Investment-specific technology shocks and consumption

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Abstract

We develop a DSGE model with variable capacity utilisation, investment-adjustment costs and nominal rigidities. We show that GHH preferences and variable capital utilisation are not sufficient to generate the positive consumption response to investment-specific technology shocks suggested by recent empirical work when nominal rigidities are absent. Consumption increases only with an extreme labour supply elasticity and with a 'user cost' specification of capital utilisation costs. This questions the ability of investment-specific technology shocks to generate recognisable business cycles in neoclassical models. In contrast, with a New Keynesian specification with nominal rigidities, the response of consumption is comfortably positive for reasonable values of the labour supply elasticity, and for the alternative specifications of capital utilisation costs considered. Investment-specific technology shocks are therefore potentially important drivers of business cycles in New Keynesian models.

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1 Introduction

Investment-specific technology shocks are shocks to the marginal efficiency of investment. Following Greenwood, Hercowitz and Krusell (2000), these shocks have gained in prominence in the literature as potentially important sources of business cycle fluctuations. Recent empirical papers by Altig, Christiano, Eichenbaum and Linde (2005), Fisher (2006) and Ravn and Simonelli (2009) document that investment-specific technology shocks explain a sizeable fraction of aggregate fluctuations in key macroeconomic variables. Using structural VARs identified with long-run restrictions, they show that output, hours, investment and consumption all rise after a positive investment-specific technology shock. Such aggregate comovement of key variables, a feature of typical business cycles, is a major reason for the appeal of this type of shock.

This paper emphasises the sizeable positive response of consumption found in these empirical studies, and investigates the conditions under which it can be obtained in a New Keynesian dynamic stochastic general equilibrium model.\(^1\) This is motivated by the fact that consumption declines even in papers that find an important role for investment-specific shocks, cf. Fischer (2006) and Justiniano, Primiceri and Tambalotti (2010). The latter study emphasises the role of monopolistic competition and sticky prices in generating comovement of other variables, but it relies on neutral technology shocks to generate comovement in consumption.

Greenwood, Hercowitz and Huffman (1988) show that a particular specification of preferences – referred to as GHH preferences – which eliminates the intertemporal substitution effect on labour supply, can generate comovement of consumption and output following a temporary investment-specific technology shocks in a neoclassical model augmented with variable capital utilisation. Recently, Jaimovich and Rebelo (2006) have emphasised GHH preferences as a mechanism for generating comovement following contemporaneous investment-specific technology shocks as well as to

\(^1\)Similar objectives are pursued in different settings in the contemporaneous work by Eusepi and Preston (2009), Guerrieri, Herderson and Kim (2009), and Khan and Tsoukalas (2009).
news shocks (see also Ravn and Simonelli, 2008, and Smith-Grohé and Uribe, 2008). This is within a neoclassical model with GHH preferences, variable capital utilisation and investment adjustment costs. The effect of introducing GHH preferences in a New Keynesian setup with monopolistic competition and sticky prices is therefore of particular interest in this paper.

We develop a DSGE model with endogenous capital accumulation, variable capacity utilisation, investment-adjustment costs, and nominal rigidities. We show that introducing GHH preferences in combination with variable capital utilisation is not sufficient to generate a positive consumption response to investment-specific technology costs when nominal rigidities are absent. Only with an extreme labour supply elasticity can we generate a positive response, and only with a 'user cost' specification of capital utilisation costs. This questions the ability of investment-specific technology shocks to generate recognisable business cycles in real business cycle models. With nominal rigidities in contrast, the response of consumption is comfortably positive for reasonable values of the labour supply elasticity, and for the alternative specifications of capital utilisation costs that we consider.

The paper is organised as follows. Section 2 presents the model. It’s calibration to US data is described in section 3. Results are presented and analysed in section 4, first for the case with flexible wages and prices, then for the case with nominal rigidities. Some concluding remarks are given in section 5.

2 The model

The model is a standard New Keynesian dynamic stochastic general equilibrium model extended with endogenous capital accumulation, variable capital utilisation and investment-adjustment costs. The economy consists of a continuum of firms, a continuum of households, and an inflation-targeting central bank. There is monopolistic competition in goods and labour markets, and perfect competition in capital rental markets.
Using Cobb-Douglas technology, each firm combines rented capital with an aggregate of the differentiated labour services supplied by individual households to produce a differentiated intermediate good. It sets the price of its good according to a Calvo price-setting mechanism and stands ready to satisfy demand at the chosen price. Given this demand, and given wages and rental rates, the firm chooses the relative factor inputs to production to minimise its costs.

Each household consumes a bundle of the intermediate goods produced by individual firms. Each period, it chooses how much to consume of this final good (in addition to its composition) and how much to invest in state-contingent one-period bonds. As in Christiano, Eichenbaum and Evans (2005), it also chooses how much to invest in new capital subject to investment adjustment costs, and it chooses the utilisation rate of its current capital stock subject to utilisation costs. Finally, the household chooses the hourly wage rate for its labour service, and it stands ready to meet demand at the chosen wage.

We consider two specifications of the household felicity function. The first is a standard specification with constant elasticities of intertemporal subsitution, while the second, due to Greenwood, Hercowitz and Huffman (1988), is one that eliminates wealth effects on household labour supply decisions. We allow for habit persistence in consumption in both specifications.

Each period begins by the realisation of shocks to the economy. We concentrate on investment-specific technology shocks – or investment shocks for short – that is shocks to the extent to which output devoted to investment increases the capital stock available for use in production. We abstract from other shocks that may affect the economy.
2.1 Monopolistic competition

The labour used in production in each firm $i \in [0, 1]$, denoted by $N_t(i)$, is a Dixit-Stiglitz aggregate of the differentiated labour services supplied by households

$$N_t(i) = \left( \int_0^1 N_t(i, j) \frac{e^{jw-1}}{e^{jw-1}} dj \right)^{\frac{e^{w-1}}{e^{w-1}}}$$  \hspace{1cm} (1)

where $e_w$ is the elasticity of substitution between labour services, and $N_t(i, j)$ represents the hours worked by household $j \in [0, 1]$ in the production process of firm $i$. Denoting the wage rate demanded by household $j$ by $W_t(j)$, cost minimisation by the firm (for a given level of total labour input) leads to a downward-sloping demand schedule for the labour service offered by this particular households. Aggregating over firms gives the economy-wide demand for the work hours offered by household $j$

$$N_t(j) = \left( \frac{W_t(j)}{W_t} \right)^{-e_w} N_t$$  \hspace{1cm} (2)

where $e_w$ represents the elasticity of demand, and $N_t = \int_0^1 N_t(i) di$ represents total hours worked in firms across the economy. $W_t$ is the wage index defined as

$$W_t = \left( \int_0^1 W_t(j)^{1-e_w} dj \right)^{\frac{1}{1-e_w}}$$  \hspace{1cm} (3)

This wage index has the property that the minimum cost of employing workers for $N_t$ hours is given by $W_t N_t$.

Similarly, the final consumption good that enters household $j$’s utility function is a Dixit-Stiglitz aggregate of the differentiated intermediate goods supplied by firms

$$C_t(j) = \left( \int_0^1 C_t(i, j) \frac{e^{jw-1}}{e^{jw-1}} dj \right)^{\frac{e_p}{e_p-1}}$$  \hspace{1cm} (4)

where $e_p$ is the elasticity of substitution between product varieties, and $C_t(i, j)$ represents the consumption by household $j$ of the good produced by firm $i$. Denoting
the price demanded by firm $i$ by $P_t(i)$, expenditure minimisation by the household (for a given level of final goods consumption) leads to a downward-sloping demand schedule for the intermediate good produced by this particular firm. Aggregating over households gives the economy-wide consumption demand for good $i$

$$C_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\varepsilon_p} C_t$$

(5)

where $\varepsilon_p$ represents the elasticity of demand, and $C_t = \int_0^1 C_t(j) \, dj$ is aggregate consumption. $P_t$ is the price index defined as

$$P_t = \left(\int_0^1 P_t(i)^{1-\varepsilon_p} \, di\right)^{\frac{1}{1-\varepsilon_p}}$$

(6)

This price index has the property that the minimum expenditure required to purchase $C_t$ units of the composite good is given by $P_t C_t$.

Assuming that the elasticity of substitution between varieties of goods is the same when purchased for investment and for maintenance of machinery as when consumed, aggregate demand for an intermediate good $i$ is given by

$$Y_t^d(i) \equiv C_t(i) + I_t(i) + M_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\varepsilon_p} (C_t + I_t + M_t)$$

(7)

where $I_t(i)$ represents goods produced by firm $i$ that households devote to capital accumulation, while $M_t(i)$ denotes those devoted to covering capital utilisation costs, which we may think of as maintenance of the existing capital stock. Omission of firm indices indicate corresponding economy-wide variables (in per capita terms).

Aggregate output is defined as

$$Y_t = \left(\int_0^1 Y_t(i)^{\frac{s_p-1}{s_p}} \, dy\right)^{\frac{s_p}{s_p-1}}$$

(8)

where $Y_t(i)$ is the output of firm $i$. Market clearing requires that $Y_t^d(i) = Y_t(i)$. 6
The aggregate resource constraint in the economy is therefore

$$Y_t = C_t + I_t + M_t$$  \hspace{1cm} (9)

2.2 Households

Each household $j \in [0,1]$ maximises its expected discounted utility given by

$$E_t \sum_{k=0}^{\infty} \beta^k U(C_{t+k} (j), N_{t+k} (j))$$ \hspace{1cm} (10)

where $\beta$ is the subjective discount factor.

We consider two specifications of the instantaneous utility function. The first is standard in the New Keynesian literature (see for instance Galí, 2008)

$$U(C_t (j), N_t (j)) = \frac{(C_t (j) - hC_{t-1})^{1-\sigma}}{1-\sigma} - \chi \frac{N_t (j)^{1+\eta}}{1+\eta}$$ \hspace{1cm} (11)

The second follows Greenwood, Hercowitz and Huffman (1988)

$$U(C_t (j), N_t (j)) = \frac{1}{1-\sigma} \left( C_t (j) - hC_{t-1} - \chi \frac{N_t (j)^{1+\eta}}{1+\eta} \right)^{1-\sigma}$$ \hspace{1cm} (12)

We refer to the class of preferences represented by this utility function as GHH preferences. With both specifications we allow for habit formation in consumption, where $h \geq 0$ is the degree of habit persistence (there is no habit in consumption when $h = 0$). The habit formation is external to the household in the sense that the household ignores the effect of its current consumption choice on habit formation; it is lagged aggregate consumption that enters the felicity function next period.

With standard preferences, the marginal utilities of consumption and labour are

$$MU_{C_t}^{STD} (j) = (C_t (j) - hC_{t-1})^{-\sigma}$$ \hspace{1cm} (13)
and
\begin{equation}
MU^{STD}_{N,t} = -\chi N_t (j)^\eta \tag{14}
\end{equation}
respectively. With GHH preferences, we get
\begin{equation}
MU^{GHH}_{C,t} (j) = \left( C_t (j) - hC_{t-1} - \chi \frac{N_t (j)^{1+\eta}}{1+\eta} \right)^{-\sigma} \tag{15}
\end{equation}
and
\begin{equation}
MU^{GHH}_{N,t} (j) = -\chi \left( C_t (j) - hC_{t-1} - \chi \frac{N_t (j)^{1+\eta}}{1+\eta} \right)^{-\sigma} N_t (j)^\eta \tag{16}
\end{equation}
The two specifications therefore result in different marginal rates of substitution between consumption and labour effort. With standard preferences, we get
\begin{equation}
MRS^{STD}_t = - \frac{MU^{S}_{N,t} (j)}{MU^{S}_{C,t} (j)} = \chi N_t (j)^\eta (C_t (j) - hC_{t-1})^\sigma \tag{17}
\end{equation}
while the marginal rate of substitution with GHH preferences
\begin{equation}
MRS^{GHH}_t = - \frac{MU^{G}_{N,t} (j)}{MU^{G}_{C,t} (j)} = \chi N_t (j)^\eta \tag{18}
\end{equation}
is independent of consumption. Hence, the supply of labour is determined independently of the intertemporal consumption allocation. The implications of this for the responses of key macroeconomic variables to investment-specific shocks (to be specified below) is of particular interest in this paper.

Households own the capital stock and let this capital to firms in a perfectly competitive rental market at the real rental rate $R^K_t$. Each household chooses the rate at which its capital is utilised, $U_t (j)$, which transforms the accumulated capital stock, $\bar{K}_{t-1} (j)$, into effective capital in period $t$, $K_t (j)$, according to
\begin{equation}
K_t (j) = U_t \bar{K}_t (j) \tag{19}
\end{equation}
Following Christiano, Eichenbaum and Evans (2005), the cost of capital utilisation
is given by the increasing and convex function \(a(.)\) so that \(M_t(j) = a(U_t(j))\overline{K}_t(j)\), while the rate of depreciation is fixed at \(\delta_t = \delta\) where \(0 \leq \delta \leq 1\). Steady-state utilisation is normalised to \(U = 1\), and we assume \(a(1) = 0\) and \(a'(.) > 0\). We refer to this as the 'maintenance cost' specification. Alternatively, the cost of capital utilisation takes the 'user cost' form of Greenwood, Hercowitch and Huffman (1988). According to this specification, \(M_t(j) = 0\), while the rate of depreciation is increasing in utilisation: \(\delta_t = \delta(U_t)\) where \(\delta(1) = 0\), \(0 \leq \delta(.) \leq 1\) and \(\delta'(.) > 0\).

The capital accumulation equation is given by

\[
\overline{K}_{t+1}(j) = (1 - \delta_t)\overline{K}_t(j) + Z_t \left(1 - S \left(\frac{I_t(j)}{I_{t-1}(j)}\right)\right) I_t(j) \tag{20}
\]

where \(I_t(j)\) is the amount of the final good acquired by the household for investment purposes, \(\delta\) represents the depreciation rate of capital, and \(S(.)\) is a function representing investment-adjustment costs. We assume that \(S(1) = S'(1) = 0\) and \(S''(1) > 0\).

\(Z_t\) is the investment-specific technology shock, which affects the extent to which resources allocated to investment (net of investment-adjustment costs) increase the capital stock available for use in production next period. It is therefore a shock to the marginal efficiency of investment. The shock evolves according to the autoregressive process

\[
\log Z_t = \rho_z \log Z_{t-1} + \epsilon_{z,t} \tag{21}
\]

where \(0 < \rho_z < 1\), and \(\epsilon_{z,t}\) is white noise.

Household maximisation is subject to a sequence of budget constraints taking the following form

\[
P_t \left[ C_t(j) + I_t(j) + M_t(j) \right] + E_t \left( \Lambda_{t,t+1} B_{t+1}(j) \right) \\
\leq B_t(j) + W_t(j) N_t(j) + T_t(j) + P_t R_t K_t(j) \tag{22}
\]
The left-hand side gives the allocation of resources to consumption, investment, capital adjustment costs, and to a portfolio of bonds, \( E_t (\Lambda_{t,t+1} B_{t+1} (j)) \), where \( \Lambda_{t,t+1} \) is the stochastic discount factor and \( B_{t+1} (j) \) represents contingent claims.\(^2\) Hence, the risk-free (gross) nominal interest rate is defined by \( R_t = (E_t \Lambda_{t,t+1})^{-1} \).

The right-hand side gives available resources as the sum of bond holdings, labour income, dividends from firms, denoted by \( T_t \), and rental income from capital.

First-order conditions with respect to consumption and bond holdings gives rise to an Euler equation summarising the intertemporal consumption allocation choice of households. It takes the standard form

\[
1 = R_t E_t \Lambda_{t,t+1}. \tag{23}
\]

where the stochastic discount factor is given as

\[
\Lambda_{t,t+1} = \beta \frac{MU_{C,t+1}^{l} P_t}{MU_{C,t}^{l} P_{t+1}}
\]

\( l \in \{STD, GHH\} \) is an index for the type of preferences assumed so that \( MU_{C,t}^{l} \) is the marginal utility of consumption as specified above. The assumption of complete markets allows us to drop household indices in this expression (and in many of those that follow). First-order conditions imply that risk-sharing is complete in consumption and investment under the complete market assumption as long as initial endowments are identical. That is, \( C_t (j) = C_t, I_t (j) = I_t, K_t (j) = K_t \) and \( U_t (j) = U_t \) for all \( j \in [0, 1] \).

First-order conditions with respect to investment and capital equates marginal

\(^2\)The stochastic discount factor \( \Lambda_{t,t+1} \) is defined as the period-\( t \) price of a claim to one unit of currency in a particular state in period \( t + 1 \), divided by the period-\( t \) probability of that state occurring.
cost and benefits of additional investment and capital

\[
1 = Q_t Z_t \left[ 1 - S \left( \frac{I_t}{I_{t-1}} \right) - S' \left( \frac{I_t}{I_{t-1}} \right) \frac{I_t}{I_{t-1}} \right] \\
+ E_t \left[ \Lambda_{t,t+1} \frac{P_{t+1}}{P_t} Q_{t+1} Z_{t+1} S' \left( \frac{I_{t+1}}{I_t} \right) \left( \frac{I_{t+1}}{I_t} \right)^2 \right] 
\]

(24)

\[
Q_t = \beta E_t \left\{ \Lambda_{t,t+1} \frac{P_{t+1}}{P_t} \left[ R_{t+1}^K U_{t+1} - \frac{M_{t+1}}{K_{t+1}} + Q_{t+1} (1 - \delta_t) \right] \right\} 
\]

(25)

The variable \( Q_t \), representing Tobin’s \( q \), is equal to the ratio of the Lagrange multipliers attached to the capital accumulation equation and the budget constraint, respectively.

Similarly, the first-order condition with respect to capital utilisation equates the marginal benefit of raising capital utilisation with the marginal cost of doing so. With the maintenance cost specification, this first-order condition becomes

\[
R_t^K = a' (U_t) 
\]

(26)

while the alternative user cost specification yields

\[
R_t^K = Q_t \delta' (U_t) 
\]

(27)

Households set wages following a Calvo mechanism. Each period a measure \((1 - \theta_w)\) of randomly selected households get to set a new wage rate, while remaining households must keep theirs constant. A household allowed to reoptimise at time \( t \) sets \( W_t (j) = W_t^* \) to maximise its expected life-time utility, (10), subject to its budget constraint, (22), the demand for its labour service, (2), and the restriction from the Calvo mechanism that

\[
W_{t+k+1} (j) = \begin{cases} 
W_{t+k+1}^* & \text{w.p. } (1 - \theta_w) \\
W_{t+k} (j) & \text{w.p. } \theta_w 
\end{cases} 
\]

(28)
The first-order condition is given by

\[
\sum_{k=0}^{\infty} (\beta \theta_w)^k E_t \left\{ N_{t+k} \left( j \right) \left[ \frac{W_t^*}{P_{t+k}} MU_{C,t}^l + \mu_w MU_{N,t+k}^l \left( j \right) \right] \right\} = 0
\] (29)

where \( \mu_w \equiv \varepsilon_w (\varepsilon_w - 1)^{-1} \) is the household’s desired mark-up of the real wage over the marginal rate of substitution. Again, \( l \in \{STD, GHH\} \) denotes the class of preferences.

### 2.3 Firms

Each firm \( i \in [0, 1] \) produces a differentiated good, \( Y_t(i) \), according to

\[
Y_t(i) = K_t(i)^\alpha N_t(i)^{1-\alpha}
\] (30)

where \( K_t(i) \) denotes the period-\( t \) capital stock rented by firm \( i \), and \( N_t(i) \) is the number of hours worked in the production process of firm \( i \).

Firm \( i \)'s marginal cost can be found as the Lagrange multiplier from the firm’s cost minimisation problem

\[
MC_t(i) = \frac{W_t/P_t}{(1 - \alpha) (K_t(i)/N_t(i))^{\alpha}} = \frac{R^K_t}{\alpha (N_t(i)/K_t(i))^{1-\alpha}}
\] (31)

where \( R^K_t \) denotes the real rental rate of capital. Conditional factor demand schedules imply that firm \( i \) will choose factor inputs such that

\[
\frac{K_t(i)}{N_t(i)} = \frac{\alpha}{1 - \alpha} \frac{W_t/P_t}{R^K_t}
\] (32)

This equation implies that, on the margin, the cost of increasing capital in production equals the cost of increasing labour. Since all firms have to pay the same wage for the labour they employ, and the same rental rate for the capital they rent, it follows that marginal costs (of increasing output) are equalised across firms re-
gardless of any heterogeneity in output induced by differences in prices. Hence, 
\[ MC_t(i) = MC_t \forall i \]
where
\[ MC_t = \frac{1}{1 - \alpha} \left( \frac{\alpha}{1 - \alpha} \right)^{-a} W_t \left( \frac{P_t}{1 - \alpha} \right)^a R_t \]  
(33)
follows from combining (31) and (32).

Consequently, the marginal product of labour
\[ MPL_t(i) = (1 - \alpha) Y_t(i) / N_t(i) = \frac{W_t}{MC_t(i)} \]  
(34)
is also equalised across firms so that \( MPL_t(i) = MPL_t \forall i \).

Firms follow a Calvo price-setting mechanism when setting prices. Each period, a measure \((1 - \theta_p)\) of randomly selected firms get to post new prices, while remaining firms must keep their prices constant. A firm allowed to choose a new price at time \( t \) sets \( P_t(i) = P_t^* \) to maximise the value of the firm to its owners, the households. At time \( t \), this value is given by
\[ \sum_{k=0}^{\infty} E_t \left\{ \Lambda_{t,t+k} [P_{t+k}(i) Y_{t+k}(i) - \Psi(Y_{t+k}(i))] \right\} \]  
(35)
where \( \Lambda_{t,t+k} \) is the stochastic discount factor, and \( \Psi(.) \) is the cost function (i.e. the value function from the cost minimisation problem described above). Optimisation is subject to the demand for the firm’s product, (7), its production technology, (30), and the restriction from the Calvo mechanism that
\[ P_{t+k+1}(i) = \begin{cases} P_t^{*} & \text{w.p.} (1 - \theta_p) \\ P_{t+k}(i) & \text{w.p.} \theta_p \end{cases} \]  
(36)
The first-order condition is given by
\[ \sum_{k=0}^{\infty} \theta_p^k E_t \left\{ \Lambda_{t,t+1} Y_{t+k}(i) [P_t^* - \mu P_{t+k} MC_{t+k}] \right\} = 0 \]  
(37)
where \( \mu_p \equiv \varepsilon_p (\varepsilon_p - 1)^{-1} \) is the desired mark-up of price over nominal marginal cost. This condition reflects the forward-looking nature of price-setting; firms take not only current but also future expected marginal costs into account when setting prices.

2.4 Monetary policy

We assume that the central bank reacts to inflation \( \Pi_t^P = (P_t - P_{t-1}) / P_{t-1} \) according to a simple Taylor rule

\[
\frac{R_t}{R} = \left( \frac{R_{t-1}}{R} \right)^{\rho_r} \left( \frac{\Pi_t^P}{\Pi^P} \right)^{\phi_r (1-\rho_r)} \tag{38}
\]

where the omission of time subscripts indicate steady-state values, \( 0 < \rho_r < 1 \) governs monetary policy inertia, and \( \phi_r > 1 \).

2.5 Calibration

We calibrate the model’s parameter values and solve it numerically after log-linearising the equilibrium conditions. The steady state around which we log-linearise is characterised in appendix A, and the log-linear relations are summarised in appendix B.

We consider the length of a period to be one quarter, and we let \( \beta = 0.99 \) implying that the annual interest rate is about 4 per cent in steady state. We set the depreciation rate to \( \delta = 0.025 \) and the capital share to \( \alpha = 0.33 \). We assume that utility is logarithmic by setting \( \sigma = 1 \). Desired mark-ups in both labour and goods markets are assumed to be 20 per cent, which we achieve by setting \( \varepsilon_p = \varepsilon_w = 6 \).

We use \( \chi \) to pin down hours in steady state to \( N = 1/3 \) of available time. These are values in line with those commonly found in the New Keynesian literature, see, e.g., Christiano, Eichenbaum and Evans (2005), Galí (2008), Golosov and Lucas (2007) and Smets and Wouters (2007).

We set the inverse of the second derivative of the investment adjustment cost
function to $\lambda_a = 0.2$, slightly larger than the 0.17 estimated by Smets and Wouters (2007), but smaller than the 0.4 estimated by Christiano, Eichenbaum and Evans (2005), and the 0.34 found by Justiniano, Primiceri and Tambalotti (2010). In the log-linear model, this is the only characteristic of the investment adjustment function with implications for the model’s propagation mechanism. By reducing the convexity of the adjustment cost function, an increase in $\lambda_a$ leads to a smaller investment adjustment cost for a given change in investment. Hence, the sensitivity of households’ investment decisions to changes in the current value of installed capital (Tobin’s $q$) will increase as $\lambda_a$ increases.

The remaining parameters govern the strength of the frictions that are of interest in the next section. In particular, we want to investigate the responses to an investment shock for various combinations of these variables. Our benchmark investment-specific technology shock is moderately persistent with $\rho_z = 0.45$. This is roughly the average of the estimated values by Justiniano, Primiceri and Tambalotti (2010) and Smets and Wouters (2007), who find 0.23 and 0.71, respectively. But we also consider the implication of a purely transitory shock and a more persistent shock with $\rho_z = 0.7$.

Our benchmark calibration features no habit formation, i.e. $h = 0$. But since habits have been found to be useful in generating plausible responses to other shocks, we check the sensitivity of our results to a specification with moderate habit persistence or $h = 0.4$.

We consider the implications of both fixed and variable capacity utilisation. When allowing for variable capacity utilisation, we set the elasticity of marginal utilisation costs to $\lambda_u = 0.2$ (fixed utilisation is achieved by letting $\lambda_u \to \infty$). In the log-linear model, this is the only characteristic of the capital utilisation cost function with implications for the model’s propagation mechanism. An increase in $\lambda_u$ increases the effect on the marginal capital utilisation costs from an increase in utilisation. Hence, utilisation responds less to a given increase in the rental rate. Effectively, more of the increase in rental income brought about by an increase in
capital utilisation will be off-set by maintenance costs as $\lambda_a$ increases. The value we choose for this parameter is slightly larger than the estimate of 0.17 found by Justiniano, Primiceri and Tambalotti (2010) and Smets and Wouters (2007). Similarly, when considering the user cost specification we set the elasticity of the marginal rate of depreciation to $\lambda_d = 0.2$. This is smaller than the value of 0.52 chosen by Greenwood, Hercowitz and Krusell (2000), but larger than the value of 0.15 in Jaimovich and Rebelo (2009).

We consider both the case with flexible wages and prices, i.e. $\theta_w = \theta_p = 0$, and the case with nominal wage and price rigidity. When allowing for sticky prices, we set $\theta_w = \theta_p = 0.7$. We find it convenient to choose the same values for wage and price rigidities (our results do not depend critically on this choice), and this strikes a balance between the microdata evidence provided by Bils and Klenow (2004) and Nakamura and Steinsson (2008) for prices, and the slightly larger values usually considered for wages.

Monetary policy is such that $\phi_r = 1.5$ as originally suggested by Taylor (1993). In our benchmark calibration we let monetary policy be moderately inertial by setting the interest rate smoothing parameter to $\rho_r = 0.4$. But we also consider the implications of the absence of inertia in monetary policy ($\rho_r = 0$), and of highly inertial monetary policy ($\rho_r = 0.8$). This compares with smoothing estimates of 0.8 in Justiniano, Primiceri and Tambalotti (2010) as well as in Smets and Wouters (2007).

Finally, our benchmark calibration of the inverse of the labour supply elasticity sets $\eta = 0.77$ corresponding to a labour elasticity of 1.3. This value is close to the estimates of Gourio and Noual (2009), who explicitly consider the link between micro-level data and the macro-level elasticity featuring in business cycle models. It is a labour supply elasticity in the very high end of the range of estimates from the microeconometric literature, and we consider values for the elasticity above the one implied by our benchmark to be highly implausible given this evidence. To gauge the implications of the consumption response to changes in this variable, we also
consider two alternatives to the benchmark specification. In the first alternative we set $\eta = 0.4$ as in Jaimovich and Rebelo (2009). This gives a labour elasticity of 2.5, a value much higher than estimates from microeconometric studies. The second alternative we consider is $\eta = 1.39$ resulting in a smaller elasticity of 0.72, cf. Heathcote, Storesletten and Violante (2009), and Ríos-Rull et al. (2009) for a discussion.

3 Results

We now investigate the conditions under which we can obtain a sizeable positive response of consumption to an investment shock. We do this by adding the frictions contained in the model one by one. Following Justiniano, Primiceri and Tambalotti (2010), we organise our discussion around the labour market equilibrium condition.

With sticky prices and wages, mark-ups in goods and labour markeds will generally deviate from their desired levels. We therefore implicitly define the economy’s average mark-up in goods and labour markets, respectively, as

$$\mu_{p,t} = \frac{MPL_t}{W_t/P_t}$$  \hspace{1cm} (39)

and

$$\mu_{w,t} = \frac{W_t/P_t}{MRS^l_t}$$  \hspace{1cm} (40)

where $MRS^l_t$ represents the economy’s average marginal rate of subistution for $l \in \{STD, GHH\}$. We may think of (39) as a labour demand and (40) as a labour supply schedule. Hence, equating inverse demands gives the labour market equilibrium condition

$$MPL_t = \mu_t MRS^l_t$$  \hspace{1cm} (41)

The variable $\mu_t = \mu_{p,t} \mu_{w,t}$ represents the time-varying wedge driven between the marginal rate of substitution and the marginal product of labour as a consequence of
monopolistic competition and nominal rigidities in both goods and labour markets. Notice that changes in capital utilisation affects the labour demand schedule through its effect on effective capital. An increase in the rate of capital utilisation increases the marginal product of labour for given hours and therefore works to shift the labour demand curve upwards in \((N, W/P)\) space.

### 3.1 Flexible wages and prices

We first consider the case in which prices and wages are flexible, preferences are standard, and capital utilisation is fixed. With flexible wages and prices, markups in goods and labour markets are constant and equal to their desired levels, cf. \((29)\) and \((37)\). The marginal product of labour is a negative function of aggregate hours worked, and as effective capital is predetermined when utilisation is fixed, only hours can affect the marginal product of labour on impact of a shock. With standard preferences, the average marginal rate of substitution is a positive function of consumption and of aggregate hours. Hence in this case, \((41)\) becomes

\[
MPL_t \left( \frac{H_t}{-} \right) = \mu \cdot MRS_t \left( C_t, \frac{H_t}{+} \right) 
\]  

(42)

where \(\mu = \mu_p \mu_w\).

As discussed by Barro and King (1984), Greenwood, Hercowitz and Huffman (1988) and more recently by Justiniano, Primiceri and Tambalotti (2010), the investment-specific shock will raise hours worked (as long as consumption and leisure are normal goods). The only way to satisfy the equilibrium, and therefore to have a decline in the marginal rate of substitution is through a decline in consumption, that is a downward shift in the labour supply curve. This works through an intertemporal substitution effect on hours worked. An investment-specific technology shock (increasing the marginal efficiency of capital) increases the rate of return on investment. As a consequence, intertemporal substitution makes households shift demand away from consumption towards investment. The decline in consumption shifts the labour
supply curve, i.e. the right-hand side of (42), down. As a result, while consumption declines, hours increase to produce more investment goods.

This effect is confirmed in figure 1, which present impulse responses for a version of the model with flexible wages and prices, and no habit formation in consumption.\(^3\) The solid lines represents impulse responses to a shock when preferences are standard and capital utilisation is fixed (implying that effective capital is equal to the capital stock). Hours and output increase on impact, while the real wage falls. In contrast consumption declines. This reflects the downward shift in the labour supply schedule described above.

Consider now the case with GHH preferences (keeping nominal flexibility and fixed capital utilisation). (41) now becomes

\[
MPL_t(H_t) = \mu MRS_t(H_t) + \mu MRS_t(H_t) \tag{43}
\]

In this case, the investment-specific shock has no impact on the labour market equilibrium. Neither the marginal product of labour nor the marginal rate of substitution is affected by the shock. In particular, the absence of an intertemporal substitution effect on labour supply means that the labour supply curve does not shift down as in the case with standard preferences. Consequently, hours are unaffected on impact of the shocks. Since effective capital is predetermined with fixed capital utilisation, output stays constant too. But then, equilibrium on the goods market will be achieved through intertemporal substitution of consumption and investment only, that is through a decline in consumption that exactly offsets the increase in investment brought about by the investment-specific technology shock. Only as the new investments increase the capital stock will the labour demand schedule gradually shift out, increasing hours, output and the real wage, and allowing consumption to recover.

\(^3\)Results are robust to the introduction of habit persistence (responses not shown). When wages and prices are flexible, the main effect of habit formation is to reduce the fall in consumption with standard preferences. With GHH preferences the effects are negligible.
This reasoning is confirmed in figure 1. The dashed lines are impulse responses from the model with flexible wages and prices, constant capacity utilisation and GHH preferences. We see that hours do not react on impact and that the increase in investment crowds out consumption. Hence, the introduction of GHH preferences into a neoclassical framework is in itself insufficient to generate a positive consumption response to investment-specific technology shocks as emphasised by Greenwood, Hercowitz and Huffman (1988). In fact, consumption falls more on impact in this case.

Now consider adding variable capital utilisation. Variable capital utilisation may help generate a positive response of consumption by allowing output to increase along with investment. As noted above, if the technology shock leads to an increase in capital utilisation, the labour demand curve will shift up. By increasing hours worked in equilibrium, this increase in labour demand therefore has the potential to expand output and thereby allow consumption to increase along with investment (rather than to be crowded out by it). Effectively, the shift in the labour demand curve represents an intratemporal substitution effect. By increasing the marginal product of labour, the opportunity cost of leisure increases, which induces substitution from current leisure to consumption, cf. Greenwood, Hercowitz and Huffman (1988). This effect may dominate the negative intertemporal substitution effect on consumption from the higher rate of return on investment.

So how does variable capacity utilisation affect the results in our model? With the specification chosen by Christiano, Eichenbaum and Evans (2005), it turns out that the labour market equilibrium remains undisturbed on impact of the shock when wages and prices are flexible. This is because the auctioneer in the capital rental market will realise that equilibrium can only be attained if the capital rental rate is kept unchanged at its steady-state level.\footnote{With flexible prices, the firm and household optimality conditions (26), (29), (32) and (37) reduce to a system of two equations in the real wage and the rate. The only solution to this system (solved by the auctioneer) is given by the steady-state variables of the real wage and the rental rate.} It follows by (26) that households
will keep the rate of utilisation constant, which in turn will keep effective capital constant. Thus, the labour demand relation does not shift on impact of the shock. Hours, output and the real wage therefore stay constant too, and the increase in investment will be exactly offset by a reduction in consumption.

Hence, we find that consumption unambiguously declines following an investment-specific technology shock even when the GHH utility specification is combined with variable capacity utilisation when utilisation costs are specified as in Christiano, Eichenbaum and Evans (2005). The dotted lines in figure 1 show the impulse responses for this case. As expected, hours and output do not react on impact of the shock, and consumption falls to offset the increase in investment.

In contrast to the utilisation cost specification of Christiano, Eichenbaum and Evans (2005), the 'user cost' specification of Greenwood, Hercowitz and Huffman (1988) allows for changes in capital utilisation even in the absence of rental rate movements. This is because the marginal cost of capital utilisation is made up of two components in this case, cf. (27). Specifically, the marginal cost is the product of the marginal depreciation rate, \( \delta'(U_t) \), and the replacement cost of capital given by \( Q_t \). As the investment-specific technology shocks tends to reduce the replacement cost of capital, households will choose to increase utilisation and so the depreciation of its capital stock for given levels of the rental rate. This increase in the utilisation rate on impact of the shock shifts the labour demand curve up through its effect on effective capital. Consequently, intratemporal substitution may result in an increase in consumption on impact of the shock in this case.

Figure 2 shows impulse responses for this specification. Solid lines show responses for the benchmark calibration with a labour supply elasticity of 1.3 (\( \eta = 0.77 \)). Now, the investment-specific technology shock leads to both an increase in investment and in capacity utilisation on impact of the shock. The shift in labour demand leads to an increase in hours and the real wage. But even in this case, the impact response of consumption remains negative.

Figure 2 also shows that the impact response of consumption is positively re-
lated to the labour supply elasticity. A lower value of the labour supply elasticity \((\eta = 1.39)\), leads to a sharper contraction in consumption (dotted lines), while only the alternative with a much higher labour supply elasticity \((\eta = 0.4)\) leads to an increase in consumption. Hence, not only does the a sizeable positive response of consumption depend on the specification of utilisation costs of capital, it also requires a very high labour supply elasticity.\(^5\)

The reason for the sensitivity of consumption can also be seen from (43). A high labour supply elasticity, corresponding to a low value of \(\eta\), effectively makes the inverse supply demand curve flatter, and the flatter the labour supply curve, the larger the effect on hours in equilibrium. That is, the effect on consumption of households’ intratemporal substitution of consumption for leisure is more likely to dominate the effect of their intertemporal substitution of investment for consumption. Notice also, that standard preferences would put further strain on the labour supply elasticity to generate the needed expansion in output due to the intratemporal substitution effect on labour supply.

3.2 Sticky wages and prices

Now we introduce sticky wages and sticky prices. This is interesting for our purposes for two reasons. First, sticky wages and sticky prices breaks the tight restrictions on the relation between factor prices with maintenance cost of capital utilisation that prevents utilisation from moving on impact of a shock when wages and prices are flexible (marginal costs will no longer be constant, for instance). Hence, labour demand may shift allowing output to increase on impact and intratemporal substitution of leisure and consumption to take place. Second, when wages and prices are sticky, mark-ups in both goods and labour markets will generally deviate from their

\(^5\)Our model with the user cost specification nests the model of Greenwood, Hercowitch and Huffman (1988) as a special case with \(\theta_p = \theta_w = 0\) and \(\varepsilon_p, \varepsilon_w, \lambda_s \to \infty\). We are able to reproduce the correlations of output with consumption and other key variables that they report by adjusting our calibration to match their parameter values. We also find that the impact response of consumption is negative in this case.
desired levels and will vary over time. And changes in the wedge driven between the
marginal rate of substitution and the marginal product of labour as a consequence
of monopolistic competition may amplify the effects of that shift in labour demand
on the equilibrium outcome. In particular, to the extent that mark-ups are coun-
tercyclical and hours worked are procyclical, mark-ups will be declining functions of
hours. In this case, we may write (41) as

\[ \mu_{pt}^{-1} \left( N_t^+ \right) MPL_t \left( N_t^- \right) = \mu_{wt} \left( N_t^- \right) MRS_t \left( N_t^+ \right) \]  

(44)

It follows that price rigidity makes the inverse labour demand curve flatter (less
negative slope), while wage rigidity makes the inverse labour supply curve flatter
(less positive slope) in \((N, W/P)\) space. Any upward shift in the labour demand
curve as a consequence of an increase in capital utilisation will therefore lead to a
larger effect on hours worked in equilibrium.\(^6\)

Notice, however, that nominal rigidities by themselves are unlikely to generate
a positive response to consumption on impact of an investment shock as variable
capacity utilisation is needed for the shift in the marginal product of labour to oc-
cur. Notice also that standard preferences would make it harder to generate the
needed expansion in output for the same reason as with flexible wages and prices.
Consequently, GHH preferences, variable capacity utilisation and nominal rigiditi-
ties constitute a promising combination for the purpose of generating an increase
in consumption along with hours and output on impact of an investment-specific
technology shock.

In figure 3, we present impulse responses to an investment shock for the bench-
mark specification with sticky wages and prices. With standard preferences, the
consumption response is negative (dotted lines). With GHH preferences, in con-
trast, consumption increases comfortably for both maintenance and user costs of
capital utilisation (solid and dashed lines, respectively). Notably, this occurs for the

\(^6\)Alternatively, an expansionary shock shifts labour demand further up, while at the same time
benchmark specification of the labour supply elasticity ($\eta = 0.77$). Hence, when
nominal variables are sticky, GHH preferences and variable capacity utilisation gen-
erates comovement of key macroeconomic variables including consumption without
relying on a specific specification of the utilisation costs or on implausible values for
the labour supply elasticity.

To further study the sensitivity of the results, figure 4 presents responses for
the three alternative values of the labour supply elasticity considered for flexible
prices for the case with maintenance costs of capital utilisation and sticky wages
and prices (keeping other parameters at their benchmark values). The figure shows
that consumption increases for all specification of the labour supply elasticity when
prices and wages are sticky (a similar result applies for the user cost specification).

Figure 5 presents responses for the benchmark specification of monetary policy
smoothing along with two alternatives. Remaining parameters are at their bench-
mark values, and the maintenance specification of capital utilisation costs is chosen
(similar results are obtained for user costs). The figure shows that monetary pol-
icy inertia helps to generate a positive response of consumption. This is because
interest rate smoothing makes monetary policy slower to respond to the increase
in inflation that follows the boom in investment. Effectively, interest rates do not
increase to the same extent to curb demand. Hence, a higher degree of interest rate
smoothing enhances the ability of a given degree of nominal rigidity to generate a
positive response of consumption.

Figure 6 presents responses for the benchmark specification with moderate per-
sistence of the investment-specific shock along with the alternative specifications
that shocks are purely temporary and highly persistent. Remaining parameters are
at their benchmark values, and the maintenance specification of capital utilisation
costs is chosen (similar results are obtained for user costs). The figure suggests that
the persistence of the shock has non-trivial implications for both the impact and dy-
amic effects of the shock on investment. With the benchmark calibration, a highly
persistent shock actually generates a negative impact response of consumption, while
consumption eventually increases persistently.

Finally, figure 7 presents responses for the benchmark specification of no habit formation along with the alternative specification \( h = 0.4 \). Remaining parameters are at their benchmark values, and the maintenance specification of capital utilisation costs is chosen (similar results are obtained for user costs). The main effect of introducing habit formation is to induce a highly persistent, hump-shaped consumption response.

In sum, we have found that a sizeable positive response of consumption to an investment-specific technology shock can be obtained with GHH preferences, variable capital utilisation and nominal rigidities. This is without relying on a specific form of the cost of capital utilisation costs, or on an implausibly high labour supply elasticity. Monetary policy inertia may help generate a positive response of consumption for given levels of nominal rigidities.

4 Concluding remarks

We have developed a DSGE model with monopolistic competition, sticky prices, endogenous capital accumulation, variable capacity utilisation, investment-adjustment costs and habit persistence in consumption. We have shown that introducing GHH preferences in combination with variable capital utilisation is not sufficient to generate a positive consumption response to investment-specific technology shocks in a neoclassical framework. Only under extreme assumptions about the labour supply elasticity can we generate a sizeable positive response, and only with a ’user cost’ specification of capital utilisation costs. This questions the ability of investment-specific technology shocks to generate recognisable business cycles in real business cycle models. In contrast, with nominal wage and price rigidities, the response of consumption is comfortably positive for reasonable values of the labour supply elasticity, and for the alternative specifications of capital utilisation costs that we consider. Investment-specific technology shocks are therefore potentially important
drivers of business cycles in New Keynesian models.

Our analysis can help interpreting some results in the literature. In a framework with flexible wages and prices, Greenwood, Hercowitz and Krusell (2000) find a positive consumption response with user costs of capital utilisation and standard preferences. Similarly, Ravn and Simonelli (2009) estimate a large positive consumption response on the impact of an investment shock, although in the context of a two sector real business cycle model. However, both papers effectively impose an infinite labour supply elasticity. We conjecture that this infinite labour supply elasticity is essential for their results to hold. Also, Jaimovich and Rebelo (2009) argue that GHH preferences combined with variable capacity utilisation and investment-adjustment costs can generate comovements between hours, output and consumption, both on the impact of news shocks and contemporaneous investment-specific shocks. However, Jaimovich and Rebelo (2009) impose a very high labour supply elasticity of 2.5. Based on our results, we conjecture that a highly elastic labour supply is essential to obtain comovement also following news shocks. Finally, Khan and Tsoukalis (2009) find that a user cost specification provides a better fit to US data than a maintenance cost specification. Our analysis suggests that this is because the data want prices to be more sticky and preferences to have a smaller intertemporal substitution effect on labour supply with the user cost specification.

In future work, we intend to analyse the transmission mechanisms of various shocks to the capital accumulation relation in further detail.
A The steady state

Steady-state variables are indicated by omission of time subscripts. In steady state we have $U = (P^*/P) = 1$ and $\Pi^p = \Pi^W = 0$ where $\Pi^W$ represents steady-state wage inflation. Hence from (19) $\bar{K} = K$. From (20) we get $I = \delta K$ and from (23) $R = \beta^{-1}$. From (24) we get $Q = 1$ and so from (25) $R^K = (\beta^{-1} - 1 + \delta)$. (26) now gives a restriction on $a'(1) = R^K$. (37) implies $MC = \mu^{-1}$.

Combining (30) and (31) then gives the restriction

$$\gamma_k = \frac{K}{Y} = \frac{\alpha MC}{R^K}$$

(45)

so that

$$\gamma_i = \frac{I}{Y} = \frac{\delta \alpha}{\mu (\beta^{-1} - 1 + \delta)}$$

(46)

Then, from (9) we get

$$\gamma_c = \frac{C}{Y} = 1 - \gamma_i$$

(47)

Combining (30) and (20) gives

$$Y = N (\gamma_i \delta^{-1})^{\frac{\alpha}{1 - \alpha}}$$

(48)

and consequently

$$C = \gamma_c Y$$

(49)

while (32) now gives

$$\frac{W}{P} = (1 - \alpha) MC \frac{Y}{N}$$

(50)

Taking $N$ as given, a restriction on $\chi$ follows (or, alternatively, given $\chi$ we can find $N$) from (29). With standard preferences, this restriction is

$$\chi = \frac{W/P}{\mu w N \eta (C - hC)^p}$$

(51)
and with GHH preferences
\[ \chi = \frac{W/P}{\mu w N^\beta} \]  
(52)

This completes the solution of the model in steady state.

For future reference, we define
\[ \sigma_r \equiv \sigma (1 - h) \left( 1 - h - \frac{\chi}{1+\eta} \frac{N^{1+\eta}}{C} \right)^{-1} \]  
(53)

B \ Log-linearisation

We log-linearise the equilibrium dynamics outlined in section 2 around the steady state described in appendix A. Lower case letters denote the log-deviation of a variable from its steady state value.

The relation between the stock of capital and effective capital, (19) becomes
\[ k_t = u_t + \bar{k}_t \]  
(54)

while the capital accumulation equation (20) in log-linear form is given by
\[ \bar{k}_{t+1} = (1 - \delta) \bar{k}_t + \delta (i_t + z_t) \]  
(55)

with maintenance costs and
\[ \bar{k}_{t+1} = (1 - \delta) \bar{k}_t + \delta (i_t + z_t) - (\beta^{-1} - 1 + \delta) u_t \]  
(56)

with user costs of capital utilisation.

With standard preferences, the consumption Euler equation (23) takes the form
\[ c_t = \frac{h}{1+h} c_{t-1} + \frac{1}{1+h} E_t c_{t+1} - \frac{1}{\sigma} \frac{1-h}{1+h} \left( r_t - E_t \pi^p_{t+1} \right) \]  
(57)
With GHH preferences, it becomes

$$c_t = \frac{h}{1+h} c_{t-1} + \frac{1}{1+h} E_t c_{t+1} - \frac{1}{\sigma_r} \frac{1-h}{1+h} \left( r_t - E_t \pi_{t+1}^r \right) - \frac{1-h}{1+h} (1+\eta) (1-\sigma_r^{-1}) (E_t n_{t+1} - n_t)$$

(58)

where $\sigma_r$ is defined in (53).

The linearised first-order conditions with respect to investment and capital read

$$i_t = \frac{1}{1+\beta} \left( \beta E_t i_{t+1} + i_{t-1} + \lambda_s (q_t + z_t) \right)$$

(59)

$$q_t = - (r_t - E_t \pi_{t+1}) + (1-\beta (1-\delta)) E_t r_{t+1}^k + \beta (1-\delta) E_t q_{t+1}$$

(60)

where the value of $\lambda_s^{-1} \equiv S''(1) > 0$ governs investment-adjustment costs.

With maintenance costs of capital utilisation, the first-order condition with respect to capital utilisation (26) becomes

$$r_t^k = \lambda_u u_t$$

(61)

in its log-linear form where

$$\lambda_u \equiv \frac{a''(U)U}{a'(U)} = \frac{a''(1)}{a'(1)}$$

(62)

is the elasticity of the marginal costs of capital utilisation. The alternative condition (27) for the user cost specification is

$$r_t^k = \lambda_\delta u_t + q_t$$

(63)

where

$$\lambda_\delta \equiv \frac{\delta''(U)U}{\delta'(U)} = \frac{\delta''(1)}{\delta'(1)}$$

(64)

is the elasticity of the marginal depreciation rate.
By combining (29) with the law of motion of the wage index and the labour demand schedule, a standard New Keynesian Phillips curve for wage inflation, \( \pi_t^W \), is derived as

\[
\pi_t^W = \beta E_t \pi_{t+1}^w + \kappa_w (\text{mrs}_l^t - (w_t - p_t))
\]

(65)

for \( l \in \{ \text{STD}, \text{GHH} \} \) where \( \text{mrs}_l^{\text{std}} = \sigma (1 - h)^{-1} (c_t - hc_{t-1}) + \eta n_t \) is the economy’s average marginal rate of substitution under standard preferences, and \( \text{mrs}_l^{\text{ghh}} = \eta n_t \) is the same average under GHH preferences. The slope is given by

\[
\kappa_w = \frac{(1 - \beta \theta_w) (1 - \theta_w)}{\theta_w (1 + \eta \epsilon_w)}
\]

Up to a first-order approximation, aggregate production is given by

\[
y_t = \alpha k_t + (1 - \alpha) n_t
\]

(66)

By combining (37) with the law of motion of the price index, the standard New Keynesian Phillips curve is derived

\[
\pi_t^p = \beta E_t \pi_{t+1}^p + \kappa_p m c_t
\]

(67)

where \( \kappa_p = (1 - \beta \theta_p) (1 - \theta_p) \theta_p^{-1} \) and

\[
m c_t = (1 - \alpha) (w_t - p_t) + \alpha r_t^k
\]

(68)

The factor input relation (32) becomes

\[
r_t^k = (w_t - p_t) + n_t - k_t
\]

(69)

The aggregate resource contraint (9) in log-linear from is given as

\[
y_t = \gamma_c c_t + \gamma_1 i_t + \gamma_k (\beta^{-1} - 1 + \delta) u_t
\]

(70)
with maintenance costs and

\[ y_t = \gamma_c c_t + \gamma_i i_t \]  \hspace{1cm} (71)

with user costs. The monetary policy rule, (38), is

\[ r_t = \rho_r r_{t-1} + (1 - \rho_r) \phi \pi_t^{p} \]  \hspace{1cm} (72)

while the exogenous driving force is specified as

\[ z_t = \rho_z z_{t-1} + \epsilon_{z,t} \]  \hspace{1cm} (73)

where \( \epsilon_{z,t} \sim iid \left(0, \sigma_z^2\right) \).

Finally, the model in log-linear form is closed by adding the identity

\[ \pi_t^{w} - \pi_t^{p} = (w_t - p_t) - (w_{t-1} - p_{t-1}) \]  \hspace{1cm} (74)
References


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Figure 1: Impulse responses to an investment-specific technology shock with flexible wages and prices. Solid lines represent responses for standard preferences and fixed capital utilisation. Dashed lines represent GHH preferences and fixed capital utilisation. Dotted lines represents GHH preferences and variable capital utilisation with maintenance cost of utilisation.
Figure 2: Impulse responses to an investment-specific technology shock with flexible wages and prices, and user costs of capital utilisation. Solid lines represent responses for the benchmark labour supply elasticity. Dotted lines represent responses for a low, and dashed lines for a very high labour supply elasticity.
Figure 3: Impulse responses to an investment-specific technology shock with nominal wage and price rigidities, and parameter values as in the benchmark calibration. Solid lines represent responses for GHH preferences and maintenance costs of capital utilisation. Dashed lines represent GHH preferences and user cost of capital utilisation. Dotted lines represent standard preferences and maintenance costs.
Figure 4: Impulse responses to an investment-specific technology shock with sticky wages and prices, and maintenance costs of capital utilisation. Solid lines represent responses for the benchmark labour supply elasticity. Dotted lines represent responses for a low, and dashed lines for a very high labour supply elasticity.
Figure 5: Impulse responses to an investment-specific technology shock with sticky wages and prices, and maintenance costs of capital utilisation. Solid lines represent responses for moderate interest rate smoothing. Dashed lines represent responses for no smoothing, and dotted lines a high degree of smoothing.
Figure 6: Impulse responses to an investment-specific technology shock with sticky wages and prices, and maintenance costs of capital utilisation. Solid lines represent responses with a moderately persistent shock. Dashed lines represent a purely transitory shock, and dotted lines a highly persistent shock.
Figure 7: Impulse responses to an investment-specific technology shock with sticky wages and prices, and maintenance costs of capital utilisation. Solid lines represent responses without habit persistence in consumption. Dashed lines represent moderate habit persistence.