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Essays on investment-specific technological change, factor -hoarding and business cycles

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Essays on Investment-Specific Technological Change, Factor-Hoarding and Business Cycles

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by

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The dissertation of Kwang Hwan Kim is approved, and it is acceptable in quality and form for publication on microfilm:

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The text of Chapter 4 is adapted from *Can a Labor Searching Friction Explain the Delayed Effect of Monetary Policy?* joint with Yong-Gook Jung.

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ABSTRACT OF THE DISSERTATION

Essays on Investment-Specific Technological Change, Factor-Hoarding and Business Cycles

by

Kwang Hwan Kim
Doctor of Philosophy in Economics
University of California, San Diego, 2007
Professor Valerie A. Ramey, Chair

This dissertation consists of four essays on the relations among investment-specific technological change, factor-hoarding and business cycles.

In the first chapter, I re-examines the effect of investment-specific technology shocks (I-shocks) on the business cycles from a theoretical angle. I show that Greenwood, Hercowitz and Krusell's (GHK, 2000) influential specification may overstate the contribution of I-shocks to business cycles because it produces an unrealistically high volatility of capital utilization relative to output. The reason for this is that they model only one type of cost to increasing capital utilization, an accelerated depreciation. This paper introduces worker disutility for a longer nonstandard workweek as another cost of capital utilization, which generates volatility of capital utilization relative to output quite close to what we see in the data. Adding worker disutility to the GHK model reduces the importance of I-shocks by almost 60%, cautioning against the idea that I-shocks can be a sizable contributor to output fluctuation.

Chapter two revisits the structural VAR model which shows that investment-specific technology shocks (I-shocks) account for a significant fraction of the business cycles. I show that the I-shocks estimated from a baseline model using a full sample are significantly predicted by oil shocks and Federal funds rates. When oil shocks and monetary policy are explicitly taken into account in the structural VAR model, the extent to which I-shocks account for business cycle variability declines from 55% to 16%. Furthermore, the estimated I-shocks using a split sample seem to trace the cyclical component of labor input poorly. The contemporaneous correlation between the actual labor input and the labor input due to I-shocks are -0.34 in the second subsample.

Chapter three raises warning flags about the current use of the real price of equipment as the driving process for investment-specific technology in the Real-Business-Cycle (RBC) model. Using a structural VAR approach, this chapter finds that a significant fraction of the real price of equipment is accounted for by other shocks besides investment-specific technology shocks (I-shocks). This finding indicates that the current RBC models which use the real price of equipment as the driving process of investment-specific technology might overstate the contribution of I-shocks to economic fluctuations.

Finally, chapter four shows that when the workweek of capital and efforts are allowed to vary, the employment lag itself cannot generate a hump-shaped response of output to a monetary shock. The reason for this is that despite the fact that the size of employment is predetermined, firms can rely on other low adjustment cost margins such as the workweek of capital and efforts to meet the increase in demand due to a positive monetary shock.

I

Is Investment-Specific Technological Change Really Important for Business Cycles?

I.A Introduction

The seminal work of Kydland and Prescott (1982) and Long and Plosser (1983) spawned an enormous Real-Business-Cycle (RBC) literature that emphasizes the role of neutral technology shocks in explaining U.S business cycle. Recent empirical work by Galí (1999) has challenged this view. Under the assumption that neutral technology shocks (hereafter, N-shocks) are the only source of permanent shocks to labor productivity, his structural VAR (SVAR) model indicates that labor input responds negatively to the identified neutral technology shock while output responds positively to it. Contrary to the predictions of the original RBC model, Francis and Ramey (2001) replicate Galí's (1999) finding. They build on Galí's (1999) work and demonstrate that the neutral technology shock is correctly identified by conducting a variety of robustness tests. Given that the observed correlation between output and labor input is positive, the findings of Galí (1999) and Francis and Ramey (2001) strongly suggest that neutral technology shocks account for very little of the actual business cycles. Thus, the hypothesis of the neutral technology-driven business cycle seems threatened with extinction.

However, early work by Greenwood, Hercowitz, and Huffman (1988, hereafter GHH), and recent paper by Greenwood, Hercowitz, and Krusell (2000, hereafter GHK), offer hope for the technology-driven business cycle by emphasizing the role of investment-specific technology shocks (hereafter, I-shocks) as opposed to neutral technology shocks from a theoretical point of view. In particular, the importance of I-shocks in accounting for the business cycles is motivated by the observed negative comovement between the detrended relative price of new equipment and new equipment investment[1]. GHK (2000) view this negative comovement as suggesting the role of I-shocks in aggregate fluctuations. Using the real price of equipment as the driving process for investment-specific technology, GHK (2000) explicitly model the transmission mechanism of I-shocks to output in a neoclassical framework and find that I-shocks account for a sizable fraction of the business cycles. The transmission mechanism they propose can be briefly summarized as follows: A positive I-shock stimulates the formation of new capital and the more intensive utilization and accelerated depreciation of existing capital. In their model, what prevents firms from running their machines to the fullest extent is an accelerated depreciation caused by more intensive capital utilization (hereafter, the 'depreciation-in-use' margin). As this paper will show below, the quantitative importance of I-shocks in the GHK model crucially depends on the effect of I-shocks upon this optimal utilization of capital rather than their effect upon the formation on new capital.

However, the most unsatisfactory feature of the GHK (2000) specification not discussed thus far in the literature is that it generates too high a volatility of capital utilization relative to output. In this model, capital utilization is almost four times more volatile than output[2]. If one restricts the concept of capital uti-

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[1] With the same motivation, Fisher (2005 and 2006) empirically shows that while neutral technology shocks account for little of the business cycle variation, I-shocks are an important source of the business cycles by using SVAR approach.

[2] See Table 2 (page 105) in GHK (2000).

lization to the realm of readily quantifiable times series (i.e., workweek of capital)[3], however, this extremely high relative volatility of capital utilization is inconsistent with the data. Data on the workweek of capital, which will be presented below, suggest that the workweek of capital is nearly as volatile as output. Therefore, given that the extent to which I-shocks affect output mainly rests upon the variable capital utilization mechanism induced by the 'depreciation-in-use' margin, the role that I-shocks play in accounting for output fluctuation in the GHK (2000) model seems to be overstated.

This chapter provides a more appropriate specification that permits one to evaluate the contribution of I-shocks to the business cycles more accurately with a minimal change to the GHK (2000) model. The new specification presented here generates a relative volatility of capital utilization similar to what is observed in the data, while keeping the relative volatility of other endogenous variables intact. This paper will show that this can be done by incorporating other important costs to increasing capital utilization to the GHK (2000) model. As is widely acknowledged, accelerated depreciation is not the only cost to increasing the fraction of hours per period over which capital is operated. As the firm moves to the less attractive hours of work in order to increase utilization (i.e., the number of hours the machine is operated), it faces a rising wage schedule reflecting workers' increasing marginal disutility due to a longer night and weekend work (hereafter, 'utility cost' margin[4]). When this new specification is implemented, the result is quite striking: Compared to the conservative estimate of the contribution of I-shocks on the business cycles in the GHK (2000) model, the new specification presented here reduces the effect

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[3] Capital utilization can be also interpreted as line speed. However, it is unappealing to interpret capital utilization as line speed in the GHK (2000) specification. Unlike the implicit assumption GHK (2000) make that capital utilization can adjust its new optimal level immediately, changes to the line speed seem to be an extensive margin in nature (i.e., high adjustment cost margin). Bresnahan and Ramey (1994) show in studying an auto industry that changing the line speed almost always involves changing the number of workers and the plant increases the line speed by reorganizing the assembly line and redefining jobs. This implies that it takes awhile for firms to vary the line speed to a new optimal level in response to some exogenous shocks.

[4] As opposed to the 'depreciation-in-use' margin, this 'utility cost' margin has been quite widely used as an alternative way of modelling variable utilization (for example, Oi (1981), Bils and Cho (1994), Bils and Klenow (1998), Ramey and Shapiro (1998) and Hornstein (2002)) since Lucas (1970) initially proposed it.

of I-shocks by about 60%. Hence, it seems implausible that I-shocks can resurrect the idea of technology-driven business cycles within a standard RBC framework.

The remainder of this chapter is organized as follows. Section (I.B) presents a stripped-down version of the GHK (2000) model. It then shows that the variable capital utilization mechanism due to the 'depreciation-in-use' margin is the key for I-shocks to generate output fluctuations rather than through a standard intertemporal substitution channel. Section (I.C) presents a readily quantifiable measure of capital utilization and shows that the relative volatility of capital utilization obtained from the simplified GHK model does not fit well with this measure. Section (I.D) presents the general model that incorporates both types of costs of higher capital utilization. Then it shows that this modification leads the relative volatility of capital utilization to match much better with the data presented in Section (I.C) and substantially decreases the impact of I-shocks on output. Section (I.E) concludes the chapter.

I.B GHK (2000) model revisited

I.B.1 The Simplified GHK Model

Preferences. The economy is inhabited by a continuum of identical households. The representative household maximizes the following expected lifetime utility function

$$E_0\Big[\sum_{t=0}^{\infty}\beta^t\Big(log\, c_t-\zeta\frac{L_t^{1+\eta}}{1+\eta}\Big)\Big] \tag{I.1}$$

where c_t and L_t denote consumption and total hours supplied to the market by the household in period t. β is the subjective time discount factor.

Technology. The production technology available to this economy is described by

$$y_t=F(k_tu_t,L_t)=(k_tu_t)^{\alpha}L_t^{1-\alpha} \tag{I.2}$$

where y_t is the final output, k_t denotes the time t capital stock and u_t denotes the capital utilization rate. Thus, the production function is assumed to exhibit constant returns to scale to capital services ($k_t u_t$) and total hours (L_t).

Capital accumulation. The accumulation equation for capital is

$$k_{t+1} = (1 - \delta(u_t))k_t + q_t i_t \tag{I.3}$$

where i_t, $\delta(u_t)$ and q_t denote investment, the depreciation rate, and the current state of investment-specific technology. The rate of depreciation depends on the capital utilization rate, reflecting a 'user-cost'. It is modelled as an increasing, convex function of capital utilization. The specific functional form of $\delta(u_t)$ is

$$\delta(u_t) = b\frac{u_t^\omega}{\omega}, \quad \omega > 1 \tag{I.4}$$

The inclusion of the technological shift factor, q_t, affecting the productivity of the new capital goods to capital accumulation equation differentiates the GHH (1988) and GHK (2000) models from a standard RBC model, where technology disturbances appear only in the production function. q_t serves as an impulse of this economy and captures the idea that the contribution of current investment to the production possibility frontier depends on the current state of technology producing capital that will be available next period. log q_t is assumed to follow AR(1) process.

$$\log q_t = \rho \log q_{t-1} + \epsilon_t \tag{I.5}$$

$$\text{with } \rho \in [0,1] \text{ and } \epsilon_t \sim [0, \sigma^2]$$

Furthermore, in this GHK model, the number of consumption units that must be given up to get an additional unit of capital is $1/q_t$. Thus, in the competitive equilibrium, investment-specific technology, q_t, is the inverse of the relative price of equipment to consumption goods. Based on this, GHK use the real price of equipment as a direct measure of the investment-specific technology.

The economy-wide constraint. The final output, y_t, less a capital adjustment cost can be used for either consumption or investment[5]

$$c_t + i_t = (k_t u_t)^\alpha L_t^{1-\alpha} - \phi \frac{(k_{t+1} - k_t)^2}{k_t} \tag{I.6}$$

Macroeconomic equilibrium. Assuming complete markets and no distortion, the competitive equilibrium of this economy corresponds to the solution of a social planner problem : Choose $\{c_t, k_{t+1}, L_t, u_t\}$ to maximize (I.1) subject to equations, (I.2), (I.3), (I.4) and (I.6).

I.B.2 Propagation Mechanism in the GHK Model

Before presenting the simulation results, it is worthwhile to look into how I-shocks affect the economy in some detail. The optimality conditions of the social planner's problem yield:

$$\left[2\phi\left(\frac{k_{t+1}}{k_t} - 1\right) + \frac{1}{q_t}\right] = \beta E_t\left[\frac{c_t}{c_{t+1}}\left(\alpha\frac{y_{t+1}}{k_{t+1}} + \phi\left(\left(\frac{k_{t+2}}{k_{t+1}}\right)^2 - 1\right) + \frac{1-\delta(u_{t+1})}{q_{t+1}}\right)\right] \tag{I.7}$$

$$F_2(k_t u_t, L_t) = \zeta \frac{c_t}{L_t^\eta} \tag{I.8}$$

$$F_1(k_t u_t, L_t) = \frac{\delta'(u_t)}{q_t} \tag{I.9}$$

Equations (I.7) and (I.8) are a standard intertemporal Euler equation governing capital accumulation and intratemporal Euler equation for current consumption and leisure, respectively. Equation (I.9) characterizes the optimal condition for capital utilization. It makes it clear that interpreting capital utilization as the line speed in the GHK model is unappealing, based on the empirical result that the line speed is an extensive margin from Bresnahan and Ramey (1994). Changes to the capital utilization here involve no adjustment cost and thus can be made immediately to a new optimal level in response to I-shocks.

Now consider a positive I-shock in period t (i.e., an increase in q_t). An I-shock affects output through two channels. First, there is an intertemporal substitution effect, since the increase in q_t implies a higher return to investment. The

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[5] All variables in this resource constraint are expressed in units of consumption.

household will substitute away from current consumption to investment and supply more labor services, as one can see from equations (I.7) and (I.8). Second, the increase in q_t lowers the marginal cost of capital utilization as can be seen in equation (I.9) and hence induces higher utilization (u_t). The intuition behind this is that a positive I-shock (i.e., the lower real price of future equipment) lowers the replacement value (in consumption units) of old equipment and thus its utilization cost. Since $F_{12} > 0$, this will result in a higher demand for labor input as can be seen equation (I.8). In contrast, when the depreciation rate is assumed to be constant[6], which can be interpreted as the case in which the variable capital utilization mechanism is shut down, an I-shock will affect output only through the standard intertemporal substitution effect.

I.B.3 Simulation of the Simplified GHK Model

Parameterizing the model

In order to simulate the simplified GHK model, the parameters and steady state values of endogenous variables that need to be assigned are as follows[7].

- Preference : β, η
- Technology : α
- Depreciation function : $\delta(u)$, ω
- Capital adjustment cost coefficient : ϕ
- Steady state values of endogenous variables : c/y, i/y, y/k, L
- Investment-specific technology : q, ρ, σ^2

First, the following set of parameters and steady state values of some endogenous variables are taken from GHK (2000) and are standard in the literature.

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[6] In other words, the depreciation rate is assumed to stay at its steady state value.

[7] Note that we do not need to identify the steady state value of capital utilization and the coefficient of the depreciation function, b, since it does not appear in any coefficients when all relevant equations governing this economy are log-linearized.

The discount factor (β) and the share of capital service (α) are set to be 0.97 and 0.3, respectively. The steady state depreciation rate, $\delta(u)$, is set to be 0.124 at an annual rate and the ratio of total hours worked to total household time endowment, L, is set to be 0.24.

The second set of parameters, the λ-constant labor supply elasticity (η) and the capital adjustment coefficient (ϕ), are set to achieve the conservative estimate of the extent to which I-shocks affect the economy in this simplified GHK model. The lower bound of λ-constant labor supply elasticity[8] in the literature is about one. Thus, η is set to one. For the case of the capital adjustment coefficient (ϕ), it is selected to equalize the contemporaneous correlation between output and consumption in the simplified GHK model with that in the data. This criterion is likely to yield too high a value for ϕ and thus produce a conservative estimate of the contribution of I-shocks to output fluctuations.[9] As GHK (2000) explain, this is because, in reality, disturbances other than I-shocks can also contribute to the procyclicality of consumption. The resulting ϕ that generates an output/consumption correlation in the data of 0.87 is 2.3. Hence, setting η and ϕ to 1.0 and 2.3, respectively, provides a conservative estimate on the contribution of I-shocks to business cycles in this simplified GHK model.

The following remaining parameter and steady state values, $\{\omega, c/y, i/y, y/k\}$, can be pinned down by using the optimality conditions described in equations (I.7)-(I.9), the capital accumulation equation (I.3), and the economy-wide constraint, (I.6). The values obtained solving this system are $\omega = 1.22$, $c/y = 0.75$, $i/y = 0.25$ and $y/k = 0.5$.

Finally, the AR(1) coefficient of investment-specific technology, ρ, and the standard deviation of its innovations, σ, are set to be 0.82 and 0.0267, respectively.

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[8] The typical RBC model assumes that this elasticity is around 2 as in Prescott (1986). Recent work by Kimball and Shapiro (2003) show that it is about one.

[9] If there were no adjustment cost, I-shocks would tend to generate a countercyclical pattern of consumption, opposite to what data exhibit. This is because people tend to substitute away from consumption toward investment in response to a positive I-shock. However, a higher capital adjustment cost parameter weakens this intertemporal substitution effect, because it increase investment by less in response to a positive I-shock. Thus, a higher value for ϕ enhances the procyclicality of consumption in the GHK model, but dampens the response of output.

These values of ρ and σ are obtained by following the same procedure as GHK (2000). The crucial assumption here is that investment-specific technology is identified with the inverse of relative price of new equipment. The values for ρ and σ are then estimated by using the residuals obtained after linearly detrending the logarithm of the the inverse of the relative price of new equipment.[10] The steady state value of investment-specific technology, q, is set to be one.

The Role of the 'Depreciation-in-use' Margin

Figure (I.B.3) highlights the contribution of the variable capital utilization mechanism due to the 'depreciation-in-use' margin in magnifying the effects of I-shocks.

The solid line shows the results when the 'depreciation-in-use' margin is modelled and the dashed line shows the results when the depreciation rate is assumed to stay at its steady state value. As mentioned above, assuming a constant depreciation rate is a way of shutting down the variable capital utilization mechanism and lets the model work only through a standard intertemporal channel. Compared to the case where constant depreciation is assumed, variable capital utilization generates an effect of a positive I-shock on output and hours almost 5 times as large. This illustrates that the variable capital utilization mechanism due to the 'depreciation-in-use' margin is the key to generating output fluctuations in this simplified GHK model.

As in the original GHK (2000) model, however, this simplified version of the GHK model also produces the result that capital utilization is far more variable than output. The volatility of capital utilization relative to output (i.e. σ_u/σ_y) in this model is almost 2.5. Figure (I.B.3) portrays the impulse response functions of output and capital utilization to a positive I-shock and confirms this visually. The solid line shows the response of output and dashed-dot line the response of capital

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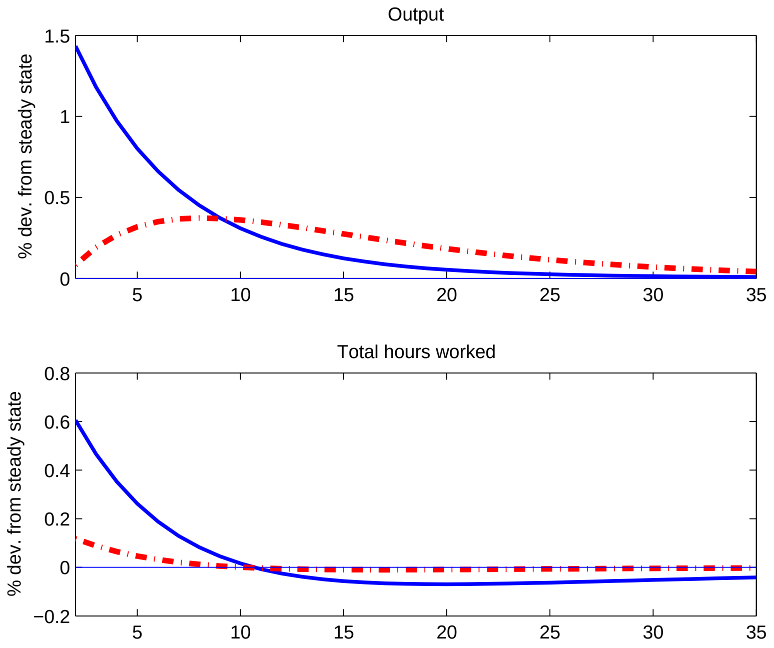
[10] The values are slightly different from those in GHK (2000), because this paper uses the Cummins-Violante (2002) series of the relative price of new equipment and a longer sample period (the annual 1951-1990 sample). The sample period is restricted only from 1951 to 1990 because the measure of capital utilization presented below is only available from 1951-1990.



The solid line shows the baseline GHK model and the dashed-dot line shows the results with constant depreciation.

Figure I.1: The role of variable capital utilization

utilization. Capital utilization reacts almost 2.5 times more than output.

I.C Data on the Workweek of Capital

This section discusses various measures of the workweek of capital [11] and investigates whether the volatility of capital utilization relative to output reported above is consistent with data. The Census Bureau's Survey of Plant Capacity (SPC) provides a direct measure of the numbers of hours per period capital is operated. In the Survey of Plant Capacity, plants are asked to report when they operate, specifically, hours per day and days per week. The product of these figures yields a direct measure of the workweek of capital. While it is the best source on

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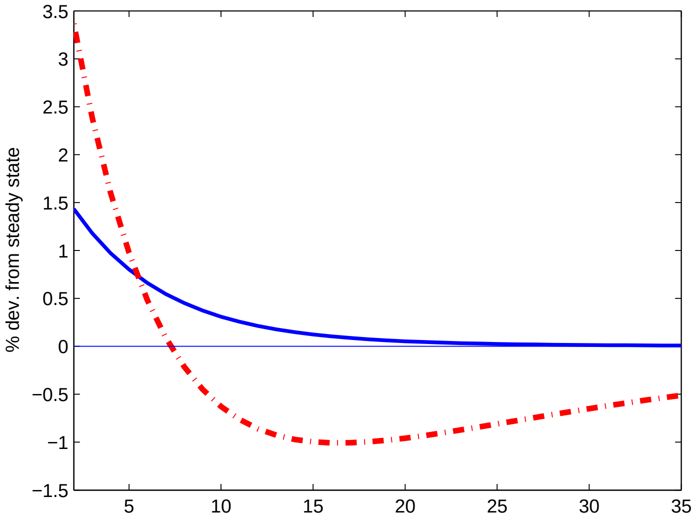
[11] The discussion about the measures of the workweek of capital here is heavily borrowed from Shapiro (1996, pp.83−90).



The solid line shows the response of output and the dashed-dot line the response of capital utilization.

Figure I.2: Impulse Response of the simplified GHK model

the workweek of capital, the annual time series is available for only a short sample period (1974-1990).

To extend the time period, this paper uses the measure based on the number of workers on late (second and third) shifts that Taubman and Gottschalk (1971) and Shapiro (1986 and 1996) propose. He proposes the following measure to estimate the workweek of capital, S, from the fraction of workers on shifts :

$$S = H(\lambda_1 + 2\lambda_2 + 3\lambda_3) \tag{I.10}$$

where H is the average workweek of labor and λ_1, λ_2, and λ_3 are the fraction of workers in plants operating one, two, and three shifts, respectively. This measure is constructed based on the assumption that the capital-production worker ratio is the same on all three shifts.

The Area Wage Survey (AWS) conducted by the Bureau of Labor Statistics provides periodic information on the fraction of workers on the second and third shifts in various U.S cities. Mayshar and Solon (1993) estimate a factor model to extract the aggregate component of shift employment, while controlling for the

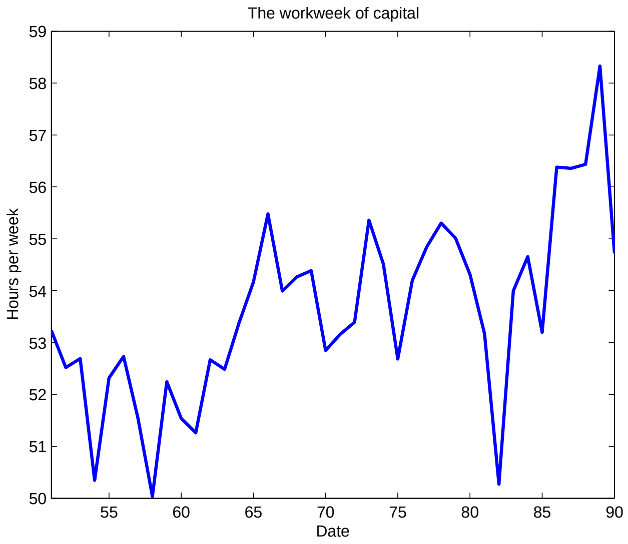


Figure I.3: Workweek of Capital Based on Area Wage Survey

city-specific effects. Their work constitutes the most up-to-date analysis of the AWS data in terms of the period of time that it covers. Hence, this paper uses the Mayshar-Solon series on the fraction of workers on late shifts (i.e., λ_1, λ_2, and λ_3) to estimate the workweek of capital, S. Figure (I.3) plots the AWS-based measure of the workweek of capital obtained from using this Mayshar-Solon series. It ranges from 1951 to 1990 and covers a longer time period than the SPC-based measure.

Figure (I.C) clearly shows that the workweek of capital can *not* be much more variable than output. It plots the cyclical component of the AWS-based measure of the workweek of capital and output[12]. The solid line shows the cyclical component of output and the dashed-dot line that of workweek of capital. The volatility of the workweek of capital relative to output, defined as the ratio of standard deviation of the workweek of capital around its Hodrick-Prescott (HP) trend to that of output around its HP trend, is 1.04.

Furthermore, another source of the workweek of capital suggests that the aggregate measure of capital workweek might be even less variable than the AWS-based measure. The AWS and SPC based measures of the workweek of capital

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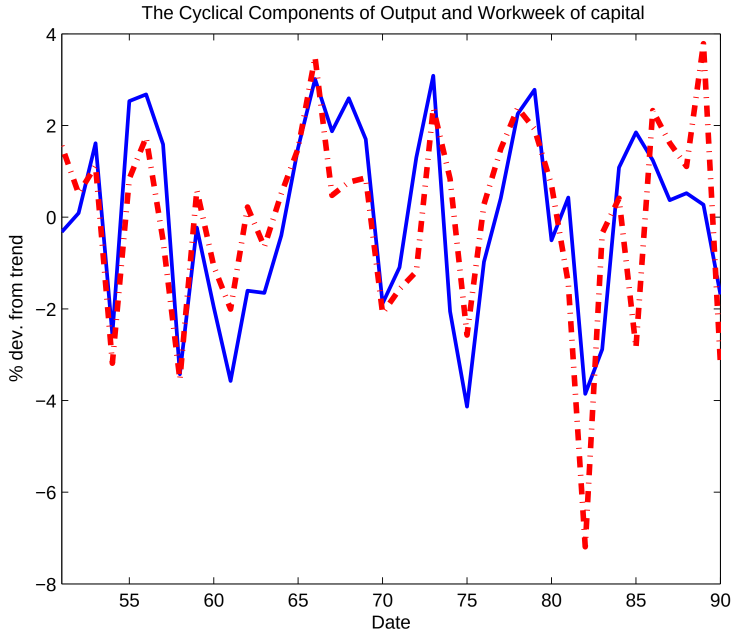
[12] The Hodrick-Prescott (HP) filter is used.



Sample period is 1951-1990. All variables are annual and H-P filtered with the weight parameter 100. The solid line shows the cyclical component of output and the dashed-dot line that of the workweek of capital.

Figure I.4: Cyclical components of output and workweek of capital

are limited to manufacturing. The Current Population Survey (CPS) data allow the calculation of capital workweeks in both nonmanufacturing and manufacturing sectors even though the data are available only for 1973-81, 1985 and 1991. For manufacturing, the CPS measure is less variable than the AWS measure over the overlapping period, 1973-81. The nonmanufacturing capital workweek is less variable and less correlated with the business cycles than the workweek in manufacturing. Hence, it appears that the economy-wide measure of capital workweek *at most* is as variable as output.

Based on these measures, GHK's (2000) model of capital utilization (i.e., modelling only the 'depreciation-in-use' margin) seems to generate too much variability in capital utilization relative to output in response to I-shocks. This implies that the contribution of I-shocks to the business cycles in the GHK (2000) model might be exaggerated, because variable capital utilization is the mechanism through which I-shocks affect output fluctuation in the GHK (2000) model.

I.D A More General Model of Capital Utilization

This section shows that integrating both types of costs (i.e., accelerated depreciation and utility cost) to increasing capital utilization improves the ability of the model to produce a relative volatility of capital utilization similar to that in the data. It then reassesses the role of I-shocks in accounting for the business cycles.

The task of introducing the 'utility-cost' margin requires one to distinguish between the extensive and intensive margin of labor inputs (i.e., employment versus hours per worker). This distinction is unnecessary in the GHK (2000) model since capital utilization is determined independently of the labor input decision. That is, the reason that the GHK (2000) model in itself cannot capture the 'utility-cost' margin is that changes to the capital utilization do not necessarily involve longer work hours because it lumps hours per worker and employment all together. In order to ensure that extending machine hours should be accompanied by making workers work longer hours, this paper assumes that workers need to be present to operate capital. This assumption is also implicit in Ramey and Shapiro (1998), which has a Leontief production technology between physical capital and employment. Rather than assuming a Leontief production function, this paper maintains the Cobb-Douglas production function to make the modified model as comparable as possible to the simplified GHK model and allow both the extensive and intensive margins of labor to be operative immediately after a shock since *ex post* substitution opportunities are surely not zero.

Furthermore, this paper also modifies the preference specification to accommodate both margins of labor adequately. The preference specifications used in the literature to model both margins of labor are those introduced by Bils and Cho

(1994), Burnside and Eichenbaum (1996) and Ramey and Shapiro (1998), among others. The specification this paper adopts resembles that of Bils and Cho (1994), because selecting a value for the parameter governing the rising marginal disutility due to a longer work week is obviated by drawing upon the estimation results on the shape of wage function by Bils (1987).

I.D.1 The Economic Environment

Preferences. The economy is inhabited by a continuum of identical households. The size of households is normalized to one. The representative household maximizes the following expected lifetime utility function

$$E_0\Big[\sum_{t=0}^{\infty}\beta^t\Big(log\, c_t - V(n_t,h_t)\Big)\Big] \tag{I.11}$$

where c_t, n_t and h_t denote consumption, the number of workers and hours per worker respectively. $V(n_t,h_t)$ describes the disutility of work hours. Similarly to Bils and Cho (1994), I specify that

$$V(n_t,h_t) = \Big[\theta_1\frac{{n_t}^{1+\nu}}{1+\nu} + \theta_2 n_t\frac{{h_t}^{1+\chi}}{1+\chi}\Big] \tag{I.12}$$

The first component of $V(n_t,h_t)$ represents the cost of sending n_t member of the households to work in a period t, even if hours worked are arbitrarily small. It may be interpreted as costs for commuting or costs incurred due to having fewer people available for home production. The second component reflects the disutility of working h_t hours per period associated with reduced leisure and longer work during nonstandard hours. However, my specification describing the disutility of working is different from that of Bils and Cho (1994) in one important way. They use the following momentary utility function describing the preference of the representative person rather than describing that of the representative of household.

$$W(\hat{n}_t,\hat{h}_t) = \Big[a\frac{\hat{n}_t^{1+\sigma}}{1+\sigma} + b\hat{n}_t\frac{\hat{h}_t^{1+\beta}}{1+\beta}\Big]$$

Here, $\hat{n}_t$ and $\hat{h}_t$ are weeks of work per period and hours per week respectively. Abstracting from changes in labor force participation, they focus on changes in the fraction of weeks in the labor force at work, which they interpret as changes in the unemployment rate. In contrast to Bils and Cho (1994), this paper explicitly models changes in the labor force while abstracting from changes in the fraction of weeks that workers in the labor force are at work.

Technology. Due to the assumption that workers must be present to operate capital, the workweek of capital is equal to the workweek of labor in the economy composed of identical workers. Thus, the production technology available to this economy becomes linear in capital utilization and can be written as follows:

$$y_t = F(k_t u_t, L_t) = (k_t u_t)^{\alpha}(n_t h_t)^{1-\alpha} = u_t {k_t}^{\alpha} {n_t}^{1-\alpha} \tag{I.13}$$

where k_t denotes the time t capital stock, u_t is capital hours and L_t is total hours worked (i.e., the numbers of workers, n_t times hours per worker, h_t).

Capital accumulation. The accumulation equation for capital remains the same as in the simplified GHK model:

$$k_{t+1} = (1 - \delta(u_t))k_t + q_t i_t \tag{I.14}$$

$$\delta(u_t) = b\frac{u_t^{\omega}}{\omega}, \quad \omega > 1 \tag{I.15}$$

$$\log q_t = \rho \log q_{t-1} + \epsilon_t \tag{I.16}$$

$$\text{with } \rho \in [0,1] \text{ and } \epsilon_t \sim [0,\sigma^2]$$

The economy-wide constraint. The final output, y_t, less capital adjustment cost can be used for either consumption or investment

$$c_t + i_t = u_t {k_t}^{\alpha} {n_t}^{1-\alpha} - \phi\frac{(k_{t+1} - k_t)^2}{k_t} \tag{I.17}$$

Macroeconomic equilibrium. Assuming complete markets and no distortion, the competitive equilibrium of this economy corresponds to the solution of a social planner problem : Choose $\{c_t, k_{t+1}, n_t, u_t\}$ to maximize (I.11) subject to equations, (I.13), (I.14), and (I.17).

I.D.2 The Decentralized Equilibrium

The economy described above can be easily decentralized in the following manner. The households purchase consumption goods, own the capital stock and save by accumulating capital. They supply factors of production to firms. First, they rent capital to the firms. Second, they choose how many of their members (n_t) should participate in the labor market and how many hours (h_t) each worker in the labor market will work. Third, they choose how many hours (u_t) they want to run their capital. Due to the assumption that workers must be present to operate capital, however, the choice of hours per worker is the same as that of capital hours. The firms produce output by using these factors supplied by the households. In return, they pay the rental rate, r_t, for use of capital and a total wage bill, $w(h_t, n_t)\, n_t$, for labor inputs to the households. $w(h_t, n_t)$ is the wage function representing the amount firms must pay for hiring one additional worker and making him or her work for a certain h_t hours.

This wage function embeds the 'utility-cost' margin to increasing capital utilization. To see this, one can easily verify that the equilibrium wage function in this economy is

$$w(h_t, n_t) = \frac{1}{\lambda_t}\left(\theta_1 n_t^{\nu} + \theta_2 \frac{{h_t}^{1+\chi}}{1+\chi}\right)$$

where $\lambda_t (= 1/c_t)$ is the Langrange multiplier on the period budget constraint of the representative household. The equilibrium wage function makes it clear that when a firm increases the length of work to extend the length over which capital operates while leaving employment unchanged, it faces the rising 'marginal wage schedule' reflecting the increasing marginal disutility of longer nonstandard work hours.

Now let us present the equilibrium conditions governing capital utilization, $u_t (= h_t)$, employment, n_t, and next period capital stock, k_{t+1}, to show how an

I-shock affects the economy in this modified model.

$$ {k_t}^{\alpha} {n_t}^{1-\alpha} = \frac{1}{\lambda_t}\theta_2 n_t {u_t}^{\chi} + \frac{\delta^{'}(u_t)}{q_t} k_t \tag{I.18} $$

$$ (1-\alpha) u_t {k_t}^{\alpha} {n_t}^{-\alpha} = \frac{1}{\lambda_t}\left(\theta_1 {n_t}^{\nu} + \theta_2 \frac{{u_t}^{1+\chi}}{1+\chi}\right) \tag{I.19} $$

$$ \left[2\phi\left(\frac{k_{t+1}}{k_t}-1\right)+\frac{1}{q_t}\right] = \beta E_t\left[\frac{\lambda_{t+1}}{\lambda_t}\left(\alpha\frac{y_{t+1}}{k_{t+1}}+\phi\left(\left(\frac{k_{t+2}}{k_{t+1}}\right)^2-1\right)+\frac{1-\delta(u_{t+1})}{q_{t+1}}\right)\right] \tag{I.20} $$

As in the simplified GHK model, equation (I.18) shows that a positive I-shock induces firms to increase the workweek of capital. Unlike the simplified GHK model, however, equation (I.18) also clearly shows that in addition to bearing the cost of increased depreciation, $\frac{\delta^{'}(u_t)}{q_t}k_t$, extending capital hours requires firms to compensate workers for an increased disutility due to a longer work hours, $\frac{1}{\lambda_t}\theta_2 n_t {u_t}^{\chi}$. Firms equate the marginal product of capital hours to these two types of marginal cost associated with increasing capital hours.

Equation (I.19) shows how firms equate the marginal product of employment to the marginal cost of employment, $w(n_t, h_t)$. However, the effect of a positive I-shock on employment in this economy is ambiguous. As a positive I-shock induces firms to extend the length over which capital runs, this has two offsetting effects. On the one hand, an increase in capital hours will result in a higher marginal product of employment. On the other hand, an increase in capital hours raises the marginal cost of employment. This is because a firm has to compensate a new worker for a longer workweek if it wants to hire one more worker and make him or her work longer hours. Thus, the net effect of a positive I-shock on employment will depend on which effect is larger.

Equation (I.20) is the standard intertemporal efficiency condition governing capital accumulation. As in the simplified GHK model, a positive I-shock leads the household to substitute away from current consumption to investment.

I.D.3 Simulation of the Modified Model

Parameterizing the model

In order to simulate the modified model, the parameters and steady state values of the endogenous variables that need to be assigned are as follows. The strategy here is to keep other elements of the modified model not related to the 'utility-cost' margin as close as to those of the simplified GHK model to highlight the effect of augmenting the 'utility-cost' margin to the simplified GHK model.

- Preference : β, θ_1, θ_2, χ, ν
- Technology : α
- Depreciation function : $\delta(u)$, ω
- Capital adjustment cost coefficient : ϕ
- Steady state values of endogenous variables : c/y, i/y, y/k, $h(=u)$, n
- Investment-specific technology : q, ρ, σ^2

The subjective discount factor β, the share of capital services α, the steady state depreciation rate $\delta(u)$, the curvature coefficient of depreciation function ω, capital adjustment coefficient ϕ, the parameters describing investment-specific technology ρ, σ^2 and the steady state level of investment-specific technology q, are not related for 'utility-cost' margin. Thus they are set to the same values as those assigned in the simplified GHK model.

The most important parameter to be assigned is χ, the parameter governing the marginal disutility from a longer workweek and thus embedding the 'utility-cost' margin. When χ rises, the amount that firms must compensate a worker increases more rapidly as they want to extend the hours over which capital runs. In this case, capital utilization becomes less responsive to a positive I-shock and thus the degree of shock amplification gets smaller. Bils (1987) provides guidance on which value to choose for χ. He calculates an elasticity of the marginal wage with respect to average hours is approximately 1.39. Since this elasticity corresponds to χ in this modified model[13], I set χ to be 1.39.

The steady state value of the fraction of hours beyond a standard 40-hour workweek is set to 0.26, taken from Ramey and Shapiro (1998). This implies a 50.4-hour workweek of capital in the steady state. Normalizing a 40-hour workweek to unity, I set the steady state value of the workweek of capital, $u(= h)$ to be 1.26. The steady state value of employment, n is set to ensure that the steady state ratio of total hours worked to the total time endowment of the household[14] is 0.24 as in the simplified GHK model. The resulting value of n is 0.56.

The steady state values for y/k, c/y and i/y can be pinned down by using the intertemporal Euler equation (I.20), the capital accumulation equation (I.14), and the economy-wide constraint (I.17). The resulting values are $y/k = 0.5$, $c/y = 0.75$ and $i/y = 0.25$.

Finally, to determine the scale coefficients θ_1 and θ_2 in the utility function and the parameter ν governing the marginal disutility from sending an additional worker to work, I make an assumption on the λ-constant elasticity of employment with respect to average wage in the steady state[15]. The reason for this additional assumption is that there are only two equations available, the equilibrium conditions for capital utilization and employment (i.e., equations (I.18) and (I.19)) in assigning these three parameters. The labor supply elasticity of 2, widely assumed in the typical RBC model, is probably too high for the elasticity of employment because this elasticity captures labor movements in the form of both employment and hours per worker. Given that Bils and Cho (1994) and Chang and Kim (2006) choose the elasticity of hours per worker is 0.4 and 0.5 respectively, it seems reasonable to assume an elasticity of employment in the steady state of 1.6. Using equations (I.18)-(I.19) along this assumption, one obtains $\theta_1 = 2.21$, $\theta_2 = 1.08$ and $\nu = 1.06$. The results of the simulations do not vary that much with choosing

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[13] Note that $MW_t = \frac{\partial w(h_t,n_t)}{\partial h_t} = \frac{\theta_2}{\lambda_t} {h_t}^{\chi}$. Then $\frac{\partial MW_t}{\partial h_t} \frac{h_t}{MW_t} = \chi$.

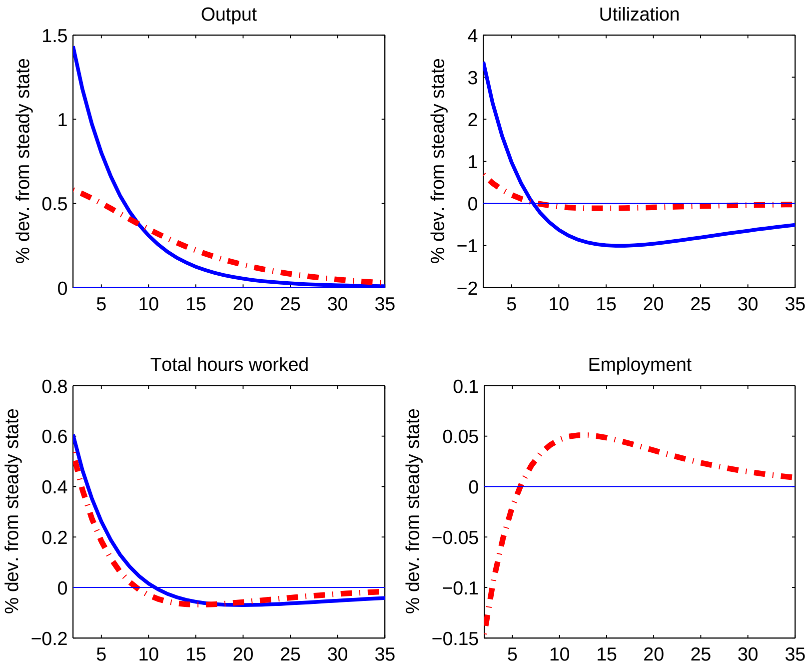
[14] The time endowment available to household is normalized to 2.63.

[15] The λ-constant elasticity of employment in the steady state equals $\frac{1}{\theta_1 \nu} \frac{(1+\chi)\theta_1 n^{\nu} + \theta_2 h^{1+\chi}}{(1+\chi) n^{\nu}}$

different values for the elasticity of employment. Since a positive I-shock increases both the marginal product and the marginal cost of employment, the effect of a positive I-shock on the employment is likely to be small regardless of the magnitude of the employment elasticity. Thus, selecting different values for the elasticity of employment does not affect the response of employment to I-shocks significantly.

The Effect of Augmenting the 'Utility-cost' Margin to the GHK model

I now examine how integrating both the 'depreciation-in-use' and 'utility-cost' margins would change the response of output compared to the conservative estimate of the extent to which I-shocks affect output in the simplified GHK model. As one can see from the procedure of parameterizing the modified model, the 'utility-cost' margin has been augmented to the simplified GHK model with a minimal perturbation of it. Figure (I.D.3) portrays the impulse response of output, capital utilization, employment and total hours to a positive I-shock. The solid line shows the results when only the 'depreciation-in-use' margin is modelled and the dashed line shows the results when both the 'depreciation-in-use' and 'utility-cost' margins are integrated. Introducing the 'utility-cost' margin to the simplified GHK model reduces the impact of a positive I-shock on capital utilization by almost 80%. Due to this dramatic decline in the response of capital utilization, the effect of a positive I-shock on output is reduced by almost 60%. The response of total hours worked remains unaffected. This implies that the different effect of I-shocks on output between the two models is only attributable to the different response of the capital utilization. As explained in Section (I.D.2), the effect of a positive I-shock on employment is ambiguous. Because a positive I-shock raises both the marginal product and marginal cost of employment, its effect on employment depends on which effect is larger. Under the parameterization adopted here, it appears that the latter effect is greater than the former and thus employment declines initially. Due to these offsetting effects, however, the impact of an I-shock on employment is small.



The solid line shows the results when only ‘depreciation-in-use’ margin is modelled and the dashed line shows the results when both the ‘depreciation-in-use’ and ‘utility-cost’ margins are integrated.

Figure I.5: The effect of introducing ‘utility-cost’ margin to GHK model

I now present formal evidence that the modified model fits the data better than the simplified GHK model by comparing the moments of time series generated from each of the models above with those from U.S annual data (1951-1990). Both the data and the generated series are H-P filtered. Table (I.1) presents the relative volatility and contemporaneous correlation with real GDP for the five series - real GDP, consumption, investment, total hours and capital utilization - for U.S data, the simplified GHK model and the modified model presented here. As documented in Section (I.C), the variability of capital utilization is nearly as large as that of output in the U.S data. Table (I.1) clearly shows that introducing the ‘utility-cost’ margin significantly enhances the ability of model to produce the volatility of capital utilization relative to output close to the one observed in the data. The modified model that integrates both the ‘utility-cost’ and ‘depreciation-in-use’ margins generates a variability in capital utilization that is only 21% higher than that in output (i.e., ${\sigma_u}^{\text{Modified}}/{\sigma_y}^{\text{Modified}} = 1.21$). As shown earlier in Section (I.B.3), however, the simplified GHK model that only takes account of the 'depreciation-in-use' margin produces the result that volatility of capital utilization is nearly 2.5 times as high as that of output (i.e., ${\sigma_u}^{\text{GHK}}/{\sigma_y}^{\text{GHK}} = 2.49$). Most interestingly, the ratio of the standard deviation of output generated from the modified model to that of output from the simplified GHK model (i.e., $\sigma_y^{\text{Modified}}/\sigma_y^{\text{GHK}}$) is 0.41. This suggests that the contribution of I-shock to output fluctuations in the simplified GHK model is likely to be overstated by about 60% compared to the modified model.

The attractive feature of the modified model is that the 'utility-cost' margin has been incorporated while keeping the variability in other variables relative to output close to what one sees in the data. As in the data, the modified model exhibits the pattern that investment is far more volatile than output, consumption far less than output and hours nearly as volatile as output.

Regarding the cyclical properties of the model, the modified model exhibits similar patterns to those of the simplified GHK model with the exception of the procyclicality of consumption. As explained earlier, the capital adjustment coefficient, ϕ, in the simplified GHK model is deliberately set to equalize the contemporaneous correlation of consumption with output to the one in the data. This criterion is selected to generate the conservative estimate of the contribution of I-shocks to business cycles in the simplified GHK model. Hence, the 'utility-cost' margin has been incorporated without worsening the cyclical property of the model.

I.E Conclusions

This chapter re-examines the role of I-shocks in explaining the business cycles from a theoretical perspective. I show that the influential specification proposed by GHK (2000) may overstate the contribution of I-shocks to business cycles

Table I.1: The relative volatility and cyclicality for the U.S data, the simplified GHK and the modified models

	Variables(x)[1]	σ_x/σ_{output}	$corr(x, output)$
US Annual data[2]	Output	1.00	1.00
	Consumption	0.51	0.87
	Investment	2.86	0.75
	Hours	0.97	0.84
	Utilization	1.04	0.68
The Simplified GHK model	Output	1.00	1.00
	Consumption	0.16	0.87
	Investment	3.64	1.00
	Hours	0.43	1.00
	Utilization	2.49	0.98
The Modified Model	Output	1.00	1.00
	Consumption	0.39	0.69
	Investment	3.35	0.97
	Hours	0.96	0.92
	Utilization	1.21	0.90

[1] All variables are H-P filtered with the weight parameter 100.

[2] For the U.S data (1951-1990), the variables are defined as follows. Output is nominal GDP divided by consumption deflator. Consumption is nominal expenditure on nondurables and nonhousing services divided by consumption deflator. Investment is nominal nonresidential investment divided by consumption deflator. Hours is employed-hours in nonagricultural establishment. Utilization is the workweek of capital based on Area Wage Survey.

because their model produces unrealistically high volatility of capital utilization relative to output. The reason for this is that they model only one type of cost to increasing capital utilization, an accelerated depreciation. This paper proposes a new modified specification which generates a volatility of capital utilization relative to output quite close to what we see in the data. This is done by introducing another important cost to increasing capital utilization, compensating a worker for a longer nonstandard workweek, to the simplified GHK model.

In striking contrast with the simplified GHK model where only the 'depreciation-in-use' margin is modelled, the impact of an I-shock declines by almost 60% when both types of costs to increasing capital utilization are modelled. This cautions against the idea that I-shocks can be a sizable contributor to output fluctuation. A virtue of this result is that the ‘utility-cost’ margin is integrated with a minimal perturbation of the simplified GHK model and a comparison is made with the conservative estimate of the extent to which the simplified GHK model can magnify I-shocks.

II

Quantifying the Contribution of Investment-Specific Technology Shocks to Business Cycles

II.A Introduction

This chapter calls into question the importance of I-shocks in accounting for business cycles from an empirical angle[1]. Fisher (2003, 2005 and 2006) modifies Galí's (1999) one neutral technology shock SVAR specification to incorporate I-shocks. More specifically, he adds the relative price of equipment and additional identifying assumption to Galí's SVAR specification to show the contribution of I-shocks to business cycles. The main finding from this modified SVAR is that while neutral technology shocks account of little of business cycles, I-shocks are an important source of business cycles.

However, I show that the I-shocks estimated from a baseline model using a

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[1] From a theoretical angle, my own work (Kim, 2006) shows that the influential specification proposed by GHK (2000) is ill-equipped to evaluate the contribution of I-shocks to business cycles accurately. This is because their model produces an unrealistically high volatility of capital utilization relative to output. He presents a new modified specification that generates a volatility of capital utilization relative to output quite close to what we see in the data with a minimal perturbation of the GHK (2000) model. In striking contrast with the GHK model, the impact of a positive I-shock declines by almost 60% when a new modified model is implemented. Hence, it seems that I-shocks cannot resurrect the idea of technology-driven business cycles within the standard RBC framework.

full sample do not represent true I-shocks. The estimated I-shocks are significantly predicted by oil shocks and Federal funds rates. This implies that the effects of I-shocks in the baseline model are compounded by those of oil shocks and monetary policy. When oil shocks and monetary policy are explicitly taken into account in the structural VAR model, the extent to which I-shocks account for business cycle variability declines from 55% to 16%. Furthermore, when I-shocks are estimated using a split sample, I show that they fit the actual movement of the business cycle component of labor input poorly. In the second subsample, the contemporaneous correlation between the actual labor input and the labor input due to I-shocks is -0.34.

The remainder of this chapter is organized as follows. Section III.B presents the SVAR model that enables one to quantify the extent to which I-shocks account for the business cycles. In section III.C, I describe data used in the paper. Section III.D and III.E present the results based on using a full sample and split sample respectively. Section II.F summarizes the results.

II.B Econometric strategy

This paper adopts the SVAR model used by Fisher (2003, 2005 and 2006). Fisher modifies Galí's one-technology shock SVAR model to separately estimate I-shocks and N-shocks. In a manner consistent with the identifying assumption in Galí (1999), Fisher's SVAR model allows both types of technology shocks to have a permanent effect on labor productivity, with only I-shocks affecting the relative price of equipment in the long-run. In other words, while this assumption restricts the secular trend in the real price of equipment to originate solely in I-shocks, it does not prevent other types of shocks not related to I-shocks from affecting the real price of equipment in the short-run. With this identification scheme[2], Fisher

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[2] In addition to these two identifying assumptions, Fisher(2005 and 2006) makes another assumption. He assumes that exogenous I-shocks which lower (raise) real investment good price by an amount x, raise (lower) labor productivity in a known fixed proportion to x. This assumption does not affect the estimation results much.

proposes the following simple SVAR model:

$$y_t = \Phi(L)\epsilon_t \tag{II.1}$$

where $y_t = [\Delta p_t, \Delta a_t, h_t, \mathrm{x_t}]'$ and $\Phi(L)$ is a matrix of polynomials in the lag operator L. p_t denotes the log of the real price of equipment, a_t denotes the log of labor productivity, h_t denotes the log of hours and $\mathrm{x_t}$ is a vector of other endogenous variables in the SVAR model. ϵ_t is a vector of exogenous shocks with ϵ_{i_t} and ϵ_{n_t} as the first two elements. ϵ_{i_t} denotes the investment-specific technology shock and ϵ_{n_t} denotes the neutral technology shock. Technology shocks and non-technology shocks are orthogonal to each other, so that $E\epsilon_t\epsilon_t' = \Omega$ is a diagonal matrix.

The estimated series of I-shocks and N-shocks can be obtained by using the instrumental variables (IV) method proposed by Shapiro and Watson (1986). Because the details for estimating this SVAR model appear in many parts of the literature, I move directly to the estimation results.

II.C Data

All series used in this paper are quarterly data from 1955:I-2000:IV. The real price of equipment is defined as the quality-adjusted price index for producer durable equipment (PDE) divided by the consumption deflator. The consumption deflator corresponds to nondurable consumption plus services consumption plus government consumption plus the service flow from consumer durables [3]. For the series on labor productivity and labor input, the BLS series “Index of output per hour, nonfarm business” and “Index of hours in nonfarm business” are used. Labor productivity is measured in consumption units using the consumption deflator and labor input is put on a per capita basis by dividing by the population ages 16 and over. Inflation is measured with the consumption deflator and the nominal interest rate is the Federal funds rate.

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[3] Fisher kindly provided the equipment and consumption deflators.

II.D Results based on a full sample

II.D.1 Results from a baseline model

I begin by estimating a baseline system that consists of the real price of equipment, labor productivity and hours using a full sample[4]. To assess how much the estimated I-shocks contribute to explaining the business cycle variation in hours, I extract the predicted path of hours due to I-shocks by conducting a historical decomposition. Figure (II.1) shows the business cycle components of the actual hours (solid line) and the hours due to I-shocks (dashed line) based on a baseline model[5]. The estimated I-shocks from a baseline model explain about 50 % of the business cycle variability of hours and the correlation is 0.73 (The second column of Table (II.1)).

Table II.1: Contribution of I-shocks to hours based on a full sample

	3-variable model	Extended model
$\sigma^2_{H_I^d}/\sigma^2_{H_A^d}$	0.55	0.16
corr (H_I^d, H_A^d)	0.73	0.48

[1] The extended model means that Federal fund rates, inflation and net oil price index (NOPI) are added to 3-variable model.

[2] H_A^d denotes the detrended actual real price of equipment series and H_I^d the detrended real price of equipment due to I-shocks. The series are detrended by using Christiano-Fitzgerald's band-pass filter.

However, Figure (II.1) seems to suggest that the 3-variable SVAR model fails to isolate true I-shocks from oil shocks and monetary policy. According to Figure (II.1), the two postwar major recessions of 1973-75 and 1981-82 are entirely attributed to I-shocks. Many believe that these two recessions are due to oil

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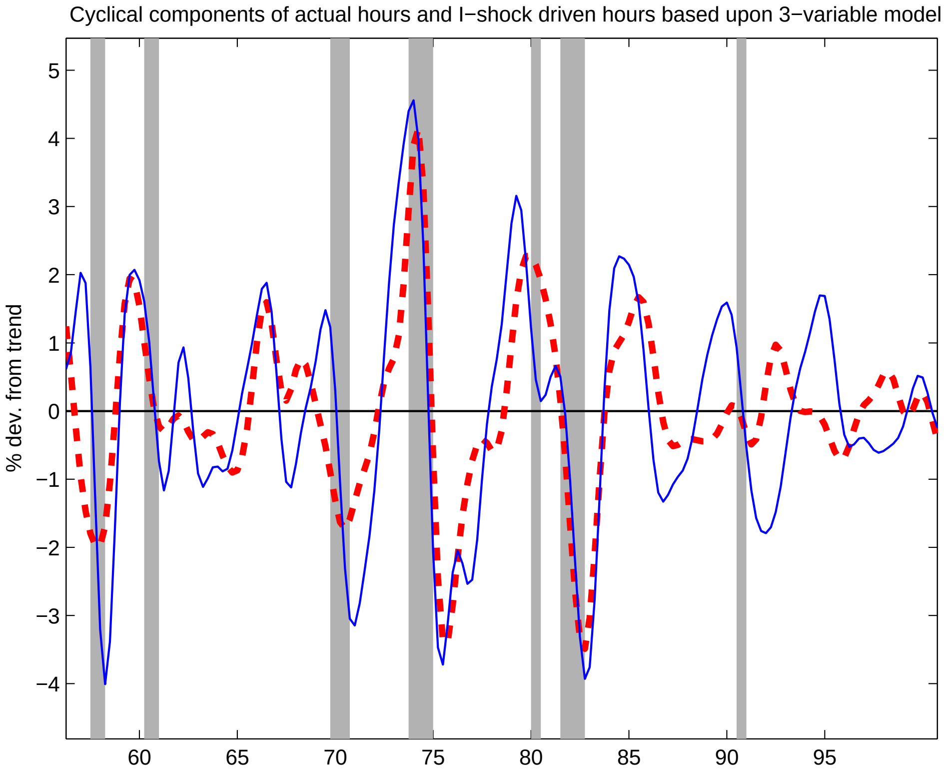
[4] Four lags are included.

[5] Business cycle components are derived using Christiano and Fitzgerald's (2002) implementation of the band-pass filter, which excludes frequencies higher than one and a half years and lower than eight years.



The solid lines denote the cyclical components of actual hours. The dashed line shows the cyclical components of hours due to I-shocks. The cyclical components are derived by using Christiano-Fitzgerald's band-pass filter. Shading indicates NBER recessions.

Figure II.1: Decomposing the contribution of I-shocks to hours: 3-variable model using a full sample

shocks or tight monetary policy in response to oil shocks. Hence, if oil shock and monetary policy have significant predictive power in explaining the estimated I-shocks, a finding that I-shocks account for most of the business cycle variation in hours becomes questionable. To investigate whether the estimated I-shock from this baseline model is indeed predicted by other shocks not related I-shocks, I subject them to Evans-Hall exogeneity tests.

I consider three types of shocks generally viewed as unrelated to technology shocks: Oil shock dummies used by Ramey and Shapiro (1998)[6], Ramey and Shapiro's (1998) war dates, and the Federal funds rate (Bernanke and Blinder, 1992). I regress the estimated I-shocks from the 3-variable model on a constant and current and four lagged values of the two sets of dummy variables (oil shocks dummies and war dates dummies), and regress the estimated I-shocks from 3-variable model on a constant and four lagged values of the Federal funds rate[7]. Table (III.3) reports the results of exogeneity tests applied to the estimated I-shocks from 3-variable model. The oil variables and Federal funds rate do have significant predictive power in the estimated I-shocks. Thus, the estimated I-shocks based on the 3-variable model do not represent true I-shocks and are compounded by oil shocks and monetary policy. This strongly suggests that oil shock and monetary policy need to be taken into account explicitly in estimating I-shocks.

Table II.2: Exogoneity Tests: 3-variable model using a full sample

	P-Values for Exogeneity Tests[1]		
	Oil dummies	Federal funds rates	Ramey-Shaprio war date
I-shocks	0.0047	0.0493	0.2398

[1] The F-test is based on a regression of the identified I-shock on a constant and current and four quarterly lags of the variable in question, except the feder where no current value is included. The hypothesis is that all of the coefficients on the variable in question are jointly equal to zero, which implies the variables in question do not have predictive power in identified technology shock.

Inflation also needs to be included since the Fed may have raised the interest rate because of its inflationary concerns attributable to oil shocks. Another reason to include inflation is that inflation has powerful prognostic implication for long run labor productivity (Barsky and Sims, 2006).

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[6] According to Ramey and Shapiro (1998), oil shocks are based on dates identified by Hamilton (1985) and Hoover-Perez (1994) and updated by them for the Iraqi invasion of Kuwait.

[7] Following Francis and Ramey (2005), I do not include lags of the estimated I-shocks since they are by assumption not serially correlated and exclude the current value of the Federal funds rates since it may respond to a current technology shock.

II.D.2 Results from an extended model

The discussions above suggest incorporating the interest rate, inflation and oil shock measures to the baseline specification when I-shocks are estimated. To this end, I consider the following specification:

$$y_t = B(L)o^*_{t-1} + \Phi(L)\epsilon_t \tag{II.2}$$

y_t is now a 5×1 vector consisting of the real price of equipment growth, labor productivity growth, hours, inflation and interest rate[8]. $\Phi(L)$ and $B(L)$ are matrices of lag polynomials. ϵ_t is a vector of exogenous shocks with I-shock and N-shock as the first two elements and non-technology non-oil shocks as the next three elements. The covariance matrix $E\epsilon_t\epsilon_t^{'} = \Omega$ is a diagonal matrix. o^*_t is an indicator of oil shocks proposed by Hamilton (2003). o^*_t is 100 times the logarithmic amount by which oil prices exceed their peak over the previous 12 quarters. If $o^*_t = 0$, no oil shock is said to have occurred. That is,

$$o^*_t = max[0, 100 \times (\ln o_t - \ln(max(o_{t-1}, o_{t-2}, ..., o_{t-12}))]$$

where o_t is nominal oil price. The appropriate measure of oil shocks should represent an exogenous movement in the price of oil and incorporate a plausible mechanism that allows oil shocks to impact the economy. Hamilton (2003) shows that this oil shock measure, named as “net oil price increase index (NOPI)” , meets these two criteria. It isolates the exogenous components of nominal oil price change and captures the asymmetric effect of oil shocks on the economy.

Figure (II.2) shows the business cycle components of the actual hours (solid line) and the hours due to I-shocks (dashed line) based on an extended model. Controlling for the oil variable and incorporating the interest rate and inflation reduces the role of I-shocks in accounting for the business cycles. I-shocks account for only 16 percent of the business cycle variability of hours and the correlation coefficient decreased from 0.73 to 0.48 (The third column of Table (II.1)).

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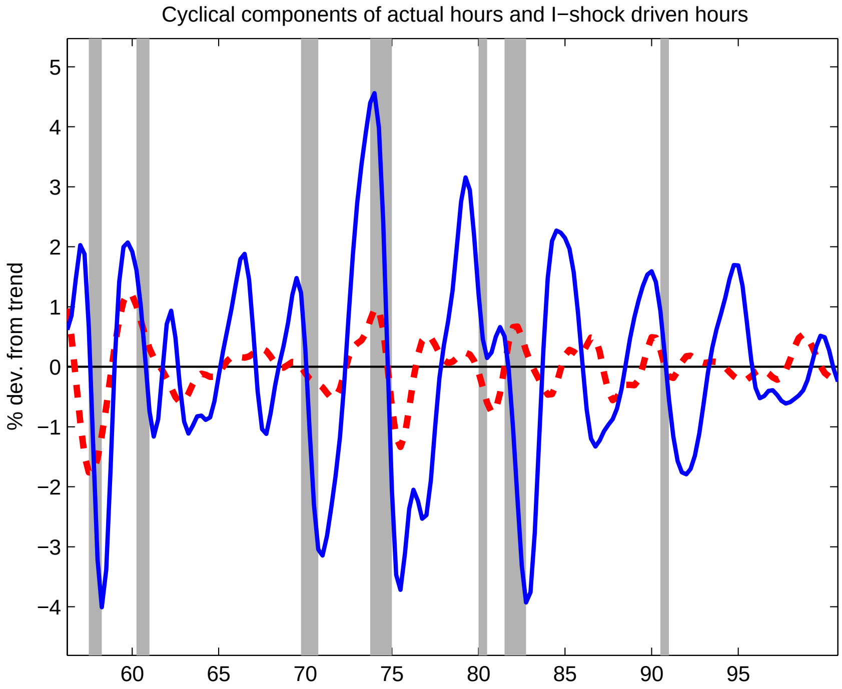
[8] Federal funds rate is used.



The solid lines denote the cyclical components of actual hours. The dashed line shows the cyclical components of hours due to I-shocks. The cyclical components are derived by using Christiano-Fitzgerald's band-pass filter. Shading indicates NBER recessions.

Figure II.2: Decomposing the contribution of I-shocks to hours: Extended model using a full sample

II.E Results based on a split sample

The analysis of quantifying the contribution of I-shocks to hours has been based upon using a full sample. Fisher (2005 and 2006) argues that the sample should be split when I-shocks are estimated. He enumerates the four reasons to split the sample. These are that around 1982 there were significant changes in (i) the equipment price's average rate of decline, (ii) the conduct of monetary policy, (iii) macroeconomic volatility, and (iv) the regulatory environment. He splits the sample following Galí, López-Salido and Vallés's (2003) split dates. The first subsample is 1955:I-1979:II and the second is 1982:II-2000:IV. His SVAR specification consists of the real price of equipment growth, the labor productivity growth, hours, inflation and interest rate[9].

He reports that even when the sample is split, I-shocks are still an important factor in accounting for business cycles. The metric he uses to quantify the importance of I-shocks for business cycles is the relative volatility of hours due to I-shocks, $\sigma^2_{H^d_I}/\sigma^2_{H^d_A}$. H^d_A denotes the detrended[10] actual hours and H^d_I denotes the detrended hours due to I-shocks. In terms of this measure, I-shocks seem to be important for business cycles because the variance ratio is almost 0.41 in both subsamples (see Table (II.3)).

Table II.3: Contribution of I-shocks to hours based on a split sample

	Sample period	
	1955:I-1979:II	1982:III-2000:IV
$\sigma^2_{H^d_I}/\sigma^2_{H^d_A}$	0.41	0.41
$\mathrm{corr}(H^d_I, H^d_A)$	0.50	-0.34

[1] Results are based on the specification in which interest rate (3-month T-bill rate) and inflation are added to 3-variables model.

[2] H^d_A denotes the detrended actual hours and H^d_I the detrended hours due to I-shocks. The series are detrended by using Christiano-Fitzgerald's band-pass filter.

However, it might be very misleading to measure the contribution of I-shocks to business cycles in terms of variance ratio alone. The fact that the relative volatility is almost 0.41 does not imply that the hours due to I-shocks trace the actual path of hours well. A careful inspection of Figure (II.3) reveals this problem with considering only variance ratio in gauging the importance of I-shocks for business cycles. It appears that the hours due to I-shocks move in the opposite direction as the actual path of hours in the second subsample. To confirm this visual impression, I calculate the contemporaneous correlation between the actual

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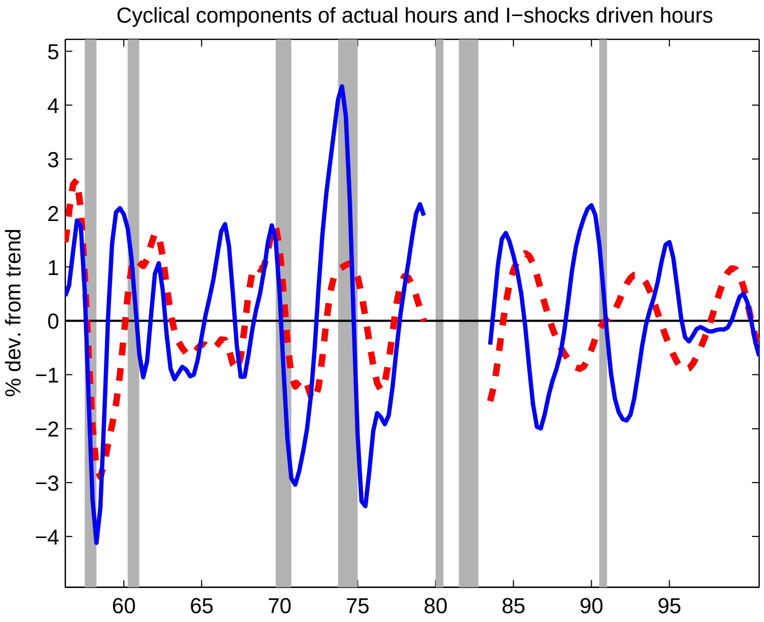
[9] He uses the 3-month T-bill rates

[10] The series are detrended by using Christiano-Fitzgerald's band-pass filter.



The solid lines denote the cyclical components of actual hours. The dashed line shows the cyclical components of hours due to I-shocks. The cyclical components are derived by using Christiano-Fitzgerald's band-pass filter. Shading indicates NBER recessions.

Figure II.3: Decomposing the contribution of I-shocks to hours based on using a split sample

hours (H_A^d) and the hours due to I-shocks (H_I^d) and report it in Table (II.3). While the correlation coefficient is 0.50 in the first subsample, it is -0.34 in the second subsample. This result casts doubt on the idea that business cycle fluctuations are mainly driven by I-shocks in both subsamples.

II.F Summary

This chapter re-examines the role of I-shocks in explaining the business cycles from an empirical perspective. I show that the SVAR specifications used in the literature may overstate the contribution of I-shocks substantially irrespective of whether they use the full sample or split the sample.

The baseline specification using a full sample fails to identify the true I-shocks correctly. Oil shocks and monetary policy were a significant part of the estimated I-shocks under this specification. Once oil shocks and monetary policy are explicitly taken into account in the SVAR model, the extent to which I-shocks account for business cycle variability of labor input declines from 55% to 16%.

When splitting the sample, I find that the variance ratio Fisher (2006) uses is not a sufficient statistic to determine that I-shocks are the main driver of business cycles. While the relative volatility of hours due to I-shocks is about 0.41 in both subsamples, the estimated I-shocks in the second subsample does a very poor job of predicting the actual path of hours. The contemporaneous correlation between the actual labor input and the labor input due to I-shocks are -0.34 in the second subsample.

III

Decomposing the sources of the changes in the real price of equipment

III.A Introduction

This chapter raises warning flags about the current use of the real price of equipment as a direct measure of investment-specific technological change in the Real-Business-Cycle (RBC) model. Greenwood, Hercowitz and Krusell (2000) identify the inverse of the real price of equipment as investment-specific technology shocks (hereafter, I-shocks) when they show that contemporaneous I-shocks are a sizable contributor of the business cycles. Jaimovich and Rebelo (2006) also adopt this identification scheme when they show that recessions are caused by not contemporaneous negative shocks but by lackluster news about investment-specific technical change. This assumption is based upon the fact that the equilibrium real price of equipment in these RBC models is the number of consumption units that must be exchanged to acquire an efficiency unit of the equipment, which is in turn equal to the inverse of investment-specific technical change.

Because in principle the real price of equipment is an endogenous variable determined by the demand and supply for it, however, it is important to check whether assumptions of exogeneity actually hold. Utilizing an econometric specification that allows types of shocks other than I-shocks to affect the real price of equipment, this paper finds that other shocks significantly affect the real price of equipment. The finding here is analogous to that of Evans (1992). He finds that the measured Solow residuals do not represent a truly exogenous measure of neutral technology. According to his VAR specification, about one-quarter of the forecast-error variance of the Solow residuals is attributable to variation in aggregate demands. As he argues, his finding implies that the RBC models using the standard Solow residuals as a measure of the impulse to a neutral technology shock overstate the role of neutral technology shocks in generating economic fluctuations. By the same token, this finding indicates that using the real price of equipment as the driving process for investment-specific technology might overstate the role of I-shocks in generating business cycles in a RBC model.

The remainder of this chapter is organized as follows. Section III.B presents the structural VAR (SVAR) model that enables one to quantify the contribution of I-shocks to accounting for the variations in the real price of equipment. In section III.C, I describe data used in the paper. Section III.D and III.E present the results based on using a full sample and split sample respectively. Section IV.D summarizes the results.

III.B Econometric strategy

This paper adopts the SVAR model used by Fisher (2003, 2005 and 2006). Fisher modifies Galí's one-technology shock SVAR model to separately estimate I-shocks and N-shocks. In a manner consistent with the identifying assumption in Galí (1999), Fisher's SVAR model allows both types of technology shocks to have a permanent effect on labor productivity, with only I-shocks affecting the relative price of equipment in the long-run. In other words, while this assumption restricts the secular trend in the real price of equipment to originate solely in I-shocks, it does not prevent other types of shocks not related to I-shocks from affecting the real price of equipment in the short-run. With this identification scheme[1], Fisher proposes the following simple SVAR model :

$$y_t = \Phi(L)\epsilon_t \tag{III.1}$$

where $y_t = [\Delta p_t, \Delta a_t, h_t, \mathrm{x_t}]^{'}$ and $\Phi(L)$ is a matrix of polynomials in the lag operator L. p_t denotes the log of the real price of equipment, a_t denotes the log of labor productivity, h_t denotes the log of hours and $\mathrm{x_t}$ is a vector of other endogenous variables in the SVAR model. ϵ_t is a vector of exogenous shocks with ϵ_{i_t} and ϵ_{n_t} as the first two elements. ϵ_{i_t} denotes the investment-specific technology shock and ϵ_{n_t} denotes the neutral technology shock. Technology shocks and non-technology shocks are orthogonal to each other, so that $E\epsilon_t\epsilon_t^{'} = \Omega$ is a diagonal matrix.

The estimated series of I-shocks and N-shocks can be obtained by using the instrumental variables (IV) method proposed by Shapiro and Watson (1986). Because the details for estimating this SVAR model appear in many parts of the literature, I move directly to the estimation results.

III.C Data

All series used in this paper are quarterly data from 1955:I-2000:IV. The real price of equipment is defined as the Cummins-Violante quality-adjusted equipment deflator[2] divided by the consumption deflator. The consumption deflator corresponds to nondurable consumption plus services consumption plus government consumption plus the service flow from consumer durables [3]. For the series

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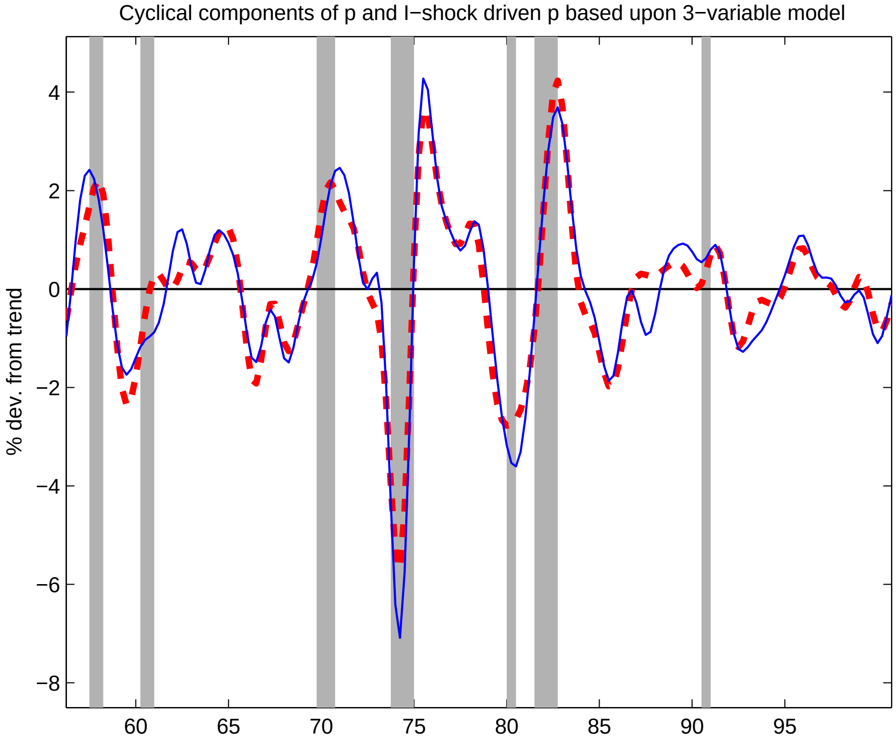
[1] In addition to these two identifying assumptions, Fisher(2005 and 2006) makes another assumption. He assumes that exogenous I-shocks which lower (raise) real investment good price by an amount x, raise (lower) labor productivity in a known fixed proportion to x. This assumption does not affect the estimation results much.

[2] The econometric analysis is based on quarterly data. Since the Cummins-Violante series is an annual series, Fisher interpolates it by using the National Income and Product Accounts (NIPA) equipment deflator.

[3] Fisher kindly provided the equipment and consumption deflators.

on labor productivity and labor input, the BLS series "Index of output per hour, nonfarm business" and "Index of hours in nonfarm business" are used. Labor productivity is measured in consumption units using the consumption deflator and labor input is put on a per capita basis by dividing by the population ages 16 and over. Inflation is measured with the consumption deflator and the nominal interest rate is the 3-month Treasury Bill rate or Federal funds rate.



The solid lines denote the cyclical components of the actual real price of equipment. The dashed line shows the cyclical components of the real price of equipment due to I-shocks. The cyclical components are derived by using Christiano-Fitzgerald's band-pass filter. Shading indicates NBER recessions.

Figure III.1: Decomposing the contribution of I-shocks to the real price of equipment: 3-variable model

III.D Results based on a full sample

III.D.1 Results from a baseline model

I begin by estimating a baseline specification that consists of the real price of equipment, labor productivity and hours using a full sample[4]. To assess how much the estimated I-shocks contribute to explaining the business cycle variation in the real price of equipment, I extract the predicted path of the real price of equipment due to I-shocks by conducting a historical decomposition. Figure (III.1) shows the business cycle components of the actual real price of equipment (solid line) and the real price of equipment due to I-shocks (dashed line)[5]. The real price of equipment driven by the estimated I-shocks tracks the variation in the real price of equipment remarkably well. Table (III.1) and (III.2) quantify the findings in Figure (III.1).

Table III.1: Contribution of I-shocks to the real price of equipment

	3-variable model	Extended model
$\sigma^2_{p^d_I}/\sigma^2_{p^d_A}$	0.83	0.16
$corr(p^d_I, p^d_A)$	0.96	0.48

[1] The extended model means that Federal fund rate, inflation and the net oil price index (NOPI) are added to the 3-variable model.

[2] p^d_A denotes the detrended actual real price of equipment series and p^d_I the detrended real price of equiment due to I-shocks. The series are detrended by using Christiano-Fitzgerald's band-pass filter.

The first column of Table (III.1) displays the relative volatility of the real price of equipment due to I-shocks, and the correlation between the real price of equipment due to I-shocks and the actual real price of equipment. I-shocks explain

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[4] Four lags are included.

[5] Business cycle components are derived using Christiano and Fitzgerald's (2002) implementation of the band-pass filter, which excludes frequencies higher than one and a half years and lower than eight years.

much of the business cycle variability of the real price of equipment (83%) and the correlation between the real price of equipment due to I-shocks and the actual real price of equipment is 0.96.

The first column of Table (III.2) shows the forecast error decomposition of the real price of equipment explained by I-shocks. From one to eight years, I-shocks virtually account for most of the forecast error of the real price of equipment (90% to 98%).

The results from this 3-variable model seem to support the idea that the real price of equipment is an excellent proxy for investment-specific technical change.

Table III.2: Forecast error decomposition of the real price of equipment

Horizon (Quarters)	Percent of forecast error variance of p explained by I-shocks	
	3-variable model	Extended model
1	83	5
4	90	24
6	92	31
12	95	47
16	96	54
32	98	74

[1] p denotes the real price of equipment.

[2] The extended model means that Federal fund rate, inflation and the net oil price index (NOPI) are added to the 3 variable model.

However, if other shocks not related to technology shock have significant predictive power in explaining the estimated I-shocks, a finding that I-shocks account for most of the business cycle variation in the real price of equipment becomes questionable. To assess the validity of the 3-variable SVAR specification, I subject the estimated I-shocks from this SVAR specification to Evans-Hall exogeneity tests. I consider three types of shocks generally viewed as unrelated to technology shocks: Oil shock dummies used by Ramey and Shapiro (1998)[6], Ramey and

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[6] According to Ramey and Shapiro (1998), oil shocks are based on dates identified by Hamilton (1985)

Table III.3: Exogoneity Tests: 3-variable model

	P-Values for Exogeneity Tests[1]		
	Oil dummies	Federal funds rates	Ramey-Shaprio war date
I-shocks	0.0047	0.0493	0.2398

[1] The F-test is based on a regression of the identified I-shock on a constant and current and four quarterly lags of the variable in question, except the Federal Fund rate where no current value is included. The hypothesis is that all of the coefficients on the variable in question are jointly equal to zero, which implies the variables in question do not have predictive power in identified technology shock.

Shapiro's (1998) war dates, and the Federal funds rate (Bernanke and Blinder, 1992). I regress the estimated I-shocks from the 3-variable model on a constant and current and four lagged values of the two sets of dummy variables (oil shocks dummies and war dates dummies), and regress the estimated I-shocks from the 3-variable model on a constant and four lagged values of the Federal funds rate[7]. Table (III.3) reports the results of exogeneity tests applied to the estimated I-shocks from the 3-variable model. The oil variables and Federal funds rate do have significant predictive power in the estimated I-shocks. Thus, the estimated I-shocks based on the 3-variable model do not represent true I-shocks and are compounded by oil shocks and monetary policy. This strongly suggests that oil shocks and monetary policy need to be taken into account explicitly in estimating I-shocks.

Figure (III.2) provides another motivation to incorporate oil shocks and monetary policy into the 3-variable model in an informal fashion. It plots the business cycle components of actual hours (solid line) and hours due to I-shocks (dashed line). According to Figure (III.2), the two postwar major recessions of 1973-75 and 1981-82 are entirely attributed to I-shocks. However, many believe

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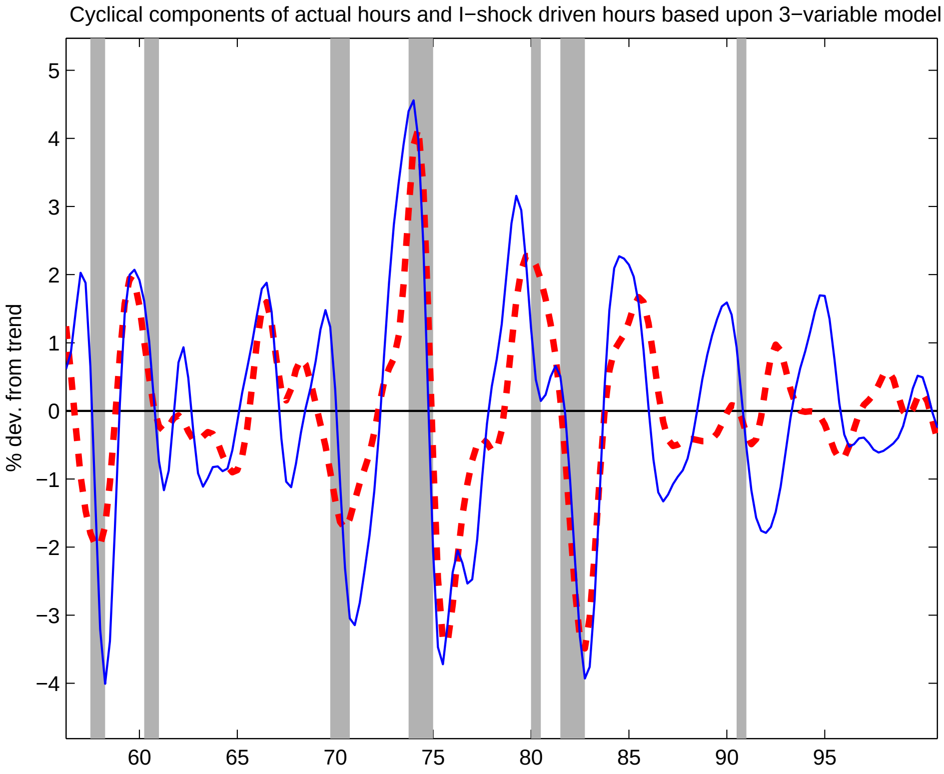
and Hoover-Perez (1994) and updated by them for the Iraqi invasion of Kuwait.

[7] Following Francis and Ramey (2001), I do not include lags of the estimated I-shocks since they are by assumption not serially correlated and exclude the current value of the Federal funds rates since it may respond to a current technology shock.

that these two recessions are due to oil shocks or tight monetary policy in response to oil shocks. It seems that the 3-variable SVAR model fails to isolate true I-shocks from oil shocks and monetary policy.



The solid lines denote the cyclical components of actual hours. The dashed line shows the cyclical components of hours due to I-shocks. The cyclical components are derived by using Christiano-Fitzgerald's band-pass filter. Shading indicates NBER recessions.

Figure III.2: Decomposing the contribution of I-shocks to hours: 3-variable model

Inflation also needs to be included since the Fed may have raised interest rate because of its inflationary concerns attributable to oil shocks. Another reason to include inflation is that inflation has a powerful prognostic implication for long run labor productivity (Barsky and Sims, 2006).

III.D.2 Results from a extended model

The discussions above suggest incorporating the interest rate, inflation and oil shock measures to the parsimonious system when I-shocks are estimated. To this end, I consider the following specification:

$$y_t = B(L)o^*_{t-1} + \Phi(L)\epsilon_t \tag{III.2}$$

y_t is now a 5×1 vector consisting of the real price of equipment growth, labor productivity growth, hours, inflation and interest rate[8]. $\Phi(L)$ and $B(L)$ are matrices of lag polynomials. ϵ_t is a vector of exogenous shocks with I-shock and N-shock as the first two elements and non-technology non-oil shocks as the next three elements. The covariance matrix, $E\epsilon_t\epsilon_t^{'} = \Omega$, is a diagonal matrix. o^*_t is an indicator of oil shocks proposed by Hamilton (2003). o^*_t is 100 times the logarithmic amount by which oil prices exceed their peak over the previous 12 quarters. If $o^*_t = 0$, no oil shock is said to have occurred. That is,

$$o^*_t = max[0, 100 \times (\text{ln}o_t - \text{ln}(max(o_{t-1}, o_{t-2}, ..., o_{t-12}))]$$

where o_t is nominal oil price. The appropriate measure of oil shocks should represent an exogenous movement in the price of oil and incorporate a plausible mechanism that allows oil shocks to impact the economy. Hamilton (2003) shows that this oil shock measure, named as "net oil price increase index (NOPI)" , meets these two criteria. It isolates the exogenous components of nominal oil price change and captures the asymmetric effect of oil shocks on the economy.

The second column of Table (III.1) and (III.2) makes it clear that other shocks not related to I-shocks account for a substantial fraction of the real price of equipment. The second column of Table (III.1) indicates that I-shocks account for only 16% of the business cycle variability of the real price of equipment. Furthermore, I-shocks track the cyclical components of the actual real price of equipment loosely. The correlation between the real price of equipment due to I-shocks and

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[8] Federal funds rate is used.

Table III.4: Contribution of I-shocks to the real price of equipment based on a split sample

	Sample period	
	1955:I-1979:II	1982:III-2000:IV
$\sigma^2_{p_I^d}/\sigma^2_{p_A^d}$	0.08	0.66
$corr(p_I^d, p_A^d)$	0.41	0.82

[1] Results are based on the specification in which interest rate (3-month T-bill rate) and inflation are added to the 3-variable model.

[2] p_A^d denotes the detrended actual real price of equipment series and p_I^d the detrended real price of equiment due to I-shocks. The series are detrended by using Christiano-Fitzgerald's band-pass filter.

the actual real price of equipment decreases from 0.96 to 0.48. The second column of Table (III.2) also conveys the same message. Over the first 12 quarters, I-shocks accounts for less than 50% of the forecast error variance of the real price of equipment. More strikingly, other shocks not related to I-shocks remain significant in explaining the forecast error of the real price of equipment even over a longer horizon. About one quarter of the 32-quarter-ahead forecast error of the real price of equipment is attributable to other shocks not related to I-shocks.

III.E Results based on a split sample

The analysis of quantifying the contribution of I-shocks to the real price of equipment has been based on a full sample. Fisher (2005, 2006) argues that sample should be split when estimating I-shocks. The four reasons to split the sample he sets forth are that around 1982 there were significant changes in (i) the equipment price's average rate of decline, (ii) the conduct of monetary policy, (iii) macroeconomic volatility, and (iv) the regulatory environment. Now I consider the specification proposed by Fisher (2006) to check whether splitting the sample alters the finding above. Fisher's SVAR specification contains the real price of equipment growth, the labor productivity growth, hours, inflation and interest

Table III.5: Forecast error decomposition of the real price of equipment based on a split sample

Horizon (Quarters)	Percent of forecast error variance of p explained by I-shocks	
	1955:I-1979:II	1982:III-2000:IV
1	0	55
4	9	67
6	14	79
12	34	92
16	44	95
32	63	98

[1] p denotes the real price of equipment.

[2] Results are based on the specification in which interest rate (3-month T-bill rate) and inflation are added to the 3-variable model.

rate[9]. He splits the sample following Galí, López-Salido and Vallés's (2003) split dates. The first subsample is 1955:I-1979:II and the second is 1982:II-2000:IV.

Tables (III.4) and (III.5) clearly show that using the real price of equipment as the driving process for investment-specific technology is inappropriate. While results based on the second subsample indicate that I-shocks account for most of the real price of equipment, those based on the first subsample strongly suggest that other shocks not related to I-shocks play a significant role in accounting for the real price of equipment over this first subsample[10]. Table (III.4) I-shocks account for only 8 percent of the business cycle variation in the real price of equipment in the first subsample. Table (III.5) shows that over a horizon of one and half- to eight-year horizon, I-shocks account for only 14 and 63 percent of the forecast error of the real price of equipment in the first subsample, respectively.

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[9] He uses the 3-month T-bill rates

[10] Fisher only reports the historical and variance decomposition of hours and output.

III.F Summary

This chapter casts a shadow over using the real price of equipment as a measure of investment-specific technology. The real price of equipment does not behave exogenously. A substantial component of the forecast-error variance in the real price of equipment comes from other shocks not related to I-shocks. I-shocks only accounts for a small fraction of the business cycle variation in the real price of equipment. These results imply that the current RBC models which use the real price of equipment as the driving process of investment-specific technology might overstate the contribution of I-shocks to the business cycles.

IV

Can a Labor Searching Friction Explain the Delayed Effect of Monetary Policy?

IV.A Introduction

This chapter investigates whether a labor searching friction can account for the delayed effect of monetary shocks that has been documented in empirical studies. Typically, after a positive money shock, output rises over several quarters and then declines. Walsh (2004) is the first to show that the dynamic stochastic general equilibrium (DSGE) model incorporating the aggregate labor searching friction with nominal price rigidity can generate a hump-shaped response of output to a monetary shock.[1] However, he only considers the searching friction that prevents employment from being instantaneously adjusted. Firms can utilize other low adjustment cost margins to adjust their production besides the high adjustment cost margin such as employment. As shown in Bresnahan and Ramey (1994), the typical way firms can change their production without bearing high adjustment

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[1] Alternatively, Christiano et al. (2005) allow for habit persistence in consumption, variable capital utilization, and investment adjustment costs as well as wage stickiness. They conclude that wage rigidity is the most important factor in explaining the hump-shaped response of output and inflation to monetary shocks.

costs is by varying the workweek of capital via overtime. Another low adjustment cost margin would be changing the effort level per worker. Hence, it seems fruitful to examine whether a labor searching friction can still lead to a hump-shaped response to a monetary shock in DSGE model when the workweek of capital and efforts are allowed to vary.

In incorporating both low adjustment cost margins (i.e., capital hours and effort) and a matching friction, we simplify the matching friction. Following Burnside and Eichenbaum (1996), we capture the labor searching friction by assuming that it is infinitely costly to make current-quarter adjustment on the employment instead of using a fully articulated labor searching model.

Despite the large built-in friction in adjusting employment, we find that the highest response of output to a monetary shock occurs on the period of impact in the standard DSGE model allowing capital hours and effort to vary. This result suggests that the sluggish adjustment of the employment due to the matching friction might not be the main factor in explaining the delayed effect of monetary shocks.

The remainder of paper is organized as follows. Section IV.B displays our baseline model economy. In section IV.C, we discuss our calibration procedures and present the main results. Section IV.D discusses the possible extension that might lead employment friction to generate the hump-shaped response of output.

IV.B The model economy

Our baseline model modifies the standard new Keynesian model (Ireland (2001)) by integrating the variations in capital hours and efforts and a labor searching friction.

The economy consists of households, a central bank in charge of the conduct of monetary policy and two productive sectors: a competitive sector producing a final good and a monopolistic sector providing intermediate goods. These intermediate goods are the only input necessary for the production of the final good, which can be used for consumption or investment. Intermediate goods are produced by combining capital services and labor inputs. Because it is infinitely costly to make current-quarter adjustment on the employment by assumption, firms in the intermediate good sector must choose the size of employment before observing monetary shocks. Even though firms in the intermediate goods sector cannot change employment in response to monetary shocks, they can adjust their production through varying the workweek of capital and effort instantaneously. However, there are costs associated with increasing the workweek of capital and effort. Firms must compensate workers for an increasing disutility associated with a longer nonstandard workweek and greater efforts. The specification governing the disutility due to the longer workweek and greater effort is based on that of Bils and Cho (1994). Obviously, compensating worker disutility for a longer nonstandard workweek is not the only cost to increasing capital hours. An accelerated depreciation is thus considered as another important cost. As a robustness check, we extend our baseline model to incorporate these two costs to increasing capital hours as Kim (2006) did.

IV.B.1 Household

The economy is populated by a continuum of identical households of unit measure. Their momentary utility function is given by

$$u\left(C_t, M_t/P_t, N_{t-1}, h_t, e_t\right) = \left(\frac{\gamma}{\gamma-1}\right) \ln\left[C_t^{\frac{\gamma-1}{\gamma}} + \left(\frac{M_t}{P_t}\right)^{\frac{\gamma-1}{\gamma}}\right] - V(N_{t-1}, h_t, e_t) \tag{IV.1}$$

where C_t, N_{t-1}, h_t, e_t, and M_t/P_t are consumption, the number of workers, hours per worker, effort per hour of work and real balances. $V(N_{t-1}, h_t, e_t)$ describes the disutility of providing labor services. Following Bils and Cho (1994), we specify that

$$V(N_{t-1}, h_t, e_t) = \left[\theta_1 \frac{N_{t-1}^{1+\nu}}{1+\nu} + \theta_2 N_{t-1} \frac{h_t^{1+\chi}}{1+\chi} + N_{t-1} h_t \frac{e_t^{1+\varsigma}}{1+\varsigma}\right]$$

The first component of $V(N_{t-1}, h_t, e_t)$ represents the cost of sending N_{t-1} member[2] of the households to work in a period t, even if hours worked are arbitrarily small. It may be interpreted as costs for commuting or costs incurred due to having fewer people available for home production. The second component reflects the disutility of working h_t hours per period associated with reduced leisure and longer work during nonstandard hours. Finally, the third term reflect disutility from exerting effort.

Next, we describe the sources of funds that can be used to purchase consumption goods and assets. Households enter each period holding an M_{t-1} amount of money stock and amount B_{t-1} of a risk free discount bond. Households receives a lump-sum nominal transfer T_t from the monetary authority and an amount D_t corresponding to intermediate firms' profits. Finally, households receive a (real) total wage bill by providing labor services from intermediate goods firms. We assume that the equilibrium wage bill is determined as Bils and Cho (1994) suggest: households present their employer with a wage bill that takes the form of $V(N_{t-1}, h_t, e_t)$ and allow firms to freely choose the size of employment, hours per worker and effort. Hence, the equilibrium (real) total wage, W_t, takes the following form:

$$W_t = \left[\theta_1 \frac{N_{t-1}^{1+\nu}}{1+\nu} + \theta_2 N_{t-1} \frac{h_t^{1+\chi}}{1+\chi} + N_{t-1} h_t \frac{e_t^{1+\varsigma}}{1+\varsigma}\right]$$

Households use their funds to purchase an amount C_t of the finished good at a nominal price P_t. Households purchase B_t risk-free bonds at an unitary cost of $1/R_t$, where R_t is the gross nominal rate of return between period t and $t+1$. The following relation, which represents households' budget constraint, must hold at every period:

$$C_t + \frac{B_t/R_t}{P_t} - \frac{B_{t-1}}{P_t} + \frac{M_{t-1}}{P_t} - \frac{M_t}{P_t} = W_t + \frac{T_t}{P_t} + \frac{D_t}{P_t} \tag{IV.2}$$

---

[2] The subscript $t-1$ is due to the assumption that the size of employment is predetermined.

This states that consumption expenditures plus asset accumulation must equal disposable income.

Household's preferences are given by the life-time utility function U_0. This function represents the expectation of the discounted sum of monetary utility function conditional on the information set at date $t = 0$.

$$U_0 = E_0 \sum_{t=0}^{\infty} \beta^t u\left(C_t, M_t/P_t, N_{t-1}, h_t, e_t\right) \tag{IV.3}$$

where β denotes households' discount factor.

Household's optimal behavior involves choosing a sequence $\{C_t,\ M_t,\ B_t\}$ that maximizes their life-time utility function (IV.3) subject to the budget constraint (IV.2).

IV.B.2 Final goods Firms

The representative final good-producing firm uses $Y_t\left(i\right)$ units of each intermediate good $i \in [0, 1]$ to produce Y_t units of the final good using the technology

$$Y_t = \left[\int_0^1 Y_t\left(i\right)^{\frac{\varepsilon-1}{\varepsilon}} di\right]^{\frac{\varepsilon}{\varepsilon-1}} \tag{IV.4}$$

Given that the price of intermediate good i is $P_t\left(i\right)$, the finished good sells at the nominal price P_t. The finished goods-producing firm chooses Y_t and $Y_t\left(i\right)$ to maximize its profits,

$$P_t Y_t - \int_0^1 P_t\left(i\right) Y_t\left(i\right) di \tag{IV.5}$$

subject to the constraint imposed by (IV.4). The first-order conditions for this problem imply that the optimal level of demand for a intermediate good i is given by

$$Y_t\left(i\right) = \left[P_t\left(i\right)/P_t\right]^{-\varepsilon} Y_t \tag{IV.6}$$

Since the firm is operating in a competitive market, the zero-profit condition determines P_t as a Dixit-Stiglitz aggregater given by

$$P_t = \left[\int_0^1 P_t\left(i\right)^{1-\varepsilon} di\right]^{\frac{1}{1-\varepsilon}} \tag{IV.7}$$

IV.B.3 Intermediate goods firms

There is a continuum of monopolistically competitive firms, each producing an intermediate good. The representative intermediate goods firm produces its output from effective units of labor, $L_t(i)$ and effective units of capital, $K_t^{'}(i)$.

We allow three dimensions of effective labor units: employment, N, hours per worker, h and effort per hour at work, e. We assume that it is infinitely costly to make current-quarter adjustment on the employment. It implies that intermediate firms start at each period t with a predetermined size of employment. $L_t(i)$ is therefore given by

$$L_t(i) = h_t(i)e_t(i)N_{t-1}(i)$$

Following Bils and Cho (1994), we assume that if a worker works longer hours or works at a more rapid physical pace, the utilization of the capital he operates will increase proportionately. $K_t^{'}$ is therefore given by

$$K_t^{'}(i) = h_t(i)e_t(i)K_{t-1}(i)$$

where K_{t-1} denotes the capital stock at the end of period $t-1$.

We assume that the technology available to intermediate goods firms exhibits a constant-returns-to scale Cobb-Douglas production function. The output of a representative intermediate goods firm at period t is therefore given by

$$Y_t(i) = A_t(K_t^{'})^{\alpha}(L_t)^{1-\alpha} = A_t h_t\left(i\right) e_t\left(i\right) \left[K_{t-1}\left(i\right)\right]^{\alpha} \left[N_{t-1}\left(i\right)\right]^{1-\alpha} \qquad \text{(IV.8)}$$

The parameter $\alpha \in$(0,1) and A_t represents an aggregate productivity parameter which follows the autoregressive process

$$\ln\left(A_t\right) = \left(1-\rho_A\right)\ln\left(A\right) + \rho_A \ln\left(A_{t-1}\right) + \varepsilon_{At} \qquad \text{(IV.9)}$$

where ε_{At} is a technology shock with standard deviations σ_A.

A representative intermediate goods firm choose a sequence of $\{K_t(i)$, $I_t(i)$, $N_t(i)$, $h_t(i)$, $e_t(i)$, $P_t(i)\}$ that maximizes the discounted stream of expected nominal profits D_t:

$$E_0 \sum_{t=0}^{\infty} \beta^t \lambda_t D_t\left(i\right)/P_t \tag{IV.10}$$

subject to the requirement that it satisfies the representative final goods firm's demand (IV.6) and the constraint imposed by production function (IV.8). In (IV.10), λ is the Lagrange multiplier on the budget constraint from the representative household's problem.

Real profits of a typical intermediate goods firm at the beginning of any period t, $\frac{D_t(i)}{P_t}$, are defined as

$$\begin{aligned} \frac{D_t\left(i\right)}{P_t} = \frac{P_t\left(i\right)Y_t\left(i\right)}{P_t} - \underbrace{\left(\theta_1 \frac{N_{t-1}^{1+\nu}\left(i\right)}{1+\nu} + \theta_2 N_{t-1}\left(i\right)\frac{h_t^{1+\chi}\left(i\right)}{1+\chi} + N_{t-1}\left(i\right)h_t\left(i\right)\frac{e_t^{1+\varsigma}\left(i\right)}{1+\varsigma}\right)}_{\text{real total wage bill}} \\ - I_t\left(i\right) - AC_{k,t}\left(i\right) - AC_{p,t}\left(i\right) \end{aligned} \tag{IV.11}$$

where

$$I_t(i) = K_t(i) - (1-\delta)K_{t-1}(i) \tag{IV.12}$$

is investment in capital goods, with δ being the rate of depreciation. The terms $AC_{k,t}$, $AC_{p,t}$ in (IV.11) represent a capital adjustment cost and a cost of changing the nominal price of the goods it produces, measured in terms of the finished goods:

$$AC_{k,t}\left(i\right) = \frac{\phi_k}{2}\left(\frac{I_t\left(i\right)}{K_{t-1}\left(i\right)} - \delta\right)^2 K_{t-1}\left(i\right) \tag{IV.13}$$

$$AC_{p,t}\left(i\right) = \frac{\phi_p}{2}\left(\frac{P_t\left(i\right)}{\pi P_{t-1}\left(i\right)} - 1\right)^2 Y_t \tag{IV.14}$$

where π is the steady-state rate of inflation.

IV.B.4 Monetary Authority

At each period of time, the monetary authority supplies the money stock which is growing at a rate

$$\mu_t = \frac{M_t}{M_{t-1}} \tag{IV.15}$$

It is assumed that the monetary authority follows an exogenous policy rule:

$$\mu_t = (1 - \rho_\mu)\,\mu + \rho_\mu \mu_{t-1} + \varepsilon_{\mu,t} \tag{IV.16}$$

where ρ_μ is the persistence parameter and serially uncorrelated policy shock $\varepsilon_{\mu,t}$ are normally distributed with mean zero and standard deviations σ_μ.

IV.C Results

IV.C.1 Parameter values

Table (IV.1) summarizes the values assigned to our baseline model's structural parameters. Specifically, the discount factor (β) is set to 0.99 so that the steady-state real interest rate is 3%. Following the estimates of Ireland (2001), we set the elasticity of money demand to the nominal interest rate (γ) to 0.1184. The capital's share on aggregate income (α) is set to 0.338. Following Ireland (2001), we set the parameters of the price adjustment costs function (ϕ_p) and capital adjustment costs (ϕ_k) to be 77.1 and 10 respectively. The elasticity of intermediate goods (ε) is set to 6 so that the steady-state markup of the intermediate-good producing firms is 1.2.

The parameter values dictating the responsiveness of the employment, workweek of capital (hours per worker) and efforts per hour are taken from Bils and Cho (1994). The values for ν, χ and ς are 1.57, 2 and 3 respectively.

The steady state value of the fraction of hours beyond a standard 40-hour workweek is set to 0.26, taken from Ramey and Shapiro (1998). This implies a 50.4-hour workweek of capital in the steady state. Normalizing a 40-hour workweek to unity, we set the steady state value of the workweek of capital, h to be 1.26.

Table IV.1: Parameter values in a baseline model

Capital share	α	0.338
Intertemporal discount rate	β	0.99
Elasticity intermediate good	ϵ	6
Price adjustment costs	ϕ_p	77.1
Capital adjustment costs	ϕ_k	10
Depreciation rate	δ	0.018
Elasticity money demand	γ	0.1184
The parameter governing the disutility of employment	ν	1.57
The parameter governing the disutility of hours per worker	χ	2
The parameter governing the disutility of efforts per worker	ς	3
Steady-state inflation rate	π	1.016
Mean money growth rate	μ	1.016
Steady-state participation rate	n	0.5
Steady-state hours per worker	h	1.2
The scale coefficient in the utility function	θ_1	4.27
The scale coefficient in the utility function	θ_2	4.46
Persistence money growth	ρ_μ	0.5
Standard deviation money growth	σ_μ	0.003

The steady state value of employment, N is set to ensure that the steady state ratio of total hours worked to the total time endowment of the household[3] is 0.24. The resulting value of N is 0.56. Finally, the scale coefficients (θ_1, θ_2) in the utility function are obtained from solving the equilibrium conditions satisfied in the steady-state.

IV.C.2 Dynamic responses to a monetary shock

Figure (IV.1) displays the response of key macroeconomic variables to a positive monetary growth shock. It shows that the employment friction is not able to generate the hump-shaped response of output to a monetary shock in a standard DSGE model. As is clearly shown in the response of hours per worker and effort, even though firms cannot change the size of employment due to the matching friction, they are able to meet the initial increase in demand induced by

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[3] The time endowment available to household is normalized to 2.63.

a positive monetary shock by raising the workweek of capital and effort.

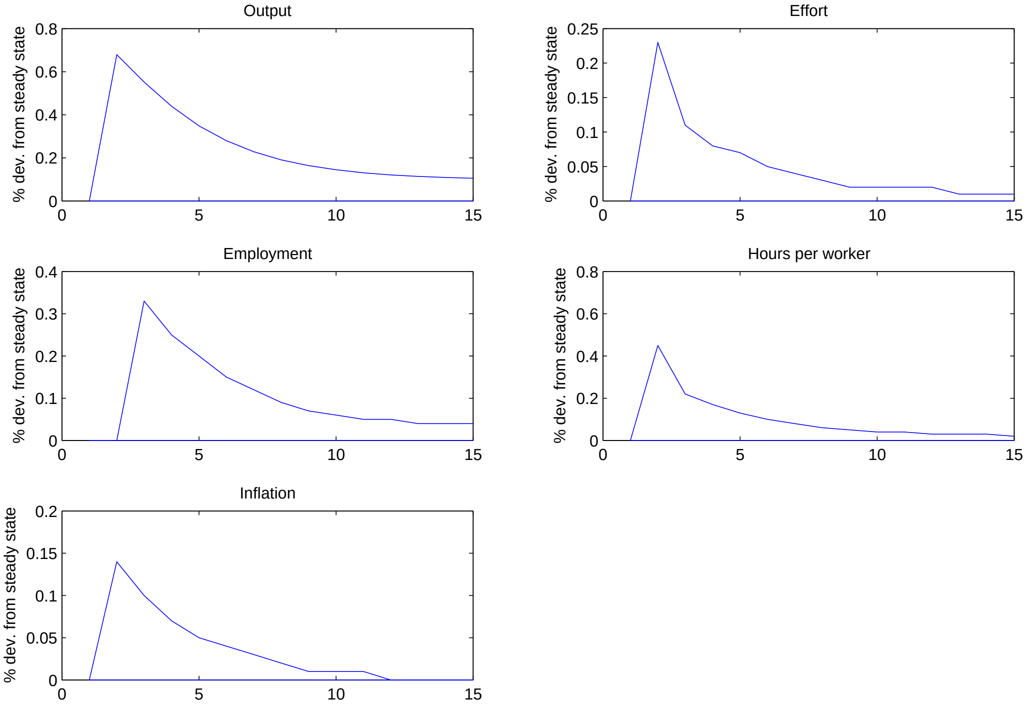

Figure IV.1: The Dynamic Response to a Positive Monetary Shock (Baseline model)

In the subsequent period when the size of employment is allowed to change, firms substitute away from the workweek of capital and efforts toward employment. The reason for this is that the model is parameterized to incorporate the idea that employment is high adjustment-low marginal cost margin whereas capital hours and efforts are low adjustment-high marginal cost margin. The parameter governing the disutility of employment ($\nu = 1.57$) is smaller than those governing the disutility of hours per worker and efforts ($\chi = 2$, $\varsigma = 3$). Hence, when firms can change the size of employment, they find it less costly to adjust employment than to vary hours per worker and efforts.

Following Kim (2006), we now investigate whether incorporating another cost to increasing the workweek of capital would change the dynamic responses.

Another important cost to increasing capital hours considered in the literature is an accelerated depreciation. To capture this depreciation cost, we modify the capital accumulation equation[4].

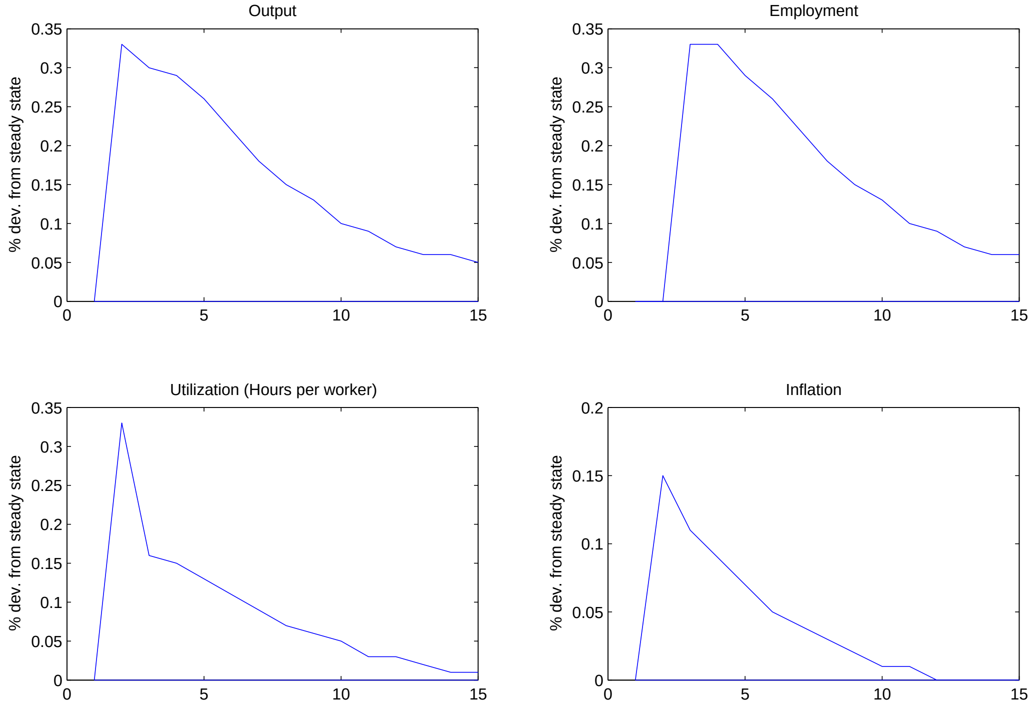

Figure IV.2: The Dynamic Response to a Positive Monetary Shock (An extended model)

$$K_t = (1 - \delta(h_t))K_{t-1} + I_t \tag{IV.17}$$

where $\delta(h_t)$ denotes the depreciation rate. The rate of depreciation depends on the capital utilization rate, reflecting a 'user-cost'. It is modeled as an increasing, convex function of capital utilization. The specific functional form of $\delta(u_t)$ is

$$\delta(h_t) = b\frac{h_t^{\omega}}{\omega}, \quad \omega > 1 \tag{IV.18}$$

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[4] Note that for simplicity, efforts per hour are assumed to be constant.

Firms now have to bear two types of cost to extending capital hours: worker disutility for a longer workweek and an accelerated depreciation. To solve the model, we assume that the quarterly depreciation rate is 0.018 and the elasticity of depreciation (ω) is set to 2, as suggested by Basu and Kimball (1997). The result presented below is not sensitive to the choice of ω.

Figure (IV.2) displays the response of key macroeconomic variables to a positive monetary growth shock when both utility and depreciation costs are incorporated. It clearly shows that even when depreciation cost is added to our baseline model, the employment friction is not able to produce a hump-shaped response of output to a monetary shock.

IV.D Concluding remarks

This chapter has shown that when the workweek of capital and efforts are allowed to vary, the employment lag itself cannot generate a hump-shaped response of output to a monetary shock. The reason for this is that despite the fact that the size of employment is predetermined, firms can rely on other low adjustment cost margins such as the workweek of capital and efforts to meet the increase in demand due to a positive monetary shock.

However, it should be noted that our result here is subject to one caveat. We have not considered another important margin that firms can use to meet the increase in demand induced by a positive monetary shock: *inventory*. Introducing inventory into our model might lead to a hump-shaped response. To clarify this point, suppose that some fraction of the increased demand can be met by adjusting inventory. Firms then have a stronger incentive to defer the change in labor input until they adjust the size of employment rather than relying on the contemporaneous change in labor input (i.e., hours per worker and efforts per hour). As shown in section IV.C.2, it is because employment adjustment is less costly than hours per worker and efforts adjustments. This will lead to a smaller response of hours per worker and efforts per hour and a greater response of the size of employment compared to our baseline model. This mechanism will in turn help to generate a hump-shaped response of output. Hence, it seems to constitute an exciting avenue for future research to investigate whether incorporating inventory margin would lead the employment friction to generate the delayed effect of monetary policy shocks.

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