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Investment-specific technology shocks and consumption*

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Abstract

Current business cycle models systematically underestimate the correlation between consumption and investment. One reason for this failure is that a positive investment-specific technology shock generally induces a negative consumption response. The objective of this paper is to investigate whether positive consumption responses to investment-specific technology shocks can be obtained in a modern business cycle model. We find that the answer to this question is yes. With a combination of nominal rigidities and non-separable preferences, the consumption response is positive for general parameterisations of the model.

JEL classification: E32.

Keywords: investment-specific technology shocks, consumption, GHH preferences, nominal rigidities, comovement.

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1 Introduction

Investment-specific technology (IST) shocks are shocks to the marginal efficiency of investment. That is, they are disturbances to the transformation of investment into productive capital. Following Greenwood, Hercowitz and Huffman, henceforth GHH, (1988) and Greenwood, Hercowitz and Krusell (2000), these shocks have gained in prominence in the literature as potentially important sources of business cycle fluctuations particularly in neoclassical models.

More recently, IST shocks have been studied also in the context of New Keynesian models. Justiniano, Primiceri and Tambalotti, henceforth JPT, (2010a) find that IST shocks are the most important drivers of aggregate fluctuations in an estimated dynamic stochastic general equilibrium (DSGE) model of the US economy with nominal and real rigidities. In their model, IST shocks account for 50 per cent of fluctuations in output, 83 per cent of those in investment and 59 per cent of the variability of hours worked. As these variables all increase on impact of the shock, this is in keeping with the empirical observation that key real variables co-move at business cycle frequencies. However, consumption fails to co-move with other key macroeconomic variables in the JPT (2010a) model in contrast to the characteristics of empirically recognisable business cycles. Specifically, a positive IST shock leads to a decline in consumption on impact and for the first five quarters after the shock. Moreover, IST shocks explain only six per cent of consumption volatility according to the variance decomposition.

Similarly, Gertler, Sala and Trigari (2008) find that the IST shock is the most important driver of output fluctuations in a model with unemployment despite a significantly negative consumption response for almost ten quarters. The same is true for all the models, with and without financial frictions, considered in Christiano, Motto and Rostagno (2010). The decoupling between consumption and investment dynamics is even larger in the estimated model with flexible prices and wages by Schmitt-Grohé and Uribe (2010). In that model the sum of anticipated and unanticipated shocks to the marginal efficiency of investment explains 63 per cent of fluctuations in investment, but only 2 per cent of fluctuations in consumption.

In this paper, we investigate whether it is possible to obtain a positive consumption reaction to IST shocks in a standard DSGE model.[1] This is interesting for two reasons. First, the lack of co-movement of consumption with other key variables in response to IST shocks is not compensated for by other shocks in the model estimated by JPT (2010a). In fact, the model underestimates the correlation between consumption and investment, which is positive in the data and negative in the model. In contrast, the JPT (2010a) model performs very well in reproducing other cross-correlations.[2] Second, evidence from VAR studies suggests that consumption increases significantly on impact of an IST shock, cf. Peersman and Straub (2007).[3]

We find that a positive consumption response can be obtained in a standard DSGE model with nominal rigidities when preferences are non-separable in consumption and hours.[4] This holds for the general class of non-separable preferences proposed by Jaimovich and Rebelo (2009) that nests as limiting cases the preferences proposed by GHH (1988) and the preferences proposed by King, Plosser and Rebelo, henceforth KPR, (1988). However, the positive effect on consumption is stronger in the GHH (1988) limit, in which the degree of complementarity between consumption and hours worked is largest, cf. Monacelli and Perotti (2008).

Nominal rigidities are essential for this result to hold. When prices and wages are flexible, we can show analytically that the impact response of hours and output is zero in the GHH limit. This implies that the boom in investment induced by an IST shock has to be exactly off-set by a decline in consumption. Unlike GHH

[1]Similar objectives are persued in different settings in the contemporaneous work by Eusepi and Preston (2009), Guerrieri, Henderson and Kim (2009), and Khan and Tsoukalas (2010).

[2]Smets and Wouters (2007) introduce a risk premium shock in the Euler equation for consumption to overcome the co-movement problem for consumption.

[3]Peersman and Straub (2007) identify IST shocks through sign restrictions on the consumption-output ratio motivated by the model in Smets and Wouters (2007). This leaves the sign of the consumption response itself unrestricted.

[4]Basu and Kimball (2002) provide empirical evidence that motivates the use of non-separable preferences.

(1988), we find that variable capacity utilisation affects the transmission mechanism for IST shocks only marginally.

The paper is organised as follows. Section 2 presents the model and its calibration. Results are presented and analysed in section 3. In section 4, we dig deeper into the transmission mechanism under various alternative assumptions. In section 5, we compare our results to other papers in the literature. Some concluding remarks are given in section 6.

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 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 the non-separable specification proposed by Jaimovich and Rebelo (2009), and the second is the separable specification proposed by Galí (2010).

Each period begins by the realisation of shocks to the economy. We concentrate on IST shocks, i.e., 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

$$N_t(i) = \left(\int_0^1 N_t(i,j)^{\frac{\varepsilon_w - 1}{\varepsilon_w}} \, dj \right)^{\frac{\varepsilon_w}{\varepsilon_w - 1}} \tag{1}$$

where ε_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

$$N_t(j) = \left(\frac{W_t(j)}{W_t} \right)^{-\varepsilon_w} N_t \tag{2}$$

where ε_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

$$W_t = \left(\int_0^1 W_t(j)^{1-\varepsilon_w} \, dj \right)^{\frac{1}{1-\varepsilon_w}} \tag{3}$$

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

$$C_t(j) \equiv \left(\int_0^1 C_t(i,j)^{\frac{\varepsilon_p - 1}{\varepsilon_p}} di \right)^{\frac{\varepsilon_p}{\varepsilon_p - 1}} \tag{4}$$

where ε_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

$$C_t(i) = \left(\frac{P_t(i)}{P_t} \right)^{-\varepsilon_p} C_t \tag{5}$$

where ε_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

$$P_t = \left(\int_0^1 P_t(i)^{1-\varepsilon_p} di \right)^{\frac{1}{1-\varepsilon_p}} \tag{6}$$

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

$$Y_t^d(i) \equiv C_t(i) + I_t(i) + M_t(i) = \left(\frac{P_t(i)}{P_t} \right)^{-\varepsilon_p} (C_t + I_t + M_t) \tag{7}$$

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

$$Y_t = \left(\int_0^1 Y_t(i)^{\frac{\varepsilon_p - 1}{\varepsilon_p}} di \right)^{\frac{\varepsilon_p}{\varepsilon_p - 1}} \tag{8}$$

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

$$Y_t = C_t + I_t + M_t \tag{9}$$

2.2 Households

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

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

where β is the subjective discount factor.

We consider two specifications of the instantaneous utility function. As a baseline, we use the non-separable specification proposed by Jaimovich and Rebelo (2009)

$$U(C_t(j), N_t(j)) = \frac{\left(C_t(j) - \chi N_t(j)^{1+\eta} X_t\right)^{1-\sigma} - 1}{1 - \sigma} \tag{11}$$

where

$$X_t = C_t^{\vartheta} X_{t-1}^{1-\vartheta}$$

is a preference shifter that depends on current and past aggregate consumption levels. The presence of X_t implies that preferences are not time-separable. These preferences nest as special cases two of the most widely used families of non-separable preferences. When $\vartheta = 1$ we recover the preference specification of KPR (1988), while we obtain the preferences suggested by GHH (1988) when $\vartheta = 0$. We refer to these special cases as KPR and GHH preferences, respectively.

To evaluate the importance of non-separability, we also consider the family of separable preferences proposed by Galí (2010):

$$U\left(C_t\left(j\right), N_t\left(j\right)\right) = \Theta_t \log C_t\left(j\right) - \chi \frac{N_t\left(j\right)^{1+\eta}}{1+\eta} \tag{12}$$

where Θ_t is a preference shifter determined by the ratio of aggregate consumption to a measure of its trend level ($\Theta_t = C_t/X_t$). Notice that when $\vartheta = 1$ we recover the standard log-separable preferences, cf. e.g. Smets and Wouters (2007), while we obtain a separable utility function without wealth effects on labour supply when $\vartheta = 0$.

With non-separable preferences, the marginal utilities of consumption and labour are

$$MU_{C,t}^{NON-SEP}\left(j\right) = \left(C_t\left(j\right) - \chi N_t\left(j\right)^{1+\eta} X_t\right)^{-\sigma} \left(1 - \chi \vartheta N_t\left(j\right)^{1+\eta} C_t^{-1} X_t\right) \tag{13}$$

and

$$MU_{N,t}^{NON-SEP} = -\left(C_t\left(j\right) - \chi N_t\left(j\right)^{1+\eta} X_t\right)^{-\sigma} \chi\left(1+\eta\right) N_t\left(j\right)^{\eta} X_t \tag{14}$$

respectively. With separable preferences, we get

$$MU_{C,t}^{SEP}\left(j\right) = \frac{\Theta_t}{C_t\left(j\right)} \tag{15}$$

and

$$MU_{N,t}^{SEP}\left(j\right) = -\chi N_t\left(j\right)^{\eta} \tag{16}$$

The two specifications therefore result in different marginal rates of substitution between consumption and labour effort. With non-separable, we get

$$MRS_t^{NON-SEP} = -\frac{MU_{N,t}^{NON-SEP}(j)}{MU_{C,t}^{NON-SEP}(j)} = \frac{\chi(1+\eta) N_t(j)^{\eta} X_t}{1-\chi\vartheta N_t(j)^{1+\eta} C_t^{-1} X_t} \tag{17}$$

while the marginal rate of substitution with separable preferences is

$$MRS_t^{SEP} = -\frac{MU_{N,t}^{SEP}(j)}{MU_{C,t}^{SEP}(j)} = \frac{\chi N_t(j)^{\eta} C_t(j)}{\Theta_t} \tag{18}$$

Households own the capital stock and let this capital to firms in a perfectly competitive rental market at the real rental rate R_t^K. 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

$$K_t(j) = U_t \bar{K}_t(j) \tag{19}$$

Following Christiano, Eichenbaum and Evans (2005), the cost of capital utilisation is given by the increasing and convex function $a(.)$ so that $M_t(j) = a(U_t(j))\bar{K}_t(j)$. Steady-state utilisation is normalised to $U = 1$, and we assume $a(1) = 0$ and $a'(.), a''(.) > 0$.

The capital accumulation equation is given by

$$\bar{K}_{t+1}(j) = (1-\delta)\bar{K}_t(j) + Z_t\left(1 - S\left(\frac{I_t(j)}{I_{t-1}(j)}\right)\right) I_t(j) \tag{20}$$

where $I_t(j)$ is the amount of the final good acquired by the household for investment purposes, δ 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 IST 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

$$\begin{aligned} & P_t \left[C_t(j) + I_t(j) + M_t(j)\right] + E_t\left(\Lambda_{t,t+1} B_{t+1}(j)\right) \\ \leq \; & B_t(j) + W_t(j) N_t(j) + T_t(j) + P_t R_t^K K_t(j) - F_t(j) \end{aligned} \tag{22}$$

The left-hand side gives the allocation of resources to consumption, investment, capital adjustment costs, and to a portfolio of bonds, $E_t\left(\Lambda_{t,t+1} B_{t+1}(j)\right)$, where $\Lambda_{t,t+1}$ is the stochastic discount factor and $B_{t+1}(j)$ represents contingent claims.[5] Hence, the risk-free (gross) nominal interest rate is defined by $R_t = \left(E_t \Lambda_{t,t+1}\right)^{-1}$. The right-hand side gives available resources as the sum of bond holdings, labour income net of a wage adjustment cost, $F_t(j)$, 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

$$\Lambda_{t,t+1} = \beta \frac{MU^l_{C,t+1}}{MU^l_{C,t}} \frac{P_t}{P_{t+1}}$$

[5] 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 occuring.

$l \in \{NON - SEP, SEP\}$ is an index for the type of preferences assumed so that $MU^l_{C,t}$ 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, $C_t(j) = C_t$, $I_t(j) = I_t$, $\bar{K}_t(j) = \bar{K}_t$ and $U_t(j) = U_t$ for all $j \in [0, 1]$.

First-order conditions with respect to investment and capital equates marginal cost and benefits of additional investment and capital

$$\begin{aligned} 1 &= Q_t Z_t \left[1 - S\left(\frac{I_t}{I_{t-1}}\right) - S'\left(\frac{I_t}{I_{t-1}}\right)\frac{I_t}{I_{t-1}}\right] \\ &\quad + E_t\left[\Lambda_{t,t+1}\frac{P_{t+1}}{P_t}Q_{t+1}Z_{t+1}S'\left(\frac{I_{t+1}}{I_t}\right)\left(\frac{I_{t+1}}{I_t}\right)^2\right] \end{aligned} \tag{24}$$

$$Q_t = \beta E_t\left\{\Lambda_{t,t+1}\frac{P_{t+1}}{P_t}\left[R^K_{t+1}U_{t+1} - \frac{M_{t+1}}{\bar{K}_{t+1}} + Q_{t+1}(1-\delta)\right]\right\} \tag{25}$$

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

$$R^K_t = a'(U_t) \tag{26}$$

Wage adjustments are assumed to be costly. In particular, it is assumed that the wage adjustment cost is a quadratic function of the increase in the wage demanded by the worker as modelled in Rotemberg (1982) for prices demanded by firms.[6] For

[6] We use Rotemberg adjustment costs in wages to avoid heterogeneity in hours worked across agents. Heterogeneity in hours – as implied, for example, by the Calvo model – would translate into heterogeneity in consumption given that utility is non-separable over time. This would make the model intractable. While obtaining the same equation for wage inflation, the Rotemberg mechanism is much simpler than the modification allowing for non-separable preferences with

simplicity, the adjustment cost is proportional to the aggregate wage bill in the economy (this parallels the specification of price adjustment costs in Ireland, 2003). Though the wage bargaining process is not explicitly modelled, one way of thinking of this cost is that workers have to negotiate wages each period and that this activity is costly; the larger the increase in wages obtained, the more effort workers would have needed to put into the negotiation process. The nominal wage adjustment cost is given by

$$F_t(j) = \frac{\phi_w}{2}\left(\frac{W_t(j)}{W_{t-1}(j)} - 1\right)^2 W_t N_t$$

where the size of the adjustment costs is governed by the parameter ϕ_w.

The first-order condition is given by

$$\begin{aligned} 0 \quad = \quad & \frac{W_t}{P_t}\left[(1-\varepsilon_w) - \phi_w\left(\Pi_t^w - 1\right)\Pi_t^w\right] + \varepsilon_w MRS_t^l \\ & +\beta E_t\left[\frac{MU_{C,t+1}^l}{MU_{C,t}^l}\phi_w\left(\Pi_{t+1}^w - 1\right)\Pi_{t+1}^w \frac{W_{t+1}}{P_{t+1}}\frac{N_{t+1}}{N_t}\right] \end{aligned} \tag{27}$$

where $\Pi_t^w = W_t/W_{t-1}$ after imposing symmetry so that $W_t(j) = W_t$ and $N_t(j) = N_t$. Again, $l \in \{NON - SEP, SEP\}$ denotes the class of preferences.

2.3 Firms

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

$$Y_t(i) = K_t(i)^{\alpha} N_t(i)^{1-\alpha} \tag{28}$$

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

Calvo wage-settting in Smets and Wouters (2007).

cost minimisation problem

$$MC_t(i) = \frac{W_t/P_t}{(1-\alpha)(K_t(i)/N_t(i))^{\alpha}} = \frac{R_t^K}{\alpha(N_t(i)/K_t(i))^{1-\alpha}} \tag{29}$$

where R_t^K denotes the real rental rate of capital. Conditional factor demand schedules imply that firm i will choose factor inputs such that

$$\frac{K_t(i)}{N_t(i)} = \frac{\alpha}{1-\alpha}\frac{W_t/P_t}{R_t^K} \tag{30}$$

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 regardless of any heterogeneity in output induced by differences in prices. Hence, $MC_t(i) = MC_t \ \forall i$ where

$$MC_t = \frac{1}{1-\alpha}\left(\frac{\alpha}{1-\alpha}\right)^{-\alpha}\left(\frac{W_t}{P_t}\right)^{1-\alpha}\left(R_t^K\right)^{\alpha} \tag{31}$$

follows from combining (29) and (30).

Consequently, the marginal product of labour

$$MPL_t(i) = (1-\alpha)Y_t(i)/N_t(i) = \frac{W_t/P_t}{MC_t(i)} \tag{32}$$

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

$$\sum_{k=0}^{\infty} E_t \left\{ \Lambda_{t,t+k} \left[P_{t+k}(i) Y_{t+k}(i) - \Psi \left(Y_{t+k}(i) \right) \right] \right\} \tag{33}$$

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, (28), and the restriction from the Calvo mechanism that

$$P_{t+k+1}(i) = \begin{cases} P^*_{t+k+1} & \text{w.p.} \left(1 - \theta_p\right) \\ P_{t+k}(i) & \text{w.p.} \theta_p \end{cases} \tag{34}$$

The first-order condition is given by

$$\sum_{k=0}^{\infty} \theta_p^k E_t \left\{ \Lambda_{t,t+1} Y_{t+k}(i) \left[P^*_t - \mu P_{t+k} MC_{t+k} \right] \right\} = 0 \tag{35}$$

where $\mu_p \equiv \varepsilon_p \left(\varepsilon_p - 1 \right)^{-1}$ 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 $\Pi^p_t = \left(P_t - P_{t-1} \right) / P_{t-1}$ and to output growth according to a simple Taylor rule with interest rate smoothing

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R} \right)^{\rho_r} \left(\frac{\Pi^p_t}{\Pi^p} \right)^{\phi_p (1-\rho_r)} \left(\frac{Y_t}{Y_{t-1}} \right)^{\phi_y (1-\rho_r)} \tag{36}$$

where the omission of time subscripts indicate steady-state values, $0 < \rho_r < 1$ governs monetary policy inertia, ϕ_p and ϕ_y measure the response to inflation and to output growth.

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 take the version of the model with GHH preferences, i.e., with $\vartheta = 0$ in the Jaimovich and Rebelo (2009) class of utility functions, to be our benchmark. By implication, the wealth effect on labour supply is zero. This is in line with the estimate in Schmitt-Grohé and Uribe (2010). But there is no consensus on the strength of this effect in the literature (Khan and Tsoukalas, 2010, estimate an intermediate value for instance), and our main motivation for choosing it is that analytical results can be derived in this limiting case. We assume a moderate amount of complementarity between consumption and hours worked by setting $\sigma = 2$. This is in line with the estimates in Basu and Kimball (2002), while the evidence in favour of a higher degree of complementarity in Kilponen, Wilmunen and Vähämaa (2010) would reinforce our main result. We compare this benchmark specification to versions of the model with KPR preferences, i.e., with $\vartheta = 1$ using the Jaimovich and Rebelo (2009) utility specification, and Galí preferences for both $\vartheta = 0$ and $\vartheta = 1$.

The benchmark model features price and wage rigidity. We set $\theta_p = 0.7$ (corresponding to slightly more than three quarters of average price duration) and $\phi_w = 407.7$ (corresponding to four quarters of average wage duration under the alternative Calvo wage setting scheme i.e., a Calvo parameter $\theta_w = 0.75$). Our choice 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, while keeping wage and price rigidities of roughly equal size. In some comparisons to the benchmark model, we let prices and wages be flexible by setting $\theta_p = \phi_w = 0$.

In the benchmark model, households are allowed to vary the rate of capital utilisation. Specifically, we set the elasticity of marginal utilisation costs to $\lambda_a = 1.17$, the value estimated by Smets and Wouters (2007). 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 λ_a 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 λ_a increases. In some comparisons to the benchmark model, we fix capital utilisation by letting $\lambda_a \to \infty$.

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 $\alpha = 0.33$. 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 χ 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) and Smets and Wouters (2007).

The inverse of the labour supply elasticity sets $\eta = 1$ corresponding to a labour elasticity of 1. This is also a common value in the business cycle literature as a relatively elastic labour supply corrects for the fact that fluctuations along the extensive employment margin are not explicitly included in the model.

We set the inverse of the second derivative of the investment adjustment cost function to $\lambda_s = 0.37$, smaller than the 0.4 estimated by Christiano, Eichenbaum and Evans (2005), but larger than the 0.34 estimated by JPT (2010a) and the 0.17 estimated by Smets and Wouters (2007). 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 λ_s 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 λ_s increases.

In calibrating the monetary policy rule, we use estimates from Galí and Rabanal (2005) and we set $\rho_r = 0.69$, $\phi_p = 1.35$ and $\phi_y = 0.26$.

Finally, the shock we consider is moderately persistent with $\rho_z = 0.7$. This is in line with values estimated by JPT (2010a) and Smets and Wouters (2007).

3 Results

Figure 1 shows responses to a positive IST shock for three versions of the model presented in the previous section. The solid lines present responses in the benchmark model with GHH preferences, i.e., utility function (11) with $\vartheta = 0$. The dashed lines show responses in an alternative version of the model with standard log-separable preferences, i.e., utility function (12) with $\vartheta = 1$, keeping all other parameter values as in the benchmark calibration. With this preference specification, the model resembles a standard New Keynesian DSGE model. Finally, the dotted lines represent the model with standard log-separable preferences, but with fixed capacity utilisation ($\lambda_a \to \infty$) and flexible prices and wages ($\theta_p = \phi_w = 0$). Essentially, this reduces the model to a standard Real Business Cycle (RBC) model.

Figure 1 shows our main result. The benchmark model with non-separable preferences delivers a positive and hump-shaped response of consumption to an IST shock. In fact, the four key macroeconomic variables output, consumption, investment and hours co-move as in an empirically recognisable business cycle. Moreover, the IST shock resembles a demand shock in that both prices and quantities increase, while the response of the real wage is limited. This behaviour of key macroeconomic variables suggests that IST shocks are potentially important drivers of business cycles in the benchmark model.

The non-separable preference specification is the main feature generating an increase in consumption. With the standard log-separable preferences (dashed lines in figure 1), consumption declines following an IST shock as in JPT (2010a).[7] The standard New Keynesian model does better than the RBC model (dotted lines), however. In that model, the negative response of consumption is stronger and the expansion in output is muted. Nominal rigidities and variable capacity utilisation are thus instrumental in generating the expansionary effects on output from IST shocks found by JPT (2010a). But the standard log-separable preference specification works to prevent the co-movement of consumption with other key variables that are typical in business cycle fluctuations. In contrast, our benchmark model with non-separable preferences, nominal rigidities and variable capacity utilisation generates both a strong expansion in the economy and co-movement of key aggregate variables.

To provide the intuition for this, we follow JPT (2010a) by considering the labour market equilibrium condition. With sticky prices and wages, mark-ups in goods and labour markets will generally deviate from their desired levels. We therefore implicitly define the economy's average mark-up in goods and labour markets, respectively, as

$$\mu_{p,t} \equiv \frac{MPL_t}{W_t/P_t} \tag{37}$$

and

$$\mu_{w,t} \equiv \frac{W_t/P_t}{MRS_t^l} \tag{38}$$

where MRS_t^l represents the economy's average marginal rate of substitution for $l \in \{NON-SEP, SEP\}$. We may think of (37) as a labour demand and (38) as a labour supply schedule. Hence, equating inverse demands gives the labour market equilibrium condition

$$MPL_t = \mu_t MRS_t^l \tag{39}$$

where the variable $\mu_t \equiv \mu_{p,t}\mu_{w,t}$ represents the time-varying wedge driven between

[7] This is not surprising as this version of the model is very similar to the one in their paper. The habit persistence in consumption and the indexation of prices and wages included in their model do not play an important role in the transmission of IST shocks.

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.

We first consider the standard RBC model, i.e., the case in which prices and wages are flexible, preferences are separable, and capital utilisation is fixed (the dotted line in figure 1). With flexible wages and prices, mark-ups in goods and labour markets are constant and equal to their desired levels, cf. (27) and (35). 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 log-separable preferences, the average marginal rate of substitution is a positive function of consumption and of aggregate hours. Hence in this case, (39) becomes

$$MPL_t\left(\underset{-}{N_t}\right) = \mu MRS_t\left(\underset{+}{C_t}, \underset{+}{N_t}\right) \tag{40}$$

where $\mu = \mu_p \mu_w$.

As discussed by Barro and King (1984), GHH (1988) and more recently by JPT (2010a), the IST 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 (40), down. As a result, while consumption declines, hours increase to produce more investment goods. This reasoning is confirmed in figure 1 (dotted line). Notice that the negative response of consumption in this version of the model does not depend on the chosen calibration.

In the standard New Keynesian model (dashed lines in figure 1), shifts in labour demand may occur as households change the rate of capital utilisation. Moreover, as wages and prices are sticky, mark-ups in both goods and labour markets will generally deviate from their desired levels and they will vary over time. These 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 shifts in labour demand on the equilibrium outcome. In this case, we may write (39) as

$$\mu_t^{-1} MPL_t \left(\underset{-}{N_t}, \underset{+}{U_t} \right) = MRS_t \left(\underset{+}{C_t}, \underset{+}{N_t} \right) \tag{41}$$

Any upward shift in the labour demand curve as a consequence of an increase in capital utilisation will be accompanied by a shift in mark-ups, leading to a larger effect on hours worked in equilibrium when mark-ups are countercyclical.

Consequently, variable capacity utilisation and nominal rigidities 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. However, it turns out that, as in JPT (2010a), variable capacity utilisation and nominal rigidities are not sufficient to overturn the intertemporal substitution effect on consumption (dashed line in figure 1).

In our benchmark model with non-separable preferences (solid lines in figure 1), an increase in hours worked has a positive effect on the marginal utility of consumption (consumption and hours are complements). Unless monetary policy is very aggressive in increasing interest rates, this complementarity will work to drive up consumption along with hours worked through the Euler equation. Indeed, the increase in consumption is comfortably positive with non-separable preferences, cf. figure 1 (solid lines). The assumption that preferences are of the GHH type is particularly useful for the purposes of generating this positive response. As shown by Monacelli and Perotti (2008), the degree of complementarity increases as ϑ is reduced towards the GHH limit in the family of non-separable preferences in (11). Also, with GHH preferences, the marginal rate of substitution is independent of consumption. In this case the labour market equilibrium condition is given by

$$\mu_t^{-1} MPL_t \left(\underset{-}{N_t}, \underset{+}{U_t} \right) = MRS_t \left(\underset{+}{N_t} \right) \tag{42}$$

It follows that shifts in labour demand are not accompanied by shifts in labor supply. This reflects the absence of wealth effects on labour supply.

4 Inspecting the mechanism

In this section, we further inspect the mechanism behind the main result discussed in the previous section by addressing three issues. First, we investigate the extent to which capacity utilisation and nominal rigidities are needed to generate a positive consumption response to IST shocks. Second, we address the role played by GHH preferences. Specifically, we want to disentangle the effects from introducing a complementarity between hours and consumption from the effects from reducing the wealth effect on labour supply. Third, we consider the generality of our result by conducting a simple sensitivity analysis.

4.1 Capacity utilisation and nominal rigidities

Figure 2 shows responses in the benchmark model (solid lines) along with two alternative calibrations. In the first, capital utilisation is fixed (but prices and wages remain sticky). In the second, prices and wages are flexible (but capital utilisation remains variable). Responses in the first alternative (dashed lines) are very similar to the benchmark model. Therefore, the benchmark model does not rely on variable capacity utilisation to generate a positive consumption response. In contrast, the positive consumption response is lost in the second alternative with wage and price flexibility. Thus, a combination of GHH preferences and variable capacity utilisation is unable to generate a positive consumption response.

This result can be shown analytically. By combining linearised first-order conditions in the economy with GHH preferences and flexible wages and prices, we obtain the following expression linking hours worked to the accumulated capital stock:[8]

$$\left[\left(1+\frac{1}{\lambda_a}\right)\left(\frac{1-\alpha}{\alpha}\right)\eta+1+\eta\right]n_t=\bar{k}_t \tag{43}$$

The capital stock, $\bar{k}_t$, is a predetermined variable that cannot respond on the impact of the shock. Hence, this relation shows that hours will remain unaffected on impact of any shock that may hit the economy. By implication, both the real wage and the rental rate of capital will be unaffected too. To see this, note that with GHH preferences and flexible wages, the real wage is simply determined by hours worked, while firms keep marginal costs constant when prices are flexible. Now, in the absence of movements in the rental rate, households keep the utilisation of capital unchanged, and as this keeps all inputs into production constant, output also remains unaffected on impact of the shock. But then, equilibrium in the goods market will be achieved through intertemporal substitution of consumption and investment only.[9]

Following an IST shock, consumption will therefore decline enough to exactly offset the increase in investment brought about by the 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, besides allowing consumption to recover (dotted line in figure 2). In fact, GHH preferences lead to a larger decline in consumption then would standard log-separable preferences in this case. With log-separable preferences, part of the intertemporal substitution works through a reduction in leisure rather than in the consumption of goods. By (43), this is not

[8] Specifically, we combine (52), (58), (61), (63), (64) and (65) in the appendix.

[9] Notice that the zero impact response of output depends neither on the calibration nor on the type of shock hitting the economy.

the case with GHH preferences.

Consequently, while capital utilisation plays a minor role in the transmission mechanism, we need a combination of non-separable preferences and nominal rigidities working through labour demand for our main result to hold.

4.2 Complementarity and wealth effect

The shift from the standard log-separable utility function to the one suggested by GHH (1988) has two implications for household preferences. The first is that the wealth effect on labour supply is eliminated. With GHH preferences, the marginal rate of substitution no longer depends on the consumption. The second is that consumption and hours worked are complements. Hours worked now affects the marginal utility of consumption.

To disentangle the importance of each of these implications for our results, we simulate our model using alternative preference specifications. The first alternative to the GHH specification that we consider is the opposing KPR limit of the Jaimovich-Rebelo utility function. That is, we simulate the model setting $\vartheta = 1$ in the family of non-separable preferences in (11). With this specification, there is a complementarity between consumption and hours worked, but the wealth effect on labour supply is positive. The second alternative, in contrast, eliminates the wealth effect on labour supply without introducing a complementarity between consumption and leisure. We achieve this by setting $\vartheta = 0$ in the Galí utility function in (12).

Figure 3 shows responses in the benchmark model (solid lines) along with responses for the two alternative preference specifications (remaining parameter values are as in the benchmark calibration). With KPR preferences (dashed lines), the consumption response is weaker, but it remains positive on impact and in all periods following the shock. Hence, while a zero wealth effect on labour supply contributes to the expansion in consumption following an IST shock, a positive consumption response is fully compatible with a positive wealth effect on labour supply.[10]

In comparison, in the model with Galí preferences (dotted lines in figure 3), the positive response of consumption is lost. In this case, as the marginal utility of consumption is constant, the real interest rate is unaffected by the shock. This favors investment, shifting more demand away from consumption compared to the log-separable case. The decline in consumption is so large that it is accompanied by a decline in hours worked. Consequently, the absence of a wealth effect on labour supply is not by itself sufficient to generate a positive response of consumption.

In sum, GHH preferences allow us to generate a positive consumption response mainly because they introduce a large degree of complementarity between consumption and labour, not because they eliminate the wealth effect on labour supply.

4.3 Sensitivity analysis

A more complete sensitivity analysis is provided in figure 4, where we plot the impact responses of consumption to the IST shock for a large spectrum of parameter values in the benchmark model. The analysis is partial in the sense that we vary one parameter at a time, while the remaining parameters are fixed at the values chosen for the baseline calibration. If a line is flat, it means that impact responses are unaffected by the specific parameter considered.

The positive response of consumption is robust to changes in the majority of the parameters considered. In particular, it does not rely on specific values for the labour supply elasticity η, on the degree of investment adjustment cost λ_s, on the persistence of the shock ρ_z, and on the elasticity of capacity utilisation costs λ_a. In line with the results discussed in section 4.1, a higher degree of nominal rigidity (an increase in θ_p or θ_w) will lead to a higher consumption response as will a reduction in investment adjustment costs (by reducing the needed substitution from consumption to investment). Similarly, high values of the labour supply elasticity (corresponding

[10] We remark that the impact response of consumption will be larger for values of ϑ lower than 1, approaching the GHH limit (solid lines) as ϑ goes to 0.

to low values of η) lead to higher impact responses of consumption essentially by flattening the labour supply schedule. But the impact response of consumption remains comfortably positive for all plausible calibrations of these parameters.

Instead, the positive response of consumption is sensitive to the degree of complementarity between hours and consumption as governed by σ in line with the argument in the previous subsection. If this complementarity is low, consumption will fail to co-move with other key macroeconomic variables. Also, the positive response depends on the specifics of the monetary policy response. As in all New Keynesian models, a very aggressive monetary policy corresponding to high values of ϕ_p and ϕ_y, or a very activistic monetary policy corresponding to low values of the interest rate smoothing parameter ρ_r, would work to undo the effects of the nominal rigidity that we have found to be crucial to allow for a positive consumption response.

5 Our results in perspective

In this section, we briefly relate our results to the existing literature. The co-movement problem of consumption following IST shocks was first addressed by GHH (1988).[11] More recently, Jaimovich and Rebelo (2009) have analyzed the issue in a similar neoclassical model with contemporaneous shocks as well as news shocks. Both papers emphasise a combination of non-separable preferences and variable capacity utilisation as a way of obtaining procyclical consumption responses in an RBC model with flexible wages and prices. This is in contrast with our conclusion that variable capacity utilisation plays a minor role in the transmission of IST shocks.

A first difference that distinguishes our paper from theirs is the way we model variable utilisation costs. We follow Christiano, Eichenbaum and Evans (2005) by

[11] GHH (1988) assess the co-movement of consumption by its correlation with output. They do not report impulse response functions. 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.

using a 'maintenance cost' specification of utilisation costs. The idea behind this specification is that an intensified utilisation of capital increases the cost of maintaining the capital stock. Instead, GHH (1988) and Jaimovich and Rebelo (2009) make use of a 'user cost' specification where an increase in utilisation increases the rate of depreciation of the capital stock. With this alternative specification, the tight restriction on equilibrium dynamics in (43) no longer holds, and hours worked are free to move on impact of the shock also in a model with flexible wages and prices.

As a cross-check, we therefore simulate an RBC version of our model (setting nominal rigidities to zero) with a user cost specification of capacity utilisation costs.[12] Results are shown in figure 5. When remaining parameters are kept at their benchmark values (bold lines), we find that hours increase only marginally, while consumption declines. If we raise the labour supply elasticity to 2.5 by setting $\eta = 0.4$, we obtain an impact response very close to zero (dashed line). But only when we let both the capital utilisation and the labour input margin be very elastic by setting $\eta = 0.4$ and $\lambda_a = 0.15$ are we able to generate a positive (albeit small) response of consumption in the RBC model (dotted lines in figure 5). Incidentally, $\eta = 0.4$ and $\lambda_a = 0.15$ are the values chosen by Jaimovich and Rebelo (2009).

Hence, while nominal rigidities and non-separable preferences deliver a positive response of consumption under very general conditions, the combination of GHH preferences and variable capacity utilisation is sensitive to the choice of specification and of parameter values when nominal rigidities are absent. In particular, it relies on the user cost specification of variable capacity utilisation costs and highly elastic labour and utilisation margins.

When we simulate our benchmark model with non-separable preferences and nominal rigidities with the user cost specification of capacity utilisation, cf. figure 6 (dashed lines), the consumption response remains positive, but it is less strong than with the benchmark maintenance cost specification (solid lines in figure 6) or in a

[12] Derivations are provided in appendix C.

version of the model with fixed capital utilisation (dotted lines). On first inspection, this result appears to be in contrast with the findings of Khan and Tsoukalas (2010). In an estimated model similar to ours, they find a stronger positive response of consumption with the user cost specification (favoured by a marginal likelihood comparison) than with the maintenance cost specification. However, they estimate a larger degree of nominal rigidity and a larger degree of complementarity in the model with the user cost specification than in the one with maintenance costs of utilisation. Our analysis suggests that these differences in estimated parameter values for the two specifications are driving the difference in the consumption response rather than the utilisation cost specifications themselves. For a given set of parameter values, we find that the user cost specification of GHH (1988) delivers a less expansionary effect as shown in figure 6. Interestingly, however, the user cost specification finds more support in the data in Khan and Tsoukalas (2010).

The discussion so far leaves open the question about the empirical relevance of the two features needed to generate co-movement. Nominal rigidities are commonly assumed, but remain a controversial ingredient in modern business cycle models. The debate on their plausibility is beyond the scope of this paper. We simply remark that any mechanism that would generate countercyclical mark-ups have the potential to stand in for nominal rigidities in this analysis. Non-separable preferences have received less attention in the literature, though they have become increasingly common, cf. for instance Smets and Wouters (2007) and Jaimovich and Rebelo (2009). Basu and Kimball (2002) provide empirical evidence in favour of complementarity between hours worked and consumption, and they show how non-separable preferences can help economists make sense of a wide variety of phenomena including the puzzle (given the life-cycle consumption theory) that consumers tend to reduce consumption at retirement. Given the uncertainty surrounding the magnitude of the wealth effect on labour supply, we find it reassuring that our results do not hinge on the size of this effect, cf. also Bilbiie (2010) for a discussion of this issue.

We note that the combination of nominal rigidities and non-separable preferences can potentially deliver co-movement across real variables in response to shocks other than IST shocks. In Furlanetto and Seneca (2010), we show that this is indeed the case for capital depreciation shocks, while Bilbiie (2010) and Monacelli and Perotti (2008) find similar results for shocks to government spending. Interestingly, Del Negro et al. (2010) argue that sticky prices are needed to generate the right co-movements in response to liquidity shocks in a model in which consumption is hand to mouth.[13] Moreover, Christiano, Motto and Rostagno (2010) suggest that nominal rigidities are important in the transmission mechanism of risk shocks to the Euler equation allowing them to generate co-movement. In the RBC tradition, the neutral technology shock plays an important role exactly because of its ability to generate co-movement of key macroeconomic variables. In our New Keynesian DSGE model, while many shocks could potentially deliver co-movement, the neutral technology shock would fail by generating countercyclical responses in hours worked, cf. Galí (1999) and Galí and Rabanal (2005).

As a final remark, we note that our results can, in principle, be related to the VAR literature that identifies IST shocks using long-run restrictions on the relative price of investment, cf. Altig et al. (2010) and Fisher (2006). This is because shocks to the marginal efficiency of investment are equivalent to shocks to the relative price of investment in our model as in most of the literature. Interestingly, these papers also find a positive response of consumption conditional on a shock to the relative price of investment. However, we prefer to interpret our shock as a disturbance to the process by which investment is transformed into productive capital. The equivalence of such a shock to a relative investment price shock holds only under strong assumptions, cf. Guerrieri, Henderson and Kim (2009) and Basu and Thoenissen (2010).[14] Moreover, shocks to the relative price of investment play only a minor role

[13] In Furlanetto, Natvik and Seneca (2010) we show how rule-of-thumb consumption may also help generate a positive consumption response to IST shocks amplifying the effect from non-separable preferences.

[14] The assumptions are that i) factor shares, depreciation rates and adjustment costs are the same in consumption and investment goods producing sectors, ii) investment goods prices are fully flexible, iii) the economy is closed.

in models recently estimated using the relative price of investment as an observable. In these models, business cycles tend to be driven, instead, by shocks directly to the marginal efficiency of investment (JPT, 2010b), anticipated shocks (Schmitt-Grohé and Uribe, 2010), risk shocks to the Euler equation (Christiano, Motto and Rostagno, 2010), or depreciation rate shocks (Liu, Waggoner and Zha, 2010).

6 Concluding remarks

We have developed a DSGE model with monopolistic competition, endogenous capital accumulation, variable capacity utilisation, investment-adjustment costs, and most importantly non-separable preferences and nominal rigidities. We have shown that the presence of these last two ingredients allows for a positive response of consumption on the impact of an IST shock under very general conditions. Therefore, our model suggests that shocks to the marginal efficiency of investment are potentially important drivers of business cycles in New Keynesian models as the co-movement of key macroeconomic variables including consumption is a common feature of empirically recognisable business cycles.

We believe that our analysis can provide some directions for future research. First, our results suggest that the role of IST shocks in explaining aggregate fluctuations could be even larger than suggested by JPT (2010a). It would be interesting to check this conjecture in an estimated model, which in contrast to JPT (2010a) also allows for risk premium shocks to the Euler equation as Smets and Wouters (2007) have documented the ability of these shocks to generate co-movement. Finally, an important shortcoming of our model, which is common to almost all papers in the literature, is that the model generates a countercyclical relative price of capital, which essentially implies that an investment boom is accompanied by a stock market bust. Christiano, Motto and Rostagno (2010) deal with this problem in a model with financial frictions. We would find it interesting to further study shocks to the marginal efficiency of investment in models with financial frictions also in the context of two-sector models with imperfect mobility of factors between consumption and investment goods producing sectors. This would extend and complement recent contributions by Basu et al. (2010), DiCecio (2009), Guerrieri, Henderson and Kim (2009), Ireland and Schuh (2008) and JPT (2010b).

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 Π^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) $R^K = \left(\beta^{-1} - 1 + \delta\right)$. (26) now gives a restriction on $a'(1) = R^K$. (35) implies $MC = \mu^{-1}$.

Combining (28) and (29) then gives the restriction

$$\gamma_k \equiv \frac{K}{Y} = \frac{\alpha MC}{R^K} \tag{44}$$

so that

$$\gamma_i \equiv \frac{I}{Y} = \frac{\delta\alpha}{\mu\left(\beta^{-1} - 1 + \delta\right)} \tag{45}$$

Then, from (9) we get

$$\gamma_c \equiv \frac{C}{Y} = 1 - \gamma_i \tag{46}$$

Combining (28) and (20) gives

$$Y = N\left(\gamma_i \delta^{-1}\right)^{\frac{\alpha}{1-\alpha}} \tag{47}$$

and consequently

$$C = \gamma_c Y \tag{48}$$

while (30) now gives

$$\frac{W}{P} = (1-\alpha) MC \frac{Y}{N} \tag{49}$$

Taking N as given, a restriction on χ follows (or, alternatively, given χ we can find N) from (27). With non-separable preferences, this restriction is

$$\chi^{NON-SEP} = \frac{1}{\vartheta N^{1+\eta} + (1+\eta) C\mu_w N^{\eta} (P/W)} \tag{50}$$

and with separable preferences is

$$\chi^{SEP} = \frac{W/P}{\mu_w C N^{\eta}} \tag{51}$$

This completes the solution of the model in steady state.

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

$$k_t = u_t + \bar{k}_t \tag{52}$$

while the capital accumulation equation (20) in log-linear form is given by

$$\bar{k}_{t+1} = (1-\delta)\,\bar{k}_t + \delta\,(i_t + z_t) \tag{53}$$

The consumption Euler equation (23) takes the form

$$\lambda_t^l = E_t \lambda_{t+1}^l + r_t - E_t \pi_{t+1}^p$$

where λ_t^l represents marginal utility of consumption (in log-deviation from the steady state) that under non-separable preferences is equal to

$$\lambda_t^{NON-SEP} = d_2 n_t + d_3 c_t + d_4 x_t \tag{54}$$

where the law of motion for x_t is given by

$$x_t = \vartheta c_t + (1-\vartheta)\,x_{t-1}$$

and $d_1 = \chi\vartheta N^{1+\eta}, d_2 = \left(\frac{-d_1(1+\eta)}{1-d_1}\right) + \frac{\sigma\chi(1+\eta)N^{1+\eta}}{1-\chi N^{1+\eta}}, d_3 = \left(\frac{d_1}{1-d_1}\right) - \frac{\sigma}{1-\chi N^{1+\eta}}, d_4 = -\left(\frac{d_1}{1-d_1}\right) + \frac{\sigma\chi N^{1+\eta}}{1-\chi N^{1+\eta}}$.

The marginal utility of consumption under separable preferences becomes

$$\lambda_t^{SEP} = -x_t \tag{55}$$

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

$$i_t = \frac{1}{1+\beta}\left(\beta E_t i_{t+1} + i_{t-1} + \lambda_s\left(q_t + z_t\right)\right) \tag{56}$$

$$q_t = -\left(r_t - E_t\pi_{t+1}\right) + \left(1 - \beta\left(1-\delta\right)\right)E_t r_{t+1}^k + \beta\left(1-\delta\right)E_t q_{t+1} \tag{57}$$

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

The first-order condition with respect to capital utilisation (26) becomes

$$r_t^k = \lambda_a u_t \tag{58}$$

in its log-linear form where

$$\lambda_a \equiv \frac{a''(U)\,U}{a'(U)} = \frac{a''(1)}{a'(1)} \tag{59}$$

is the elasticity of the marginal costs of capital utilisation.

By combining (27) with the law of motion of the wage index and the labour demand schedule, a standard New Keynesian Phillips curve for wage inflation, π_t^W, is derived as

$$\pi_t^w = \beta E_t\pi_{t+1}^w + \kappa_w\left(mrs_t^l - \left(w_t - p_t\right)\right) \tag{60}$$

for $l \in \{STD, GHH\}$ where $mrs_t^{NON-SEP} = \left(\frac{1+d_1}{1-d_1}\right)x_t + \left(\eta + \frac{d_1(1+\eta)}{1-d_1}\right)n_t - \frac{d_1}{1-d_1}c_t$ is the economy's average marginal rate of substitution under non-separable preferences, and $mrs_t^{SEP} = x_t + \eta n_t$ is the same average under separable preferences. The slope is given by

$$\kappa_w = \frac{\varepsilon_w - 1}{\phi_w}$$

Notice that with GHH preferences and flexible wages the wage equation becomes

$$w_t - p_t = \eta n_t \tag{61}$$

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

$$y_t = \alpha k_t + (1 - \alpha) n_t \tag{62}$$

By combining (35) with the law of motion of the price index, the standard New Keynesian Phillips curve is derived

$$\pi_t^p = \beta E_t \pi_{t+1}^p + \kappa_p mc_t \tag{63}$$

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

$$mc_t = (1 - \alpha)(w_t - p_t) + \alpha r_t^k \tag{64}$$

The factor input relation (30) becomes

$$r_t^k = (w_t - p_t) + n_t - k_t \tag{65}$$

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

$$y_t = \gamma_c c_t + \gamma_i i_t + \gamma_k \left(\beta^{-1} - 1 + \delta\right) u_t \tag{66}$$

The monetary policy rule, (36), is

$$r_t = \rho_r r_{t-1} + (1 - \rho_r) \phi_\pi \pi_t^p \tag{67}$$

while the exogenous driving force is specified as

$$z_t = \rho_z z_{t-1} + \epsilon_{z,t} \tag{68}$$

where $\epsilon_{z,t} \overset{iid}{\sim} \left(0, \sigma_{\psi}^2\right)$.

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

$$\pi_t^w - \pi_t^p = (w_t - p_t) - (w_{t-1} - p_{t-1}) \tag{69}$$

C The user cost specification

The cost of capital utilisation takes the 'user cost' form of GHH (1988). According to this specification, the rate of depreciation is increasing in utilisation: $\delta_t = \delta\left(U_t\right)$ where $\delta\left(1\right) = 0$, $0 \leq \delta\left(.\right) \leq 1$ and $\delta'\left(.\right), \delta''\left(.\right) > 0$.

The capital accumulation equation is given by

$$\bar{K}_{t+1}\left(j\right) = (1 - \delta_t)\bar{K}_t\left(j\right) + Z_t\left(1 - S\left(\frac{I_t\left(j\right)}{I_{t-1}\left(j\right)}\right)\right)I_t\left(j\right) \tag{70}$$

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

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 user cost specification, this first-order condition becomes

$$R_t^K = Q_t\delta'\left(U_t\right) \tag{71}$$

The loglinearised version of the previous equations is

$$\bar{k}_{t+1} = (1-\delta)\,\bar{k}_t + \delta\,(i_t + z_t) - \left(\beta^{-1} - 1 + \delta\right) u_t \tag{72}$$

$$r_t^k = \lambda_a u_t + q_t \tag{73}$$

where

$$\lambda_a \equiv \frac{\delta''\,(U)\,U}{\delta'\,(U)} = \frac{\delta''\,(1)}{\delta'\,(1)} \tag{74}$$

is the elasticity of the marginal depreciation rate.

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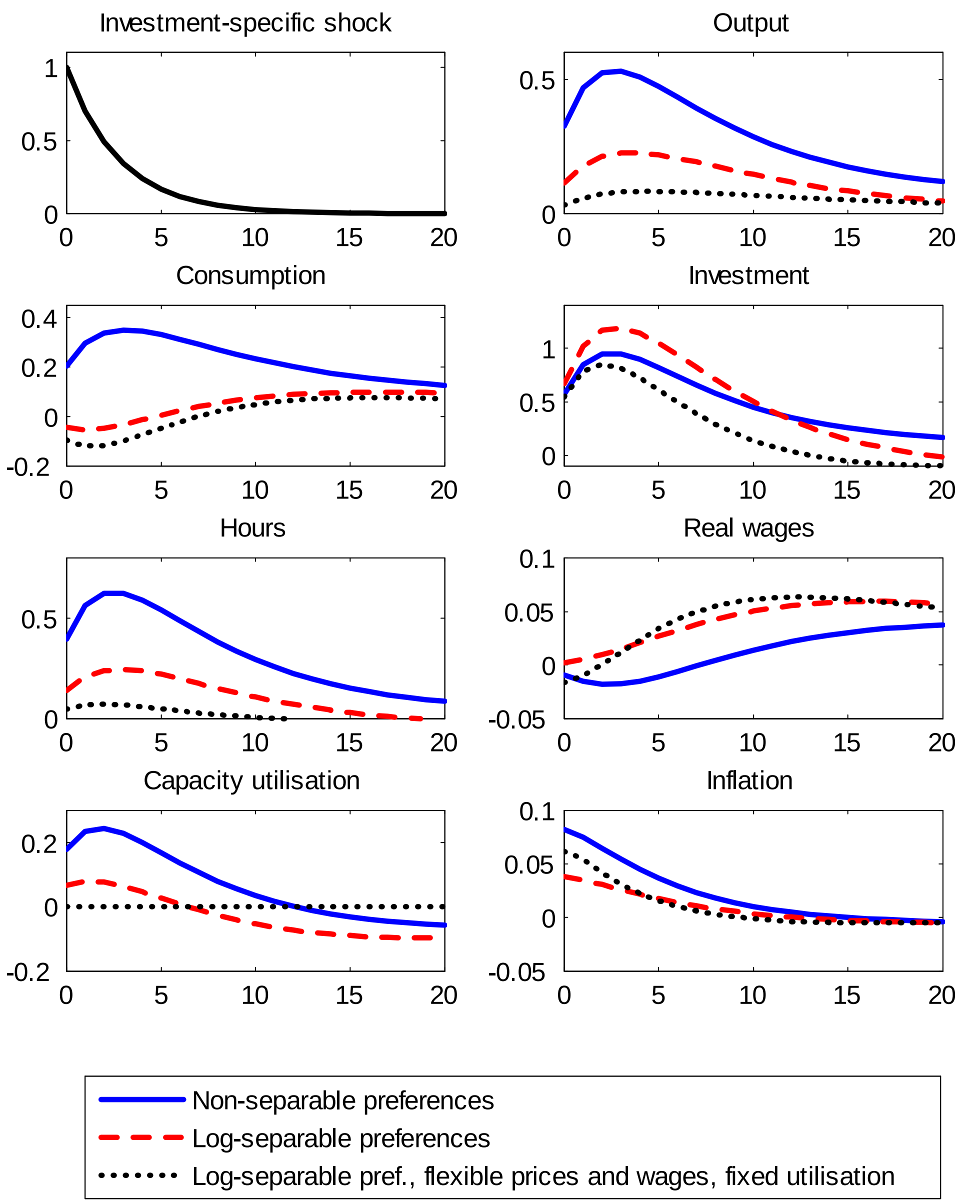

Figure 1: Impulse-responses to an IST shock in the a version of our model with flexible prices and wages

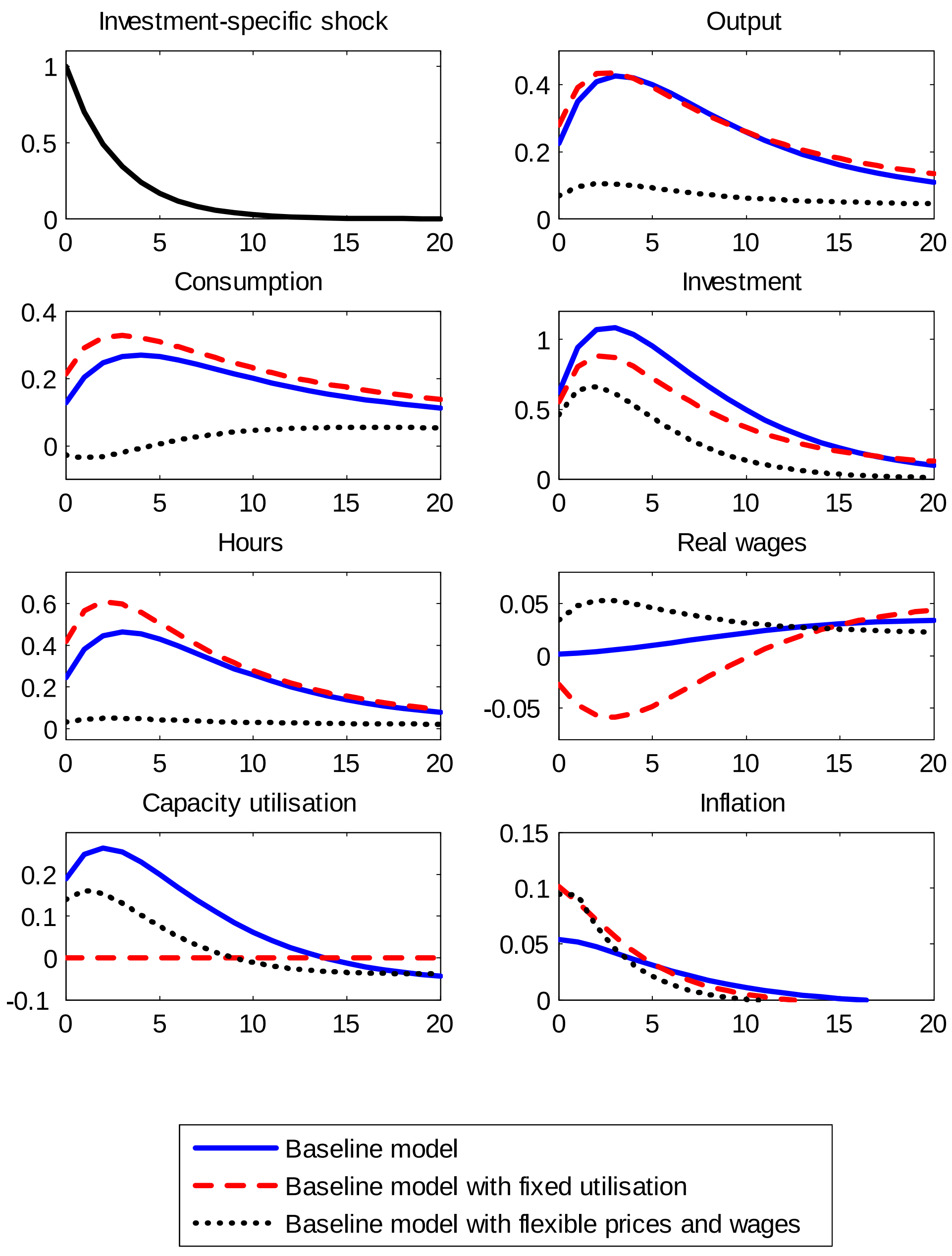

Figure 2: Impulse-responses to an IST shock in the baseline version of our model with different assumptions on nominal rigidities and variable capacity utilisation

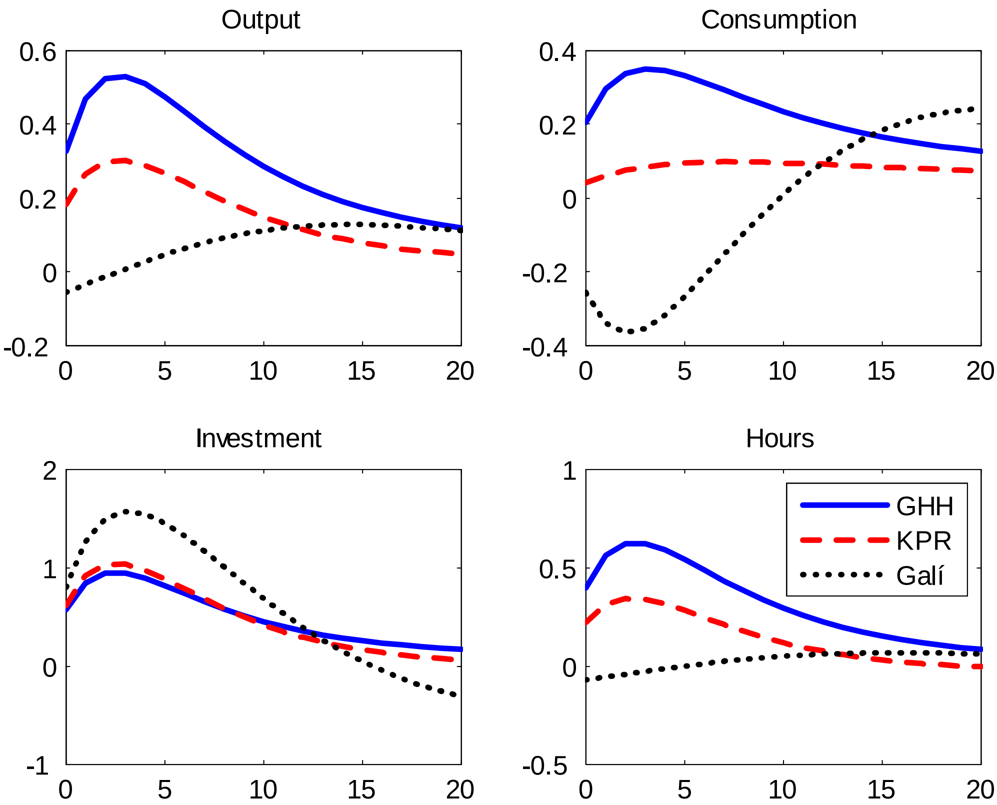

Figure 3: Impulse-responses to an IST shock in the baseline version of our model with different assumptions on preferences

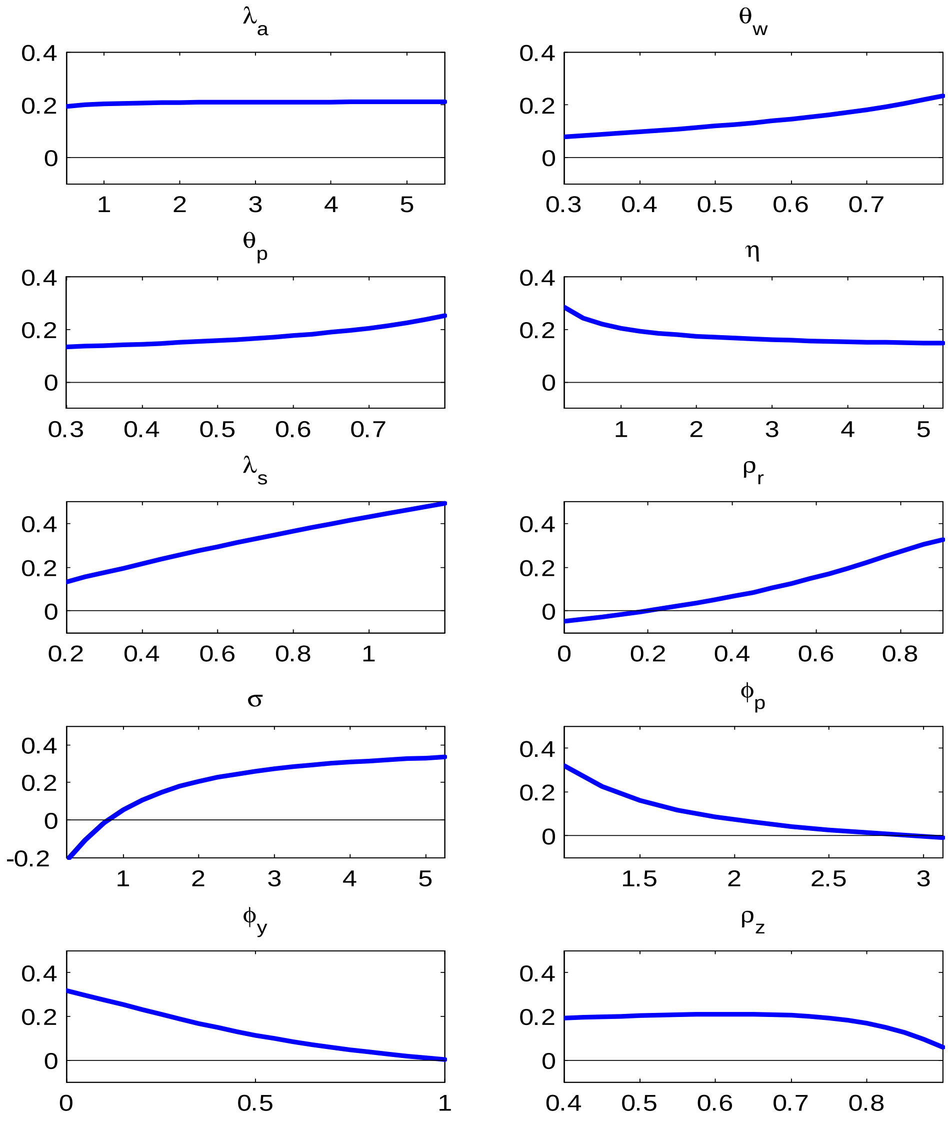

Figure 4: sensitivity analysis

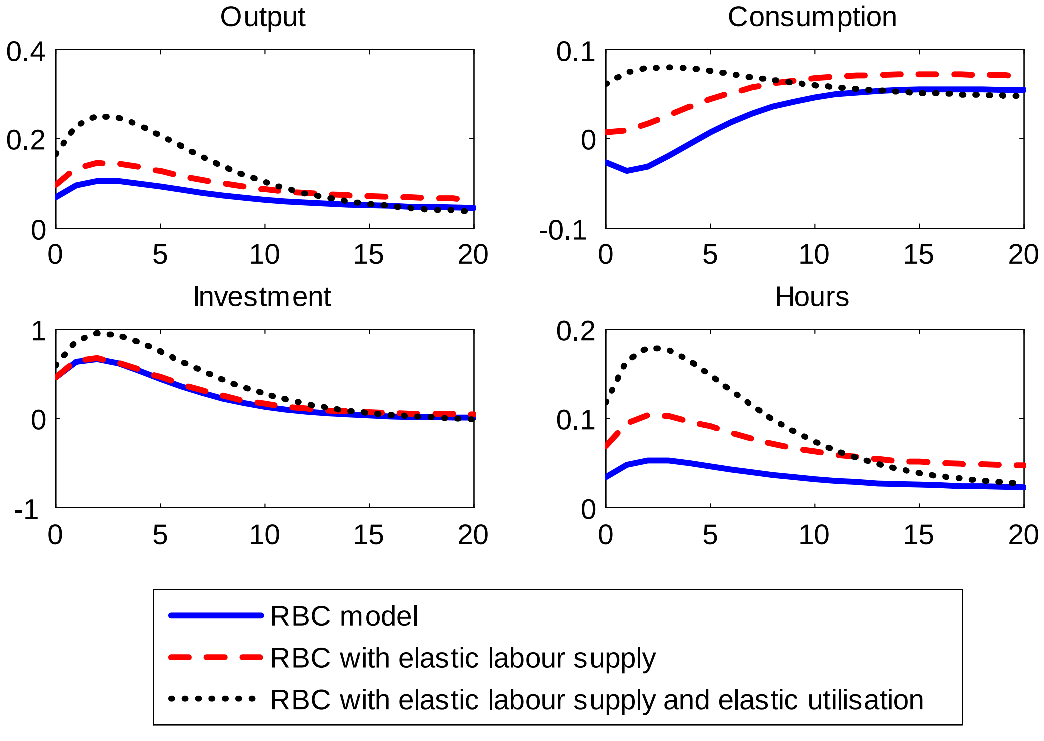

Figure 5: Impulse-responses to an IST shock in the version of our model with flexible prices and wages

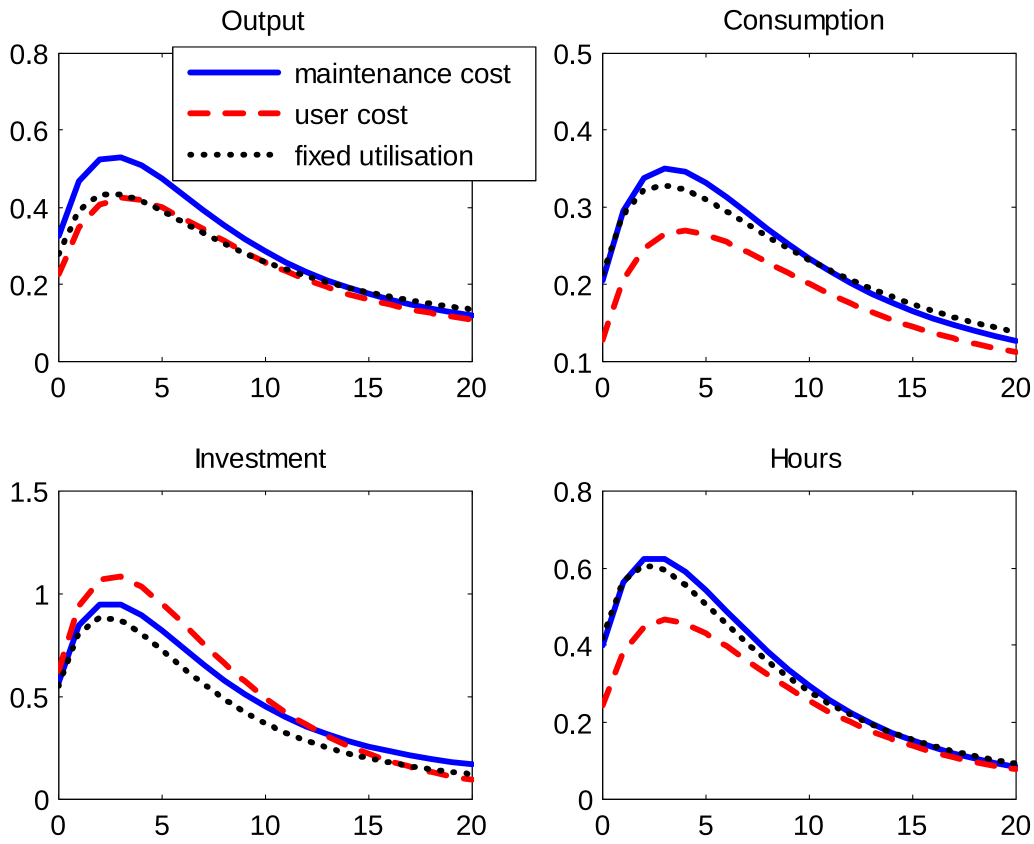

Figure 6: Impulse-responses to an IST shock in the baseline version of our model with different assumptions on variable capacity utilisation