$$

Manufacturing plants take prices and wages as given and choose labor to maximize profits. Given the nominal wage w the plant will hire labor in accordance with the following static maximization problem.

$$\Pi_i(k_i, w) = \max_{l_i} \{pk_i^\alpha l_i^\omega - wl_i\} \tag{2.3}$$

where p is the nominal price of a consumption good. The first order condition associated with this problem is

$$w = \omega p k_i^\alpha l_i^{\omega-1} \tag{2.4}$$

substituting this into (2.3) results in the following profit function

$$\Pi_i^c(k_i, w) = p(1 - \omega) k_i^\alpha l_i^\omega \tag{2.5}$$

The representative firm manager must also decide how much capital to place in the new plants. The firm pays wages out all of current revenues, but borrows

from the financial intermediary at the nominal interest rate to finance investment expenditures. Any profits are payed out as dividends. An alternate setup would be to have the firm pay out a fraction of its profits as dividends and use retained earnings to finance renovations, but the results would be similar. Either way, the firm will incur an opportunity cost equal to the prevailing nominal interest rate r . The setup here is chosen for simplicity. This decision is in line with the following dynamic programming problem. Note that primed variables indicate next period values.

$$V(k_1, \dots, k_N; s) = \max_{k'_1} \left\{ \sum_{i=1}^N p \left(\frac{1}{N} \right) \Pi_i^c(k_i, w) - (1+r) \left(\frac{1}{N} \right) \left(\frac{1}{q_t} \right) k'_i + E_t \left\{ \frac{V(')}{1+r} \right\} \right\} \quad (2.6)$$

subject to

$$k'_{i+1} = k_i, i = 1, \dots, N - 1 \quad (2.7)$$

$$k_{N+1} = 0$$

Equation (2.7) is the rule for capital accumulation. Age i capital today will be

age $i + 1$ capital tomorrow. The first order condition associated with this problem is

$$(1 + r) \left(\frac{1}{q} \right) = E_t \left\{ \frac{V_1 (')}{1 + r'} \right\} \quad (2.8)$$

with

$$V_i (') = \psi_i \Pi_i^c (k_i', w') + E_{t+1} \left\{ \frac{V_{i+1} ('')}{1 + r''} \right\} \quad (2.9)$$

Equation (2.8) determines the amount of capital to be placed in a new plant. The cost of an extra unit of capital is $\frac{(1+r)}{q}$ while the benefit is $V_1 (') / (1 + r)$ represents the derivative of the value function with respect to k_1 . This can be solved forward to yield

$$(1 + r_t) \left(\frac{1}{q_t} \right) = E_t \sum_{i=1}^N \left\{ \prod_{j=1}^i (1 + r_{t+j})^{-1} \right\} \Pi_{i1}^c (k_{t+i}, w_{t+i}) \quad (2.10)$$

This expression states that today's marginal cost of capital must equal the present value of value marginal products over its lifetime. This is much different from the standard first order condition for capital which only depends on the marginal product one period forward.

2.2. Consumers

Consumers in the economy have preferences defined over random streams of consumption and leisure represented by the expected utility function

$$E_0 \sum_{t=0}^{\infty} \beta^t W(c_t, 1 - l_t) \quad (2.11)$$

$$W(c, l; \lambda) = \ln \left(c - \lambda \frac{\Theta l^{1+\nu}}{1+\nu} \right)$$

where c represents consumption, l represents labor, $\beta < 1$ is the discount rate and E_0 represents the conditional expectation based on information available at time 0. The form of the utility function is justified by Greenwood, Rogerson, and Wright (1994) as being consistent with household production theory. The term λ represents the state of technology in the household production sector.

At the beginning of period t , the economy's money supply is held by consumers in the form of cash and deposits. One can think of cash as money held in a checking account which earns zero interest and deposits as money held in a savings account earning nominal interest $r_t > 0$. A key assumption is that the composition of an individual's portfolio is made in the previous period. Although cash earns no

interest, it is required to purchase goods through the familiar cash in advance constraint

$$p_t c_t \leq m_t^c \quad (2.12)$$

At the end of the period, households receive income from the following sources: wage income, interest earned on their savings, dividends from banks and dividends from the firm (of which they are the owners).

$$p_t I_t = w_t l_t + (1 + r_t) m_t^d + \Pi_t^b + \Pi_t^f \quad (2.13)$$

Money income can be allocated for consumption purposes or can be saved. Saved income is divided between a household's checking account and savings accounts

$$s_t = (m_{t+1}^c - m_t^c) + (m_{t+1}^d - m_t^d) \quad (2.14)$$

Where $m_{t+1}^d, m_{t+1}^c \geq 0$ (households cannot issue money). Also, the household faces the budget constraint

$$p_t c_t + s_t = w_t l_t + (1 + r_t) m_t^d + \Pi_t^b + \Pi_t^f \quad (2.15)$$

the household's decision problem is to choose a contingency plan for

$\{c_t, l_t, m_{t+1}^c, m_{t+1}^d\}_{t=0}^{\infty}$ that maximizes expected lifetime utility subject to the series of constraints.

The unskilled workers problem can be written in the following recursive formulation. Note that to save on notation, time subscripts have been left out. Primed variables indicate their $t+1$ values. s represents the state of the world which will be defined later.

$$J(m^c, m^d; s) = \underset{c, l, m^{c'}, m^{d'}}{\text{Max}} \left\{ \begin{array}{l} W(c, l) + \beta E_t J(m^{c'}, m^{d'}; s') \\ + \lambda_1 \left(\begin{array}{l} w l + (1 + r) m^d + \Pi^b + \Pi^f \\ - m^{c'} - m^{d'} \end{array} \right) \\ + \lambda_2 (m^c - p c) \end{array} \right\} \quad (2.16)$$

The upshot of the dynamic programming problem are the following first order conditions

$$W_1(c, l) = p\lambda_2 \quad (2.17)$$

$$-W_2(c, l) = w\lambda_1 \quad (2.18)$$

$$\beta EJ_1(m^{c'}, m^{d'}, s') = \lambda_1 \quad (2.19)$$

$$\beta EJ_2(m^{c'}, m^{d'}, s') = \lambda_1 \quad (2.20)$$

Along with the following envelope conditions

$$J_1(m^c, m^d, s) = \lambda_2 \quad (2.21)$$

$$J_2(m^c, m^d, s) = (1 + r)\lambda_1 \quad (2.22)$$

Using the first order conditions along with the envelope conditions, the unskilled worker's problem can be reduced to the following two efficiency conditions.

$$\frac{W_2(c, l)}{w} = \beta E \left\{ \frac{W_1(c', l')}{p'} \right\} \quad (2.23)$$

$$\frac{W_2(c, l)}{w} = \beta E \left\{ (1 + r) \frac{W_2(c', l')}{w'} \right\} \quad (2.24)$$

Equation (2.23) is the efficiency condition for cash balances. On the left hand side is the marginal cost of obtaining one unit of cash in terms of foregone leisure time. That is, $1/w$ hours of work is required to earn one unit of cash. The marginal disutility of labor $W_2(c, l)$ converts the hours into utility. The left hand side of (2.23) is the expected benefit of the extra unit of cash in terms of the expected utility of the consumption it can purchase. Equation (2.24) is the efficiency condition for deposits. Deposits cannot be used for consumption, but can be used to purchase the credit good in this economy - leisure. Therefore, the left hand side of (2.24) is the marginal cost of obtaining an additional unit of deposits while the left hand side is the marginal benefit of the leisure time that can be purchased next period.

2.3. Financial Intermediaries

Financial intermediaries collect deposits from consumers and loan the money out to firms. They also receive cash injections from the government. Denoting cash transfers by τ , the financial intermediaries profits are the difference between interest collected from the firm and interest paid out on deposits to consumers and can be written as

$$\begin{aligned}\Pi^b &= (m^d + \tau)(1 + r) - (m^d)(1 + r) \\ &= (1 + r)\tau\end{aligned}\tag{2.25}$$

2.4. Government

The government in this model has only one purpose which is to regulate the supply of money. The rule for money supply is given by

$$m_{t+1} = (1 + \mu_{mt}) m_t\tag{2.26}$$

$$\mu_{mt+1} = \rho\mu_{mt} + \phi_t\tag{2.27}$$

$$\phi \sim N(0, 1)$$

The government adds to the money supply by transferring τ_t to the financial intermediary.

$$\tau_t = m_{t+1} - m_t = \mu_{mt} m_t \tag{2.28}$$

3. Equilibrium

The model is completed by a description of the state of the world. This is given by the vector $s = \{k_1, \dots, k_N, \mu_m, m\}$. Given the definition of the state, the competitive equilibrium can be defined as a set of decision rules $\{c, l, m^c, m^d, k_i\}$ and a set of pricing functions $\{p, r, w\}$ such that

- 1) Consumers optimize, taking interest rates, wages, and prices as given, resulting in decisions for consumption, labor, cash and deposits given by c, l, m^c, m^d
- 2) The representative firms and all plants maximize profits taking interest rates, wages, and prices as given. The resulting decisions are represented by k'_1, l_i .
- 3) Given the behavior of consumers and producers, prices adjust such that markets clear, as represented by the following conditions

$$\tau + m^d = \psi_1 k_1' \quad (3.1)$$

$$c + k_1' = \sum_{i=1}^N \psi_i k_i^\alpha l_i^\gamma \quad (3.2)$$

$$\sum_{i=1}^N \psi_i l_i = l \quad (3.3)$$

$$m^d + m^e = m' \quad (3.4)$$

4. Calibration

The model is calibrated using *a priori* information or so that along the model's balanced growth path various endogenous variables assume the long run values seen in the US. data. The method used in this paper follows Cooley, et. al. (1997). The model has 10 parameters which need to be calibrated. They are as follows

technology: $\alpha \quad \omega \quad \gamma_\eta \quad N$

preferences: $\beta \quad \nu \quad \Theta$

policy: $\gamma_m \quad \rho$

A time period is chosen to correspond to one year. Over the post war period, labor's share of income has averaged .65. This implies that $\omega = .65$. The value of $1/\nu$ corresponds to labor supply elasticity. Following Greenwood, Hercowitz and Huffman (1988), a value of .6 was chosen. This implies a value of 1.7 for the labor supply elasticity, which is an average found by earlier researchers.

The average growth rate of output per hour was 1.24 percent between 1954-90. Thus, the model should satisfy the property

$$\gamma_y = 1.0124 \tag{4.1}$$

The average ratio of hours to non sleeping hours of the working age population is .25. Therefore,

$$l = .25. \tag{4.2}$$

Money growth is chosen to be 5%. This implies that $\gamma_m = 1.05$. For the AR(1) process governing the evolution of money growth, an autocorrelation coefficient

of .6 is chosen. Finally, the nominal interest rate is chosen to be 9%. This yields the restriction

$$\frac{\gamma_m}{\beta} = 1.09 \tag{4.3}$$

Using these restrictions implies the following parameter values

$$\begin{aligned} \alpha &= .2 \\ \omega &= .65 \\ \gamma_k &= 1.06 \\ \beta &= .9633 \\ \nu &= .6 \\ \Theta &= .476 \\ \gamma_m &= 1.05 \\ \rho &= .6 \end{aligned}$$

The only parameter left is the lifetime of capital, N . It is unclear what the appropriate value should be. This depends on the specific definition of capital. Here, the value was set to 8. The results were qualitatively the same when N was increased.

5. Steady State

Money in this model is neutral, but not super-neutral. That is, the level of money supply does not affect real variables. It only rescales nominal prices. Changes in money growth, however effect the steady state through an "inflation tax" on both investment and labor supply. Firms must repay the loans they make to purchase new capital before revenues are received the following period. Therefore, higher inflation implies lower steady state investment in new plants and consequently a lower aggregate capital stock. A smaller capital stock in itself implies lower levels of employment due to the fact that labor and capital are compliments, but in addition, workers also pay an inflation tax on earnings. This is due to the fact that workers are paid after the consumption market has closed. Therefore, they can't use their earnings to purchase consumption goods until the following period. Higher money growth lowers the real return to working and hence lowers labor supply.

With regards to the effects of changes in the lifetime of capital, a caveat needs to be added. The lifetime of capital should not be thought of as a purely exogenous parameter. Clearly, the decision on when to replace capital should be endogenous. For simplicity, this decision is not modeled explicitly here and N

should be thought of as a closed form solution to that decision. For example, N could be thought of as a function of taxes and subsidies aimed at capital formation as in Cooley, et al(1997). An increase in the lifetime of capital could be the result of decreases in investment tax credits. With this in mind, consider a change in the number of vintages. The age distribution of plants in this economy is uniform. Therefore, the measure of plants with age i capital is $1/N$. Each period, the age N plant is retired and all its capital is lost. Therefore, the aggregate capital stock falls by k_N/N . As the number of vintages increases, two there are two opposing effects. If a new plant has a longer lifetime, more capital is placed in that plant. However, with a larger number of vintages, the measure of a new plant is smaller and therefore has a smaller impact on the aggregate capital stock. It turns out that the second effect dominates. Therefore, with a larger number of vintages, the fraction of the aggregate capital stock that is scrapped declines. This would be analogous to a decrease in the depreciation rate in the standard neoclassical model.

6. Transitional Dynamics

The experiment run in this section is an unexpected one standard deviation increase in money growth. To compute the dynamics, the model is linearized around

the steady state. The system of difference equations characterizing the model's dynamics has $N + 1$ eigenvalues with modulus less than one. This corresponds to the model's $N + 1$ state variables k_1, \dots, k_N and m^c . Therefore, the transition path is stable and unique. The dynamics of the vintage capital are strikingly different from standard models. Figures 1 – 8 represent the impulse responses of key variables in the economy. The period of the money shock produces the standard result of most liquidity effects models. The nominal interest rate falls and output, employment, and consumption increases. The magnitude of the drop in the nominal is smaller than in previous studies, but is easily explained by the first order condition for capital. The persistent decline in the nominal interest rate simultaneously raises the present value of future marginal products as well as lowers the current marginal cost. Therefore, the current rate doesn't need to fall by as much to entice firms to purchase more capital. It is in the periods following the shock that the vintage capital structure alters the dynamic paths returning the economy to the steady state. Notice the hump shaped pattern of output, and consumption along with the persistent drop in the nominal interest rate. This comes out of the enhanced persistence mechanism of the vintage capital framework. . With the life of capital set at ten years, a money shock creates a persistent rise in new capital formation. With new investment persistently above

steady state, the aggregate capital stock builds on ot . It should be noted that the experiment was run using several values of N . The results were qualitatively the same with the degree of persistence varying in proportionately with N . These results are drastically different from the standard monetary models. This might possibly be too much persistence. One way to alleviate some of this would be to add physical depreciation into the model.

7. Conclusions

Monetary models of the US. economy are capable of producing realistic contemporaneous correlations with respect to nominal interest rates and output, but tend to fail in generating the amount of persistence seen in the data. The stance taken here is that the monetary transmission mechanism which translates changes in money supply into changes in the real economy is the correct one. The propagation mechanism of capital investment, however, needs to be altered in order to generate the amount of persistence required.

Empirical studies at the microeconomic level show that plant level expenditures do not adjust smoothly as the standard neoclassical framework suggests, but are in fact "lumpy"- occurring infrequently and in bursts. This suggests that a model with vintage capital might be a more accurate representation of capital

expenditures. Further, studies have shown that technological progress which is specific to investment goods is an important source of growth in the US. economy. While previous vintage capital models have been used to examine the effect of tax policy on capital accumulation, the vintage framework has yet to be used to examine monetary issues. This paper attempts to fill that gap.

I construct a vintage capital model where new technology is embodied in new capital goods. The monetary transmission is introduced through a limited participation setup where monetary injections do not coincide with individual's savings decisions. The resulting excess liquidity in the financial sector acts to drive down nominal interest rates and boost investment spending. While the manner in which money is introduced into the model is not unique, adding a vintage structure to capital formation is. The results show that unexpected monetary shocks can create lasting effects on the real economy. Further, the dynamics reveal the hump shaped pattern seen in empirical studies.

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Figure 1: New Investment

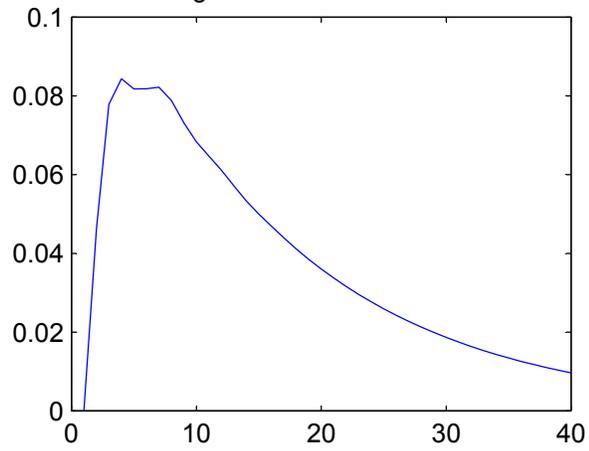


Figure 2: Consumption

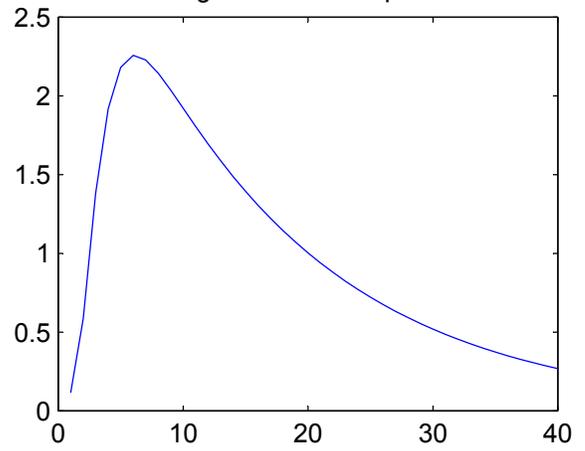


Figure 3: Labor Supply

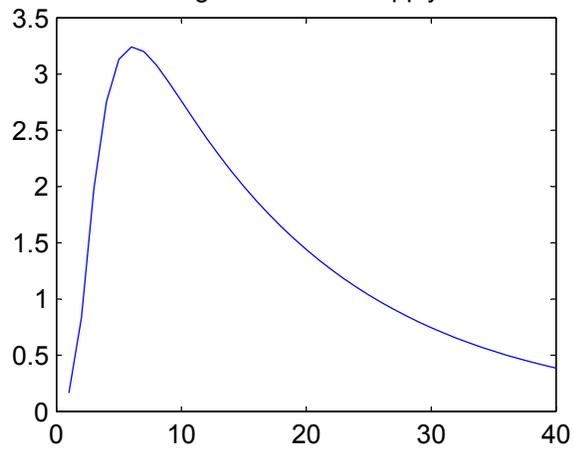


Figure 4: Output

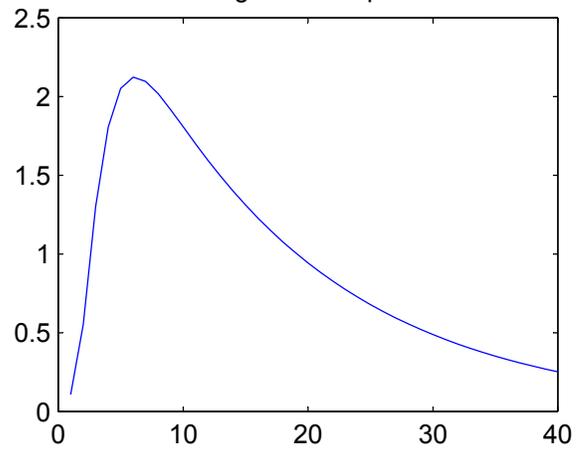


Figure 5: Price Level

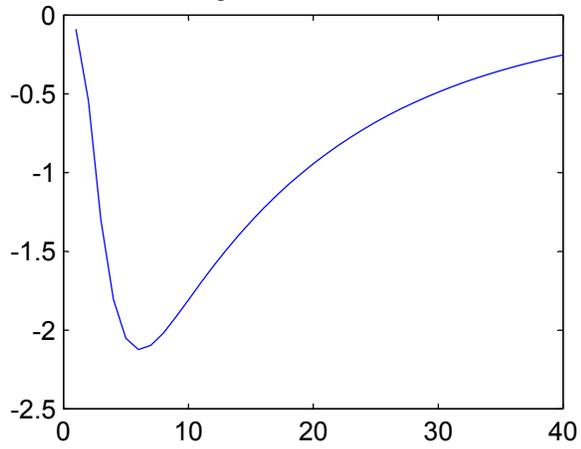


Figure 6: Nominal Interest Rate

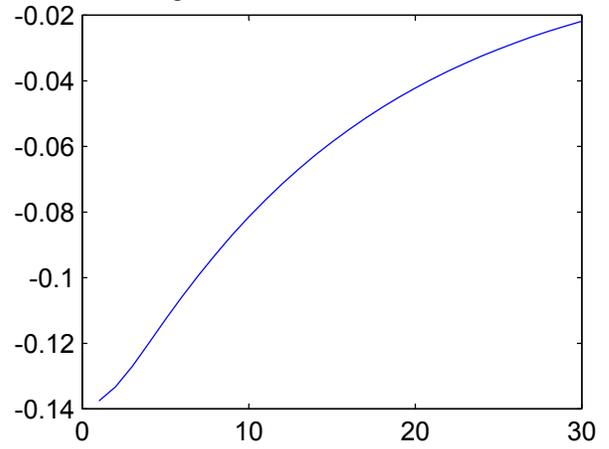


Figure 7: Wage Rate

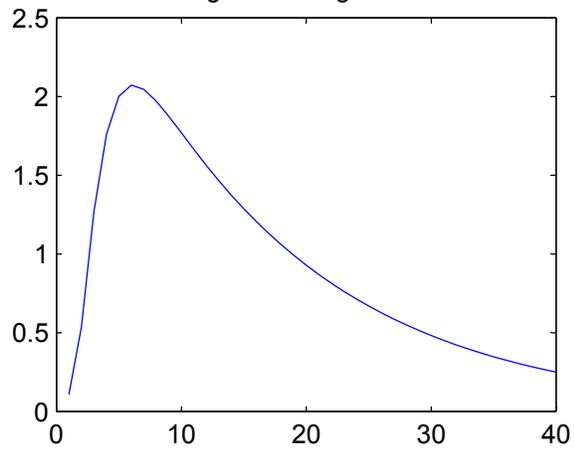


Figure 8: Cash Balances

