Investment-Specific Technology Shocks, Neutral Technology Shocks and the Dunlop Tarshis Observation: Theory and Empirics

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Abstract

The Dunlop-Tarshis observation has played a crucial role in business cycle research and has often played the role of a litmus test of business cycle theories. According to this observation, aggregate hours and aggregate labor productivity are near-othogonal at the business cycle frequencies. We she some new light on this showing that the near othogonality does not hold true in terms of conditional moments. We concentrate on the conditional correlation between these variables in response to permanent neutral technology shocks and permanent investment-specific technology shocks. We show that the latter are associated with negative hours-productivity comovements while the former give rise to positive hours productivity correlations. We also examine the congruency between these findings and a two-sector technology driven business cycle model. We find that the model is consistent with the aggregate evidence but not with sectoral level conditional moments.

Keywords: Hours-productivity correlation, neutral technology shocks, investment-specific technology shocks, structural VAR, sectoral reallocation

JEL Classifications: E13, E22, E23, E32

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1 Introduction

Dunlop (1938) and Tarshis (1939) documented that hours worked and real wages are nearly orthogonal at the business cycle frequencies. This orthogonality property has been confirmed in a large number of empirical studies and has been shown also to hold for the correlation between hours worked and aggregate labor productivity. This finding, long seen as a litmus test for business cycle theories, was initially interpreted in terms of evidence against Keynesian models of the business cycle but has in recent years resurfaced in the real business cycle literature. This latter line of research has argued that aggregate business cycle fluctuations may be well understood in terms of simple dynamic stochastic general equilibrium models in which the main impulses to the economy are stochastic shocks to total factor productivity. In such a setting there is a strong tendency for an almost perfect correlation between hours worked and labor productivity or real wages since the labor demand impact of technology shocks tends to dominate labor supply responses. One line of research has explored the role of introducing shocks that impact mainly on labor supply. Christiano and Eichenbaum (1992) analyze the impact of stochastic shocks to government spending while Braun (1993) and McGrattan (1993) examine the consequences of stochastic shocks to tax rates. Hansen (1986) instead introduces labor indivisibilities which in a lottery setting give rise to increased labor supply responses to changes in the intertemporal path of real wages. Benhabib, Rogerson and Wright (1991) introduce homework which also leads to more substantial labor supply responses to changes in real wages.

Not much of the recent literature, however, has paid much attention to how hours and labor productivity (or real wages) comove conditionally upon the shocks to the economy nor to the sectoral aspects of the Dunlop-Tarshis observation. This is the theme of this paper. We use a vector autoregression approach to derive measures of conditional correlations between hours worked and aggregate labor productivity in response to identified shocks to the economy. We focus on two types of technology shocks studied in much of the recent business cycle literature, neutral total factor productivity shocks and investment specific technology shocks. We identify these two types of shocks using long run impact assumptions applied earlier by Gali (1999), Altig et al (2005), Fisher (2006) and Ravn and Simonelli (2008), amongst many others. We find that there is a remarkable difference between unconditional and conditional moments. The unconditional correlation between hours worked and labor productivity in the post war US data is negative but small numerically. Conditioning on neutral technology shocks only, we find a positive and substantial cross-correlation between labor productivity and hours worked while the cross correlation is negative and substantial conditional on investment specific technology shocks. We then examine the impact on hours worked and labor productivity in consumption and capital goods producing sectors separately. We find that labor reallocation may be at the heart of the low overall covariance between productivity and hours worked. Regardless of the shock, there is a positive covariance between labor productivity and hours worked in the investment sector but a negative correlation in the consumption sector.

Given this evidence we ask if the conditional correlation structures are consistent with a two-sector business cycle model. We study a generalized version of the Greenwood, Hercowitz and Krusell (1997) model. The model is restricted so that it is consistent with the long run identifying assumptions that we adopt when measuring these shocks in the empirical data. In this model a consumption sector produces consumption goods taking as inputs capital services and labor services. The investment sector produces a storable good that is used for accumulating capital. This good is also produced using inputs of capital and labor services. The neutral technology shock affects the production technologies of both sectors while the investment specific shock has no direct impact on the consumption sector technology. We assume that there are costs of adjusting the inputs of capital and labor which serves to limit the extent to which resources can be reallocated across sectors.

We estimate key parameters of the model economy using a limited information approach subject to restrictions imposed to render the model consistent with the long run identifying assumptions. We show that the model provides an excellent account of the impact of the two types of productivity shocks on aggregate variables such as output, consumption, investment and hours worked. We then ask whether the model can account for (a) the conditional covariance structure between aggregate labor productivity and aggregate hours worked, and (b) the sectoral conditional covariance structures. We find that the answer to the first question is positive. In particular, the model can account for the fact that aggregate hours and aggregate labor productivity are positively correlated in response to neutral technology shocks but negatively correlated in response to investment specific shocks. Given that more investment goods must be produced in order to take full advantage of the investment specific technology shock, this shock sets off a large increase in hours worked in the investment sector which limits the initial increase in productivity in this sector. At the same time, the investment specific shock also raises demand for consumption which is achieved through an increase in hours worked in this sector. Therefore, the investment specific shock is associated with a rise in hours worked but little initial impact on labor productivity therefore giving the model the ability to account for a negative hours-productivity correlation at the business cycle frequencies. At the same time, a neutral productivity shock by shifting labor demand is associated with positive comovements in hours and labor productivity.

However, at the sectoral level, the simple two-sector model has mixed success: While theory can account for a consistently positive relationship between hours worked and labor productivity in the investment sector, it is inconsistent with the negative cross correlation between hours and labor productivity in the consumption sector following a neutral productivity shock that we estimate in the US data. This result is a restatement of the high correlation between hours worked and labor productivity in one-sector RBC models driven by neutral technology shocks. This finding points towards the relevance of introducing further features of sectoral reallocation such as differences in skill intensities.

The remainder of the paper is structured as follows. Section 2 provides empirical evidence for the US on the impact of neutral and investment specific technology shocks. Section 3 lays out the model. Section 4 discusses the estimation results. Finally, we conclude and summarize in Section 5.

2 Empirical Evidence

In this section we present the analysis of the identification of structural shocks, their dynamic impact on the economy, and the implications for the relationship between hours worked and labor productivity.

Our estimation strategy is based upon an SVAR approach. Following Gali (1999), Altig et al (2005), Fisher (2006), and Ravn and Simonelli (2008), we adopt long-run impact identifying assumptions that allow us to derive measures of neutral technology shocks and of investment specific technology shocks. Consider the following VAR:

$$x_t = k + B(L)\, x_{t-1} + e_t \tag{1}$$

x_t is the following 5-dimensional vector:

$$x_t = \left[\ \triangle\, p_t^i, \quad \triangle\, a_t, \quad h_t, \quad c_t^n/y_t^n, \quad i_t^n/y_t^n,\ \right]'$$

where L is the lag operator, $\triangle$ is the first-difference operator, p_t^i denotes the logarithm of the price of investment to consumption,[1] a_t denotes the logarithm of aggregate labor productivity defined as chained GDP divided by aggregate hours worked, h_t denotes the logarithm of aggregate hours worked per adult[2], c_t^n/y_t^n is the logarithm of the ratio of nominal consumption expenditure to nominal GDP, and i_t^n/y_t^n is the logarithm of the ratio of nominal investment expenditure to aggregate GDP. $B(L)$ is a lag polynomial of order M and k denotes deterministics including constant terms and time trends. The sample period is 1960:1 - 2003:1. The precise definitions of the variables are summarized in Table 1.

The vector of innovations e_t are usually referred to as "reduced form errors" and $B(L)$ are the "reduced form" coefficients. We introduce assumptions that allows us to identify two "structural" shocks and their impact on the vector of observables, x_t. We identify permanent neutral technology shocks and permanent investment specific technology shocks by assuming that (i) only permanent investment specific technology shocks can affect the long-run *level* of the relative investment price, and (ii) permanent investment specific and neutral technology shocks are the only shocks that can affect

[1] Following Justiniano and Primiceri (2006), the relative investment price is defined as the implict investment deflator divided by the implicit consumption deflator.

[2] We include hours in levels rather than first-differences because (detrended) hours are stationary in our sample. Details on the stationarity tests are reported in Ravn and Simonelli (2008).

the long-run *level* of labor productivity. These assumptions have been applied by Altig et al (2005), Fisher (2006) and Ravn and Simonelli (2008) and generalizes the approach of Gali (1999) to the case of multiple technology shocks. In Section 3 we study a model in which they hold true given certain parameter restrictions.

The structural VAR is:

$$\beta_0 x_t = \kappa + \beta(L) x_{t-1} + \varepsilon_t \tag{2}$$

where ε_t denotes the vector of structural shocks. We will assume that the covariance matrix of ε_t, $V_\varepsilon = E(\varepsilon_t' \varepsilon_t)$ is diagonal. The parameters of the structural VAR and of the reduced form VAR are related through $k = \beta_0^{-1}\kappa$, $B(L) = \beta_0^{-1}\beta(L)$, and $V_e = \beta_0^{-1\prime} V_\varepsilon \beta_0^{-1}$ where $V_e = E(e_t' e_t)$. In what follows we normalize the diagonal of β_0 to consist of a 5x1 vector of ones.

The two structural shocks are estimated from the following equations (in that order):

$$\triangle p_t^i = \alpha^p + \sum_{j=1}^{M} \beta_{p,j}^p \triangle p_{t-j}^i + \sum_{j=0}^{M} \beta_{a,j}^p \triangle^2 a_{t-j} + \sum_{j=0}^{M-1} \beta_{z,j}^p \triangle z_{t-j} + \varepsilon_t^p \tag{3}$$

$$\triangle a_t^i = \alpha^a + \sum_{j=0}^{M} \beta_{p,j}^a \triangle p_{t-j}^i + \sum_{j=1}^{M} \beta_{a,j}^a \triangle a_{t-j} + \sum_{j=0}^{M-1} \beta_{z,j}^a \triangle z_{t-j} + \varepsilon_t^a \tag{4}$$

where z_t is defined as the vector $z_t = \left[\begin{array}{ccc} h_t, & c_t^n/y_t^n, & i_t^n/y_t^n, \end{array}\right]'$, ε_t^p is the investment specific technology shock, and ε_t^a is the neutral technology shock. $\triangle^2$ denotes the double difference operator.

Equation (3) identifies the investment specific technology shock. Our identifying assumption is that only investment specific shocks can affect the long run level of the relative investment goods price. Thus, in this regression, we difference all the regressors in x_t apart from the relative investment goods price itself. This difference implies that the long-run impact of any other structural shock is constrained to be zero. This equation cannot be estimated with least squares due to simultaneity since $\triangle a_t$ and z_t may depend on ε_t^p. Following Shapiro and Watson (1988) we use a 2SLS estimator using as instruments a constant, the vector $[\triangle p_{t-j}, \triangle a_{t-i}, z_{t-j}]_{j=1}^M$.

The neutral technology shock is estimated from equation (4). The specification of this equation imposes that only investment specific and neutral technology shocks can have permanent effects on long-run labor productivity. Again, to address simultaneity, this relationship is estimated using 2SLS. The instruments are the same as those above extended with $\widehat{\varepsilon}_t^p$ (estimated in the preceding regression).

Estimating the parameters of the equations for the components of the vector z_t is laborious due to simultaneity. We adopt the recursive 2SLS approach of Altig et al (2005). Let the components of z_t be denoted z_t^i, $i = 1, ..3$. The parameters of the first of these equations are estimated as:

$$\triangle h_t = \kappa^1 + \sum_{j=0}^{M} \beta_{j,p}^1 \triangle p_{t-j}^i + \sum_{j=0}^{M} \beta_{j,a}^1 \triangle a_{t-j} + \sum_{j=1}^{M} \beta_{j,z}^1 z_{t-j} + e_t^1 \tag{5}$$

using as instruments a constant, $\left[\triangle p_{t-i}^i, \triangle a_{t-i}, z_{t-i}\right]_{i=1}^M$ and $\left[\widehat{\varepsilon}_t^p, \widehat{\varepsilon}_t^A\right]'$. The coefficients of the equations for the consumption and investment shares are estimated equivalently (augmenting the instrument vector with the innovations of the preceding equation). We confirmed that the ordering of these equations (which is arbitrary) does not matter for the results that we are interested in.

Having estimated the structural shocks of interest, we then examine their impact on sector level measures of hours worked and labor productivity. We distinguish between sectors that produce durables and non-durables sectors. The former of these is our approximation of the investment producing sector and the latter is our approximation for the consumption sector.

The responses of sectoral hours are estimated from the following regressions (estimated with ordinary least squares):

$$\widetilde{h}_t^s = \kappa^s + \sum_{j=0}^{M} \beta_j^{h^s} y_{t-j} + \sum_{j=1}^{M} \gamma_j^s \widetilde{h}_{t-j}^s + \varepsilon_t^{hs} \tag{6}$$

where $\widetilde{h}_t^s$ denotes linearly detrended log hours per capita in sector s. The vector y_t is consists of the two identified shocks. From this regression we compute the responses of sectoral hours to each of the identified shocks. Combining these responses with those of consumption and investment, we derive the dynamics of sectoral labor productivity. We choose this estimation strategy rather than incorporating sector level hours data in the VAR in equation (2) in order to minimize problems of multicollinearity.

2.1 The SVAR Results

On the basis of the structural VAR estimations we now discuss the dynamic impact of the two types of technology shocks. Figures 1 and 2 illustrate the impulse responses of the key variables in response one percent increases in the neutral and the investment-specific technology shock, respectively. The point estimates of the impulse responses are shown with full drawn lines and the shaded areas indicate 66 percent (bootstrapped) confidence intervals.

A positive neutral technology shock gives rise to hump-shaped increases in output, consumption and investment and to a persistent rise in aggregate hours worked. In each case, we find that the variables settle down at their new long-run levels around 6 quarters after the technology shock. It is worth noticing that we do not find a decline in hours worked after a neutral technology shock in this sample, see Gali (1999) for a different result. Our estimates of the impact of technology shocks on aggregate hours worked are similar to the results of Fisher (2006) although we find a somewhat less persistent rise in hours worked. We also find an increase in aggregate labor productivity which eventually levels out around 2 years after the neutral technology shock.

We find much the same impact on output, consumption, investment, and hours worked after an investment-specific technology shock the main differences being that (i) investment falls marginally on impact after a neutral shock but rise 0.5 percent on impact after an investment specific shock, and (ii) the hours response is larger in response to an investment specific shock. This latter result is completely in line with Fisher (2006) and Ravn and Simonelli (2008). The impact on output and its components stabilize around 1-2 years after the technology shock with the adjustment to the investment-specific shock being slightly faster than the adjustment to the neutral shock. By construction, the long run impact on the relative investment price differs across the two technology shocks but we also find short run impact differences. The investment-specific technology shock leads to a gradual and permanent decrease in the relative price of investment goods while we find a temporary increase in the relative investment price after a neutral technology shock. These results are similar to the estimates of Altig et al (2005) and Fisher (2006) apart from the former of these authors only find a short-lived increase in the relative investment price after a neutral technology shock.

A key difference between the effects of the two types of technology shocks concerns the impact on aggregate labor productivity. Recall that labor productivity rises after a neutral technology shock. The investment specific technology shock instead sets of a small decline in labor productivity initially. Over time the productivity impact grows and the long run impact is positive. Intuitively, the long-run impact of investment-specific technology shocks occurs gradually because its impact on the consumption sector occurs through an increase in the capital stock. These results are similar to Altig et al (2005) and Fisher (2006).

Decomposing the hours and labor productivity responses to the impact at the sectoral level yields some further interesting insights. The two types of technology shocks give rise to an increase in hours worked in both sectors with the impact being faster, larger and taking its full impact a bit earlier in response to the embodied technology shock. This result is natural given that the elasticity of investment to the two technology shocks is larger than the elasticity of consumption.

The dynamic impact on labor productivity, however, is sector specific. In particular, we find that while the long-run responses to the two types of productivity shocks are similar across sectors, the short run dynamics differ quite substantially. In the consumption sector, the short run response of labor productivity is muted for the first year or so after either type of productivity. In the investment sector instead, there is a substantial rise in labor productivity in response to the investment specific technology shock and also quite a rapid rise following a neutral technology shock.

These differences across shocks and across sectors impact on the relationship between labor productivity and hours worked. Figure 3 illustrates the scatter plots of hours worked and labor productivity at the aggregate level and across sectors. We illustrate two series for investment measured either in quantities (as in the results discussed above) or adjusting for the change in the relative price. We illustrate the Hodrick-Prescott filtered hours and productivity data for three alternative scenarios. The first column shows the unconditional relationship. The second and third columns illustrate the data conditional on either of the two productivity shocks. The conditional data (and their moments) are derived using the estimated VARs to compute counterfactual paths of hours worked and labor productivity assuming that the only shocks to the time-series are one (or both) of the two identified technology shocks. We then Hodrick-Prescott filter the resulting time series. Table 1 reports the correlations between hours worked and labor productivity corresponding to these scatter plots.

At the aggregate level, the unconditional correlation between hours worked and labor productivity is approximately zero which confirms the conventional wisdom. However, the lack of a strong unconditional correlation between hours and productivity does not hold conditioning on the two shocks individually. Investment-specific shocks give rise to a strong negative relationship between hours and productivity while there is a positive hours-productivity correlation conditionally on neutral technology shocks. These results paint a rather different picture than the Dunlop-Tarshis observation which suggests that there is little relationship between hours and labor productivity at the business cycle frequencies. Instead, hours and labor productivity once measured conditional on the identified shocks appear to be systematically related but the conditional correlation hinges critically on the shock. Moreover, it is clear that investment specific technology shocks are more important determinants of the covariance structure between labor productivity and hours worked than neutral technology shocks (see Figure 3).

At the disaggregate level, there are stark differences across sectors. We find a systematically negative correlation between labor productivity and hours worked in the consumption sector. This is evidence from Figure 3 and from the conditional correlations reported in Table 1. Regardless of the type of productivity shock, the cross correlation between labor productivity and hours worked is smaller than -0.60. For the investment sector, the results depend on whether we correct for relative price movements or not. When measured in quantities, the cross correlation between labor productivity and hours worked is positive for this sector for both productivity shocks. However, recall that the relative investment price falls in response to a positive investment-specific technology shock but increases after a positive neutral technology shock. When we correct for the relative price changes, the cross correlation between hours and labor productivity in the investment sector is negative contingent upon an investment specific technology shock but large and positive after a neutral technology shock. These results are consistent with findings for the relationship between hours and real wages reported in Ravn and Simonelli (2008).

We take the following main messages from this analysis. First, the Dunlop-Tarshis observation holds for unconditional moments but not when we examine conditional moments. Neutral permanent technology shocks are associated with positive comovements between aggregate hours and aggregate labor productivity while investment-specific technology shocks give rise to negative comovements between hours and labor productivity. Secondly, sectoral reallocation appears to be important. The investment sector reacts much more elastically to productivity shocks than the consumption sector. Third, at the sectoral level, there are large differences in how productivity shocks affect the hours-labor productivity comovements.

3 The Model

In this section we examine the extent to which the empirical results derived in the previous section can be accounted for by a DSGE model. Similarly to Ireland and Schuh (2008) and Justiniano, Primiceri and Tambalotti (2008), the model is a version of Greenwood, Hercowitz and Krusell's (1997) two-sector model extended with features meant to be relevant for business cycle fluctuations. Our extensions include the introduction of adjustment costs associated with accumulation of capital, labor adjustment costs, and variable capacity utilization. We estimate key structural parameters and examine the extent to which investment-specific technological change is helpful for understanding the Dunlop-Tarshis observation. In order to focus attention on the sectoral aspects of the model, we neglect other features studied earlier in the literature such as the impact of government spending, tax changes, and home-work that have been explored in other parts of the literature.[3]

There are two sectors in the economy, a consumption sector and an investment sector. Firms are competitive and rent labor and capital services from the household sector. Goods produced by the consumption sector cannot be converted into investment goods and are perishable. Goods produced by the investment sector cannot be consumed but can be accumulated. Factors of production are sector-specific to the extent that adjustment costs hinder the free and instantaneous reallocation of labor and capital.

The production functions are given as:

$$C_t = A_1 z_t \left(K_{c,t} u_{c,t}\right)^{\alpha_c} h_{c,t}^{1-\alpha_c} \tag{7}$$

$$I_t = A_2 z_t x_t \left(K_{i,t} u_{i,t}\right)^{\alpha_i} h_{i,t}^{1-\alpha_i} \tag{8}$$

where C_t denotes the output of consumption goods and I_t denotes the output of investment good. A_1, $A_2 > 0$ are constants, $K_{s,t}$ denotes the use of capital in sector s

[3]Benhabib, Rogerson and Wright (1991) explore the role of home-production for generating a low covariance between labor productivity and (market) hours worked while Christiano and Eichenbaum (1992) look at government spending shocks. Braun (1994) and McGrattan (1994) examine the impact of changes in distortionary tax rates. Hansen (1985) instead argues that indivisibilities of hours worked are important.

at date t, $u_{s,t}$ is the capital utilization rate in sector s, and $h_{s,t}$ is the effective input of labor in sector s.

The two sectors are subject to stochastic productivity shocks. z_t is a neutral productivity shock which affects both sectors simultaneously while x_t is an investment-specific productivity shock. $\alpha_s \in (0,1)$ is the elasticity of output of sector s to the input of capital services. We will assume that $\alpha_c = \alpha_i = \alpha$ which renders the model consistent with the identifying assumption applied in the previous section that permanent neutral technology shocks have no long-run impact on the relative investment price.

The consumption good is assumed to be perishable while the investment good is used for accumulating either of the two capital stocks. The investment good resource constraint is given by:

$$I_t = I_{ct} + I_{it} \tag{9}$$

where $I_{c,t}$ denotes the amount of investment goods that are used for accumulating the capital stock, $K_{s,t}$.

We assume that there are adjustment costs associated with adjusting the labor input. We model these costs as introducing a wedge between the effective labor input and raw hours worked. In particular, it is assumed that:

$$h_{c,t} = \left(1 - F_c\left(n_{c,t}/n_{c,t-1}\right)\right) n_{c,t} \tag{10}$$

$$h_{i,t} = \left(1 - F_i\left(n_{i,t}/n_{i,t-1}\right)\right) n_{i,t} \tag{11}$$

where $n_{s,t}$ denotes hours worked in sector s. These expressions define the effective labor input in sector s as $n_{s,t}$ less adjustment costs that are a function of the growth rate of the labor input to this sector. We assume that $F_s(1) = F_s'(1) = 0$, $F_s'' > 0$ so that $n_{s,t}$ and $h_{s,t}$ coincide only when labor demand is unchanged between periods $t-1$ and t. These adjustment costs limit the extent to which labor can be reallocated instantaneously between the two sectors. In the absence of such costs, the value of marginal products of labor would have to equalize across sectors period-by-period.

There is a large number of identical, infinitely-lived households that have rational expectations. Households maximize the expected present value of their utility stream. Households supply labor to the consumption and investment sectors and spend their income on purchasing capital and consumption goods. They act competitively taking all prices for given. Preferences are given as:

$$V_0 = E_0 \sum_{t=0}^{\infty} \beta^t \left(C_t^{1-\sigma}/(1-\sigma) - \phi s_{1t}^{1-\sigma}\left(n_{c,t} + n_{i,t}\right)^{1+\kappa}/(1+\kappa)\right) \tag{12}$$

where s_{1t} is a technological factor which we introduce to guarantee the existence of a balanced growth path. E_t denotes the mathematical expectations operator conditional on all information available at date t, β is the subjective discount factor, $\sigma > 0$ is the inverse of the intertemporal elasticity of substitution in consumption, $\phi > 0$ is a preference weight, and $\kappa \geq 0$ is the inverse of the Frisch elasticity of labor supply.

The evolution of the capital stocks are given by:

$$K_{c,t+1} = (1-\delta-\Lambda_c(u_{c,t}))K_{c,t} + I_{c,t} - G_c(I_{c,t}/K_{c,t})K_{c,t} \quad (13)$$
$$K_{i,t+1} = (1-\delta-\Lambda_i(u_{i,t}))K_{i,t} + I_{i,t} - G_i(I_{i,t}/K_{i,t})K_{i,t} \quad (14)$$

where $\delta \in (0,1)$ denotes the "normal" rate of depreciation of the two capital stocks.

$\Lambda_c(u_{s,t})$ captures the assumption that variations in the rate of capital utilization affects the rate of depreciation of the capital stock. We introduce variable capacity utilization in order to allow for output to respond to shocks to the economy even if there are significant adjustment costs associated with variations in labor and capital inputs. We assume that $\Lambda_s(\overline{u}_s) = 0$ where $\overline{u}_s$ denotes the steady-state level of capital utilization which we will normalize to one, and that $\Lambda_s', \Lambda_s'' > 0$. Thus, by increasing the capital utilization rate, more output can be produced for a given level of inputs of capital and labor, but this comes at the cost of faster depreciation of the existing capital stock.

The terms $G_s(I_{s,t}/K_{s,t})K_{s,t}$ denote capital adjustment costs. We assume that $G_s\left(\overline{I_s/K_s}\right) = G_s'\left(\overline{I_s/K_s}\right) = 0$ and that $G_s'' > 0$ where $\overline{I_s/K_s}$ denotes the steady-state value of the I_s/K_s ratio. This implies that Tobin's Q is one along the balanced growth path and that there are adjustment costs when the investment to capital stock ratio deviates from its steady-state value.

Finally, we define aggregate output as:

$$Y_t = C_t + P_t I_t \quad (15)$$

where P_t denotes the relative investment price (the price of the investment good to the price of the consumption good).

We assume that the productivity levels evolve according to the following stochastic processes:

$$z_t = z_{t-1}\gamma_z^{1-\rho_z}(z_{t-1}/z_{t-2})^{\rho_z}\exp(\varepsilon_t^z) \quad (16)$$
$$x_t = x_{t-1}\gamma_x^{1-\rho_x}(x_{t-1}/x_{t-2})^{\rho_x}\exp(\varepsilon_t^x) \quad (17)$$

where $\rho_s \in (-1,1)$ denotes the persistence of the growth rate of s, γ_s is the long run growth rates of s, and ε_t^s is the innovation to the growth rate of s at date t. It is assumed that ε_t^z and ε_t^x are iid over time and mutually independent.[4] Consistently with the assumptions of the previous section, equations (16) and (17) imply that the technology shocks ε_t^z and ε_t^x have permanent effects on labor productivity, output, investment and consumption and that only ε_t^x affects the relative price in the long-run.

[4] Whelan (2005) allow for correlation of the innovations. But this case is not easily identifiable given our empirical estimation approach. Moreover, when the two shocks are correlated, it is not clear how one can assume that only the investment-specific shock has permanent effects on the long run level of the relative investment price.

The presence of long-run growth in productivity implies that the variables in the economy will be growing over time. Along the balanced growth path, the growth rates are given as:

$$\begin{aligned} g_I &= g_K = (\gamma_z \gamma_x)^{1/(1-\alpha)} && \text{(18a)} \\ g_C &= g_Y = \gamma_z^{1/(1-\alpha)} \gamma_x^{\alpha/(1-\alpha)} && \text{(18b)} \\ g_P &= \gamma_x^{-1} && \text{(18c)} \\ g_n &= g_u = g_h = 1 && \text{(18d)} \end{aligned}$$

where g_s is defined as the gross growth rate of s along the balanced growth path, $g_s = s/s_{-1}$. The absence of growth in hours worked rests upon the assumption that s_{1t} which enters equation (12) is given as:

$$s_{1t} = z_t^{1/(1-\alpha)} x_t^{\alpha/(1-\alpha)}$$

which corresponds to the growth factor that renders consumption and output stationary along the balanced growth path.[5] Given the non-stationarity of the economy, we solve the model by transforming the growing variables into their stationary equivalents, log-linearizing the optimality conditions, and solving the resulting set of linear stochastic difference equations. The stationarity inducing transformations are obtained by defining:

$$\begin{aligned} c_t &= C_t/s_{1t}, \; y_t = Y_t/s_{1t} \\ k_{c,t+1} &= K_{c,t+1}/s_{2t}, \; k_{i,t+1} = K_{i,t+1}/s_{2t} \\ i_{c,t} &= I_{c,t}/s_{2t}, \; i_{i,t} = I_{i,t}/s_{2,t} \\ p_t &= P_t/\left(s_{1t}/s_{2t}\right) \end{aligned}$$

[5] Justiniano, Primiceri and Tambalotti (2008) instead assume that the utility function is logarithmic in consumption (adjusted for habits). In this case, hours worked are stationary despite technological progress.

The first-order conditions for the stationary version of the model are given as:

$$
\begin{aligned}
c &: c_t^{-\sigma} = \lambda_{c,t} && (19)\\
n_c &: \phi n_t^{\kappa} = \lambda_{c,t}^{n}\left(-F_c'\left(n_{c,t}/n_{c,t-1}\right)\frac{n_{c,t}}{n_{c,t-1}} + \left(1 - F_c\left(n_{c,t}/n_{c,t-1}\right)\right)\right)\\
&\quad +\beta E_t g_{1t+1}^{1-\sigma}\lambda_{c,t+1}^{n}F_c'\left(n_{c,t+1}/n_{c,t}\right)\left(\frac{n_{c,t+1}}{n_{c,t}}\right)^2 && (20)\\
n_i &: \phi n_t^{\kappa} = \lambda_{i,t}^{n}\left(-F_i'\left(n_{i,t}/n_{i,t-1}\right)\frac{n_{i,t}}{n_{i,t-1}} + \left(1 - F_i\left(n_{i,t}/n_{i,t-1}\right)\right)\right)\\
&\quad +\beta E_t g_{1t+1}^{1-\sigma}\lambda_{i,t+1}^{n}F_i'\left(n_{i,t+1}/n_{i,t}\right)\left(\frac{n_{i,t+1}}{n_{i,t}}\right)^2 && (21)\\
h_c &: \lambda_{c,t}^{n} = \lambda_{c,t}\left(1-\alpha\right)A_1 g_{2t}^{-\alpha}\left(k_{c,t}u_{c,t}\right)^{\alpha}h_{c,t}^{-\alpha} && (22)\\
h_i &: \lambda_{i,t}^{n} = \lambda_{i,t}\left(1-\alpha\right)A_2 g_{2t}^{-\alpha}\left(k_{i,t}u_{i,t}\right)^{\alpha}h_{i,t}^{-\alpha} && (23)\\
u_c &: \lambda_{c,t}^{k}\Lambda_c'\left(u_{c,t}\right)/g_{2,t} = \lambda_{c,t}\alpha A_1 g_{2t}^{-\alpha}\left(k_{c,t}u_{c,t}\right)^{\alpha-1}h_{c,t}^{1-\alpha} && (24)\\
u_i &: \lambda_{i,t}^{k}\Lambda_i'\left(u_{i,t}\right)/g_{2,t} = \lambda_{i,t}\alpha A_2 g_{2t}^{-\alpha}\left(k_{i,t}u_{i,t}\right)^{\alpha-1}h_{i,t}^{1-\alpha} && (25)\\
i_c &: \lambda_{i,t} = \lambda_{c,t}^{k}\left(1 - G_c'\left(g_{2t}i_{c,t}/k_{c,t}\right)\right) && (26)\\
i_i &: \lambda_{i,t} = \lambda_{i,t}^{k}\left(1 - G_i'\left(g_{2t}i_{i,t}/k_{i,t}\right)\right) && (27)\\
k_c' &: \lambda_{c,t}^{k} = \beta E_t g_{1t+1}^{1-\sigma}\lambda_{c,t+1}^{k}[\left(1-\delta_c-\Lambda_c\left(u_{c,t+1}\right)\right)/g_{2,t+1}\\
&\quad -G_c\left(g_{2,t+1}i_{c,t+1}/k_{c,t+1}\right)/g_{2,t+1} + G_c'\left(g_{2,t+1}i_{c,t+1}/k_{c,t+1}\right)\left(i_{c,t+1}/k_{c,t+1}\right)]\\
&\quad +\beta E_t g_{1t+1}^{1-\sigma}\lambda_{c,t+1}\alpha A_1 u_{c,t+1}g_{2t+1}^{-\alpha}\left(k_{c,t+1}u_{c,t+1}\right)^{\alpha-1}h_{c,t+1}^{1-\alpha} && (28)\\
k_i' &: \lambda_{i,t}^{k} = \beta E_t g_{1t+1}^{1-\sigma}\lambda_{i,t+1}^{k}[\left(1-\delta_i-\Lambda_i\left(u_{i,t+1}\right)\right)/g_{2,t+1}\\
&\quad -G_i\left(\gamma_{2,t+1}i_{i,t+1}/k_{i,t+1}\right)/g_{2,t+1} + G_i'\left(g_{2,t+1}i_{i,t+1}/k_{i,t+1}\right)\left(i_{i,t+1}/k_{i,t+1}\right)]\\
&\quad +\beta E_t g_{1t+1}^{1-\sigma}\lambda_{i,t+1}\alpha A_2 u_{i,t+1}g_{2t+1}^{-\alpha}\left(k_{i,t+1}u_{i,t+1}\right)^{\alpha-1}h_{i,t+1}^{1-\alpha} && (29)
\end{aligned}
$$

where $\lambda_{c,t}$ is the multiplier on the (stationary version of) technological constraint in equation (7), $\lambda_{c,t}^{n}$ is the multiplier on equation (10), $\lambda_{i,t}^{n}$ is the multiplier on equation (11), $\lambda_{i,t}$ is the multiplier on equation (8), and $\lambda_{c,t}^{k}$ and $\lambda_{i,t}^{k}$ are the multipliers on (13) – (14). g_{1t} and g_{2t} are defined as the growth rates of s_{1t} and s_{2t}, respectively.

Combining equations (20) – (23) implies that

$$
\begin{aligned}
& mp_{n,t}^{c}\left(-F_c'\left(n_{c,t}/n_{c,t-1}\right)\frac{n_{c,t}}{n_{c,t-1}} + \left(1 - F_c\left(n_{c,t}/n_{c,t-1}\right)\right)\right)\\
& +\beta E_t g_{1t+1}^{1-\sigma}\left(\frac{c_{t+1}}{c_t}\right)^{-\sigma} mp_{n,t+1}^{c}F_c'\left(n_{c,t+1}/n_{c,t}\right)\left(\frac{n_{c,t+1}}{n_{c,t}}\right)^2\\
= \; & p_t mp_{n,t}^{i}\left(-F_i'\left(n_{i,t}/n_{i,t-1}\right)\frac{n_{i,t}}{n_{i,t-1}} + \left(1 - F_i\left(n_{i,t}/n_{i,t-1}\right)\right)\right)\\
& +\beta E_t p_{t+1} g_{1t+1}^{1-\sigma}\left(\frac{c_{t+1}}{c_t}\right)^{-\sigma} mp_{n,t+1}^{i}F_i'\left(n_{i,t+1}/n_{i,t}\right)\left(\frac{n_{i,t+1}}{n_{i,t}}\right)^2 \qquad (30)
\end{aligned}
$$

where $mp_{n,t}^{s}$ denotes the marginal product of labor in sector s at date t (which are defined in equations $(22)-(23)$).

Within each sector the marginal rate of substitution between consumption and leisure (work) equal the marginal rate of transformation. The latter consists of the marginal product of labor, denoted by $mp_{n_c,t}^{s}$, corrected for labor adjustment costs. The condition in equation (30) determines the division of labor across the two sectors. It equalizes the value of the marginal product of labor across sectors but with an adjustment for fact that it is costly to reallocate labor. In the absence of such adjustment costs, $mp_{n_c,t}^{c}$ will equal $p_t mp_{n_i,t}^{i}$ period-by-period which introduce a tight link between labor productivity across sectors. Whenever $F_c'' > 0$ *or* $F_{ii}' > 0$, labor will not instantaneously adjust across sectors in which case the value of marginal products of labor may differ temporarily across sectors. Given the proportionality of marginal and average products that follows from the Cobb-Douglas production structure it is therefore immediate that labor adjustment costs may play an important role.

4 Estimation of Structural Parameters

The model presented above is consistent with the identifying assumptions that were adopted in Section 2 under the restriction that the capital share in the two sectors is identical. We now wish to examine whether the model is also consistent with the dynamics that we estimated in the U.S. data and, importantly, if it can account for the covariance structure between hours worked and labor productivity. This exercise cannot be performed without a quantitative evaluation of the model and this is only feasible to the extent that the structural parameters are either calibrated or estimated formally.

The model involves quite a large number of structural parameters. Some of these parameters can be calibrated because there is broad consensus about their appropriate value. There are other parameters instead for which we have little knowledge or for which there may not be a broad consensus. This last set of parameters are estimated rather than calibrated. We take a limited information approach and estimate those parameters by matching the identified impulse response functions that were estimated in Section 2.

Let the vector of structural parameters be given by Φ. We partition Φ into the two subsets $\Phi = [\Phi_1', \Phi_2']'$ and distinguish between these two subsets on the basis of whether their elements will be calibrated or estimated. Φ_1 consists of the structural parameters that we will calibrate while Φ_2 contains the parameters that we estimate formally.

4.1 Calibrated Parameters

The vector of parameters that we calibrate consists of the 8 parameters in $\Phi_1 = [\alpha,\ \beta^*,\ \delta,\ \gamma_x,\ \gamma_z,\ \phi,\ \Lambda_c'(1),\ \Lambda_i'(1)]$. Common to these parameters is that they can be calibrated using restrictions on the long-run properties of the model.

α is the elasticity of output in any of the two sectors to the input of (effective) capital. This is a common parameter to the business cycle literature and there is broad agreement on realistic values. We set this parameter equal to 0.36 which implies a 36 percent capital income share. This estimate is close to the average capital income share in the U.S. national income accounts over the sample period that we examine. Moreover, minor variations in the value of this parameter have no significant impact on the results.

β^* is defined as $\beta g_1^{1-\sigma}$ where g_1 is the long-run growth rate of s_1. In the steady-state β^* is related to the long-run real interest rate through the relationship $\beta^* = 1/(1+r)$. We set the quarterly steady-state real interest rate equal to 1 percent which implies $\beta^* = 0.9901$.[6]

δ is the depreciation rate of the capital stock at "normal" levels of capacity utilization. We set this parameter equal to 2.5 percent per quarter which implies an annual depreciation rate of approximately 10 percent. This is a standard value.

The long-run growth rate of the economy is determined by γ_z, the long-run growth rate of neutral technology, by γ_x, the long-run growth rate of investment specific technology, and by α. As discussed, γ_x also corresponds to the rate of decline in the price of investment goods relative to consumption goods while γ_x and γ_z jointly determine the long-run growth rate of GDP per capita. We calibrate these parameters so that they imply a 3 percent annual decline in the relative investment price along the balanced growth path and an annual growth rate of consumption per capita of 2 percent. This implies that $\gamma_x = 1.0076$ and $\gamma_z = 1.0004$.

The preference parameter ϕ determines the number of hours worked in the steady state. We calibrate this parameter so that total hours supply in the steady state equals 30 percent. This corresponds quite closely to estimates of the amount of time that labor market participants use on market activities. Together with the benchmark estimates of the parameters in Φ_2 discussed below, this implies that $\phi = 4.18$ so that disutility of work takes quite an important role in the utility function.

Finally, $\Lambda_c'(1)$ and $\Lambda_i'(1)$ are the derivatives of the impact of capital utilization on the depreciation rate of the two capital stocks. We calibrate these derivatives so that they are consistent with the normalizations $\overline{u}_c = \overline{u}_i = 1$ using the steady-state versions of the relationships in equations $(24) - (25)$. This implies that $\Lambda_c'(1) = \Lambda_i'(1) = 0.048$.

These parameter values implies a steady-state consumption expenditure share of 71.6 percent. This estimate is similar to the average value observed in the US

[6]Given the estimate of g_1, one can also work out the implies value of β but this in itself does not not affect the properties of the model. It is the effective discount rate that matters.

economy. Given the symmetry of the modeling of the technologies of the two sectors it also follows that the consumption sector accounts for 71.6 percent of total hours worked and of the total capital stock. The aggregate capital-output ratio is around 1.9 (using annual output) which is also in the range of standard values used in the literature.

4.2 Estimated Parameters

The vector of parameters that are formally estimated using the limited information approach consists of $\Phi_1 = \left[\sigma, \kappa, \phi, \lambda_c, \lambda_i, F_c''\left(\overline{n}_c\right), F_i''\left(\overline{n}_i\right), G_c''\left(\overline{I_c/K_c}\right), G_i''\left(\overline{I_i/K_i}\right), \rho_z, \rho_x, \mu_z^2, \mu_x^2\right]$ where $\lambda_c = \Lambda_c''(1)/\Lambda_c'(1)$, $\lambda_i = \Lambda_i''(1)/\Lambda_i'(1)$, μ_z^2 is the variance of the innovations to the neutral technology shock process, and μ_x^2 is the variance of the innovations to the investment-specific technology shock process. Each of these parameters are estimated subject to constraints that guarantee that the optimization problems of households and firms are well-specified and that the economy is stationary. To be precise, we constrain all the parameters apart from ρ_z and ρ_x to be positive. ρ_z and ρ_x are constrained to be smaller than 1 in absolute value.

We estimate these 13 parameters using a limited information approach. The idea is to search the parameter space for the parameter vector that gives the model the best fit of the identified impulse response functions that we estimated in Section 2. Let IR^d be an $(N_d T)\,x1$ vector of the (vectorized) impulse responses estimated in section 2 where N_d denotes the number of response variables and T denotes the forecast horizon. Let $IR^m(\Phi_2|\Phi_1)$ denote the model equivalents of the empirical impulse responses when the vector of unknown parameters is equal to Φ_2. We then estimate Φ_2 as the solution to the following quadratic minimization problem:

$$\widehat{\Phi}_2 = \arg\min_{\Phi_2} \Theta(\Phi_2) = \left(IR^d - IR^m(\Phi_2|\Phi_1)\right)' \Sigma \left(IR^d - IR^m(\Phi_2|\Phi_1)\right) \qquad (31)$$

where Σ is a weighting matrix. We set the latter matrix equal to a diagonal matrix with the inverse of the variances of the empirically estimated impulse responses along its diagonal. The standard errors are computed following Hall et al (2007).

We specify IR^d to include the impulse responses of output, consumption, investment, aggregate hours worked, aggregate labor productivity, and sectoral hours worked and labor productivity to the two identified productivity shocks and we use a forecast horizon of 16 quarters.[7]

4.3 Parameter Estimates

The parameter estimates are reported in Table 4. We find that the boundary restrictions are binding for some of the parameters. First, the inverse of the Frisch labor

[7] We do not target directly the relative investment price. The same strategy is followed by Altig et al (2005).

supply elasticity, κ, is estimated to be approximately 0. This is consistent with the indivisible hours model of Hansen (1985). This is a disputed value but one that often is adopted in the macro literature.

Secondly, we find that adjustment costs are relevant only for the investment sector. For the consumption sector, $F_c''(\overline{n}_c)$ and $G_c''\left(\overline{I_c/K_c}\right)$ are both estimated to be zero. The reason for this is that it is sufficient for these costs to be positive for one of the two sectors in order to limit the extent to which labor and capital can move across sectors.

The remaining parameters are precisely estimated with small standard errors. The point estimate of σ, the inverse of the intertemporal elasticity of substitution of consumption, is 3.32. This estimate is well within the range of values usually regarded as realistic. This implies a moderate response of consumption to changes in real interest rates (and moderate wealth effects).

We find that the adjustment costs of labor and capital in the investment sector are moderately large and appear to be larger for capital than for labor. Our point estimates of the adjustment cost parameters are $F_i''(\overline{n}_i) = 0.24$ and $G_i''\left(\overline{I_i/K_i}\right) = 24.1$.

The estimates of the parameters of the technology shock processes imply that they both have moderately low persistence. We find point estimates of $\rho_z = 0.18$ and $\rho_x = 0.05$. The estimated higher persistence of the neutral technology shock process relative to investment specific shocks is consistent with Altig et al (2005). However, we find much lower persistence of the technology growth rates than these authors. Next, we find that the variance of the innovations to the investment specific technology shock is much higher than the variance of the innovations to neutral technology. Thus, investment specific technology shocks appear to be a much more important source of shocks to the economy than neutral technology shocks.

4.4 Dynamics

Figure 4 illustrates the theoretical impulse response functions in response to a neutral technology shock along with their empirical counterparts. Figure 5 illustrates the case of investment specific technology shock.

The model captures extremely well the dynamics of output, consumption, investment, and aggregate hours worked to either of the two types of technology shocks. As in the data, a positive neutral technology shock or a positive investment specific technology shock brings about gradual increases in output, consumption and investment while aggregate hours worked rise persistently above their steady state level. Moreover, the model is consistent with hours and investment being more responsive to the investment specific technology shock than to the neutral technology shock. This confirms the success of technology shock driven business cycle theories in accounting for the cyclical movements in output and its components. The results here demonstrate that such models can account quite precisely for the impact of identified technology shocks In fact the simple two-sector model here appears more successful at accounting for these features of the data than the more complicated sticky-price sticky-wage model with firm specific capital analyzed by Altig et al (2005).

Next, Figure 5 makes it clear that the two-sector model also provides a very precise account of the impact of an investment specific shock on aggregate labor productivity, and on sector level movements in hours worked and labor productivity. Consistently with the empirical results, a positive investment specific shock gives initially rise to a drop in aggregate labor productivity whereafter productivity gradually rise to a new higher level in the long run. Associated with this, the model in agreement with the data implies a large increase in hours worked in the investment sector while consumption sector hours rise much less. This dynamics is due to the fact that the investment-specific shock having its direct impact on the investment goods producing sector only. This gives rise to a drop in the investment price which sets off an investment boom. As the capital stock accumulated, the productivity in the consumption sector eventually rises but only over time. In the short run, agents desire to increase consumption is attained through an increase in hours worked (and capacity utilization) in this sector. Moreover, the spur in investment gives rise to a large increase in hours worked in the investment sector limits the rise in labor productivity in this sector while higher hours in the consumption sector temporarily lowers labor productivity in this sector (until this sector accumulates sufficiently much new capital).

However, the model appears much less able to account well for the labor productivity and sectoral level impact of neutral technology shocks. Recall that in the US data we found that a positive neutral technology shock gives rise to a gradual rise in aggregate labor productivity. The model is qualitatively consistent with this but the rise in aggregate labor productivity is systematically larger in the model than in the data for the forecast horizons that we concentrate upon.[8] Moreover, while the model accounts quite precisely for the dynamic adjustment of hours worked in the investment sector it is not consistent with the relatively large rise in hours worked in the consumption sector. For this reason, the model is unable to account for the U-shaped response of consumption sector labor productivity that we documented in the US data.

We now ask whether the model can account for the conditional correlation structure between hours worked and labor productivity that we reported in Table 2. The model equivalents of the conditional moments are reported in Table 5.[9] Consistently with the evidence from the impulse response functions, we find that aggregate labor productivity and aggregate hours are positively correlated conditional upon neutral technology shocks but negatively correlated conditionally upon investment specific technology shocks. In terms of the size of these correlations, the model over-

[8] At longer forecast horizons this descrepancy disappears by construction.

[9] Note that since the model has only two shocks, the unconditional moments correspond to the last column where we allow for both types of technology shocks simultaneously.

estimates the positive hours-productivity correlation in response to a neutral productivity shock and underestimates the extent of the negative comovements following an investment-specific shock. Therefore, the hours-productivity correlation conditional upon both shocks jointly is higher in the model than in the data. Nevertheless, it is reassuring that theory is consistent with data as far as the pattern of aggregate hours-productivity correlations are concerned.

At the sectoral level, the evidence is more mixed. First, as in the US data, hours and labor productivity are consistently positively correlated in the investment sector. when we do not correct for relative price movements. Correcting for relative price changes, the model is also consistent with a negative hours-productivity correlation in the investment sector following an investment specific technology shock. However, the model cannot account well for the hours-productivity comovements in the consumption sector conditional upon a neutral productivity shock. Recall that in the US data, we find a negative hours-productivity correlation for this sector regardless of the type of productivity shock. In the model, neutral productivity shocks are instead associated with a strong positive comovements of hours and productivity in this sector. Essentially, the neutral productivity shock gives rise to a rise in the demand for labor which leads to a strong tendency for positive hours-productivity correlations.

This result may indicate that while the model's two-sector structure and the reallocation of labor are important for accounting for the Dunlop-Tarshis observation, there are further relevant aspects of sectoral reallocation that are important to consider.

5 Conclusions

The near-orthogonality of hours worked and aggregate labor productivity known as the Dunlop-Tarshis observation is a robust stylized fact of US data. This feature of the data has traditionally been seen as a litmus test of business cycle theories and would seem to cast doubt on technology driven business cycle models. We have shown that while hours worked and aggregate labor productivity are orthogonal, these central labor market indicators do display systematic covariance when measured conditional on the identified technology shocks. We focused upon the response to neutral and investment-specific technology shocks and our empirical results show that in US data aggregate hours and labor productivity are positive correlated conditionally on the first of these types of productivity shocks while investment-specific technology shocks give rise to negative hours productivity comovements. This is an important insight since it implies that the Dunlop-Tarshis observation should not be addressed by referring to factors that in general de-couples fluctuations in hours worked and fluctuations in labor productivity.

We also derived another systematic aspect of the data when we investigated the sectoral aspects of this finding. In particular, in the consumption sector we find a systematic negative hours - productivity relationship while the relationship is positive in the investment sector. Thus, there is a systematic difference across sectors indicating that multi-sector models may be appropriate for studying the relationship between hours and productivity.

A two-sector business cycle model was studied and we estimated key parameters of this model. The model that we propose introduces various frictions into the two-sector growth model of Greenwood, Hercowitz and Krusell (1997) and it consistent with the long-run identifying assumptions that we adopt when measuring the technology shocks in the US data. We found that this model gives a good account of fluctuations in aggregate variables. In particular, it can account for the dynamics of output, consumption, investment, and hours worked in response to the two types of productivity shocks. Moreover, it is entirely consistent with the pattern of hours-productivity correlations observed in the US data. The model is also very successful in accounting for the sectoral aspects of investment-specific technology shocks. However, it is not consistent with the sectoral impact of neutral productivity shocks. In particular, it implies a counterfactual high and positive correlation between labor productivity and hours worked in the consumption sector following a neutral productivity shock.

We believe that this might indicate that further sources of labor reallocation are relevant for accounting for the hours-productivity relationship. One aspect that we have not modeled is that skill-intensities may differ across sectors which might well be relevant. In US data, hourly wages are around 15-20 percent higher in the investment sector than in the consumption sector which would be consistent with the investment sector being more skill intensive than the consumption sector. Therefore, it is perceivable that skilled labor is reallocated to the investment sector in the face of productivity shocks. We leave this issue to future research.

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Tables and Figure

Table 1. Sources and Definitions of Data

Series	Definition	Source
Population	Civilian non-institutional population of age 16 and above	BLS
Real output	GDP in constant chained prices divided by population	BLS
Price level	Ratio of GDP in nominal prices divided by GDP in constant chained prices	BLS
Hours per worker	Average hours worked per worker in the private non-farm sector (Establishment data)	BLS
Employment	Number of workers in employment in the private non-farm sector divided by population	BLS
Average Hours	Product of hours per worker and employment	BLS
Sectoral hours	Hours worked in durables and consumption sectors respectively	BLS
Labor productivity	Real output divided by average hours	BLS
Relative investment price	Deflator of investment divided by the deflator of consumption	BEA

Notes: The relative investment price has been provided by Giorgio Primiceri. The deflators are computed by chain weighting the deflators of the different components of consumption (non-durable and services) and the components of investment (durable consumption and gross private domestic investment)

Table 2: Hours and Productivity Correlations: US Data

		Conditional upon		
	Unconditional	Investment specific shock	Neutral shock	Both
Aggregate	-0.09	-0.85	0.47	0.04
Consumption Sector	-0.90	-0.77	-0.65	-0.74
Durables Sector	0.31	0.63	0.47	0.58
Durables sector with price adjustment	0.28	-0.65	0.63	0.21

The numbers refer to Hodrick-Prescott filtered variables. The conditional correlations are computed from simulations of the counterfactuals.

Table 3: Calibrated Parameters

Parameter	Meaning	Value	Calibration
α	Capital share	0.36	Calibrated to capital income share estimate
γ_z	Steady-state growth rate of neutral technology	1.0004	Calibrated to average trend growth rate of output
γ_z	Steady-state growth rate of inv.spec. technology	1.0076	Calibrated to trend change in relative investment price
β^*	Effective subjective discount factor	0.99	Calibrated to imply 4% annual real interest rate in steady state
ϕ	Utility weight	4.18	Calibrated to be consistent with $\overline{n}_c+\overline{n}_i= 0.30$
$\Lambda_c'(1)$	Marginal impact of utilization rate of depreciation of capital stock in consumption sector	0.048	Calibrated to be consistent with $\overline{u}_c= 1$
$\Lambda_i'(1)$	Marginal impact of utilization rate of depreciation of capital stock in investment sector	0.048	Calibrated to be consistent with $\overline{u}_i= 1$
δ	Depreciation rate at normal rate of capacity utilization	0.025	Calibrated to imply 10 percent annual depreciation in steay state

Table 4: Parameter Estimates

Parameter	Meaning	Estimate	Standard error
σ	Inverse of intertemporal elasticity of substitution	3.322	0.011
κ	Inverse of Frisch elasticity	0.0001	-
$F_c''(\overline{n}_c)$	Adjustment costs of labor, consumption sector	0.001	-
$F_i''(\overline{n}_i)$	Adjustment costs of labor, investment sector	0.421	0.008
$G_c''\left(\overline{K}_c/\overline{I}_c\right)$	Adjustment costs of capital, consumption sector	0.0001	-
$G_i''\left(\overline{K}_i/\overline{I}_i\right)$	Adjustment costs of capital, investment sector	24.07	0.189
$\Lambda_c''(1)/\Lambda_c'(1)$	Elasticity of impact of utilization on depreciation in consumption sector	0.117	0.001
$\Lambda_i''(1)/\Lambda_c'(1)$	Elasticity of impact of utilization on depreciation in investment sector	0.001	-
ρ_z	Persistence of growth rate of neutral technology	0.177	0.001
ρ_x	Persistence of growth rate of inv.spec. technology	0.050	0.002
μ_z	Standard deviation of neutral technology shock innovations	0.069	0.0002
μ_x	Standard deviation of inv.spec. technology shock innovations	0.706	0.002

Table 5: Hours and Productivity Correlations: Benchmark Model

	Conditional upon		
	Investment specific shock	Neutral shock	Both
Aggregate	-0.53	0.75	0.52
Consumption Sector	-0.68	0.93	0.53
Durables Sector	0.83	0.66	0.53
Durables sector with price adjustment	-0.50	0.72	0.52

The numbers refer to Hodrick-Prescott filtered variables. The conditional correlations are computed from simulations of the model.

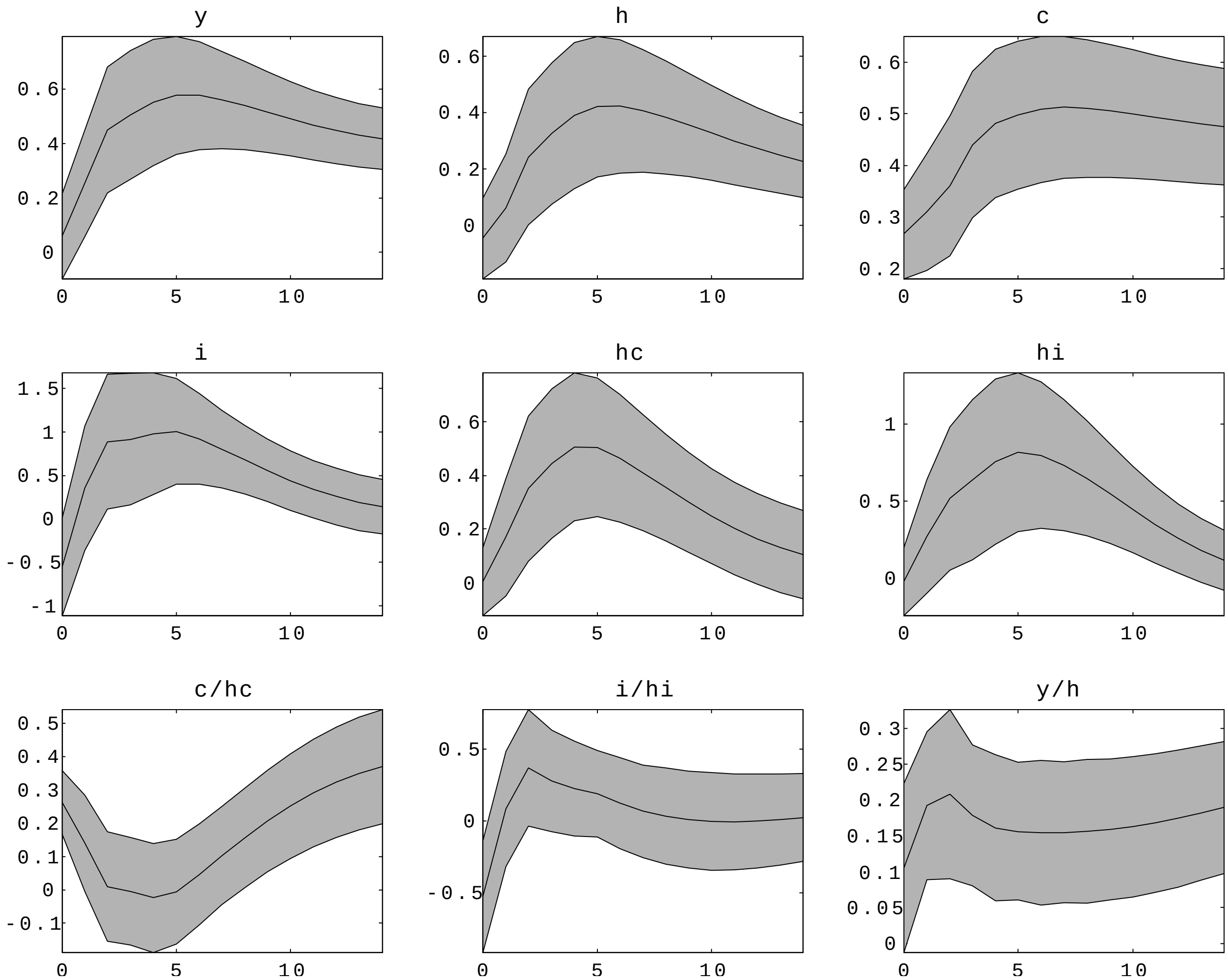
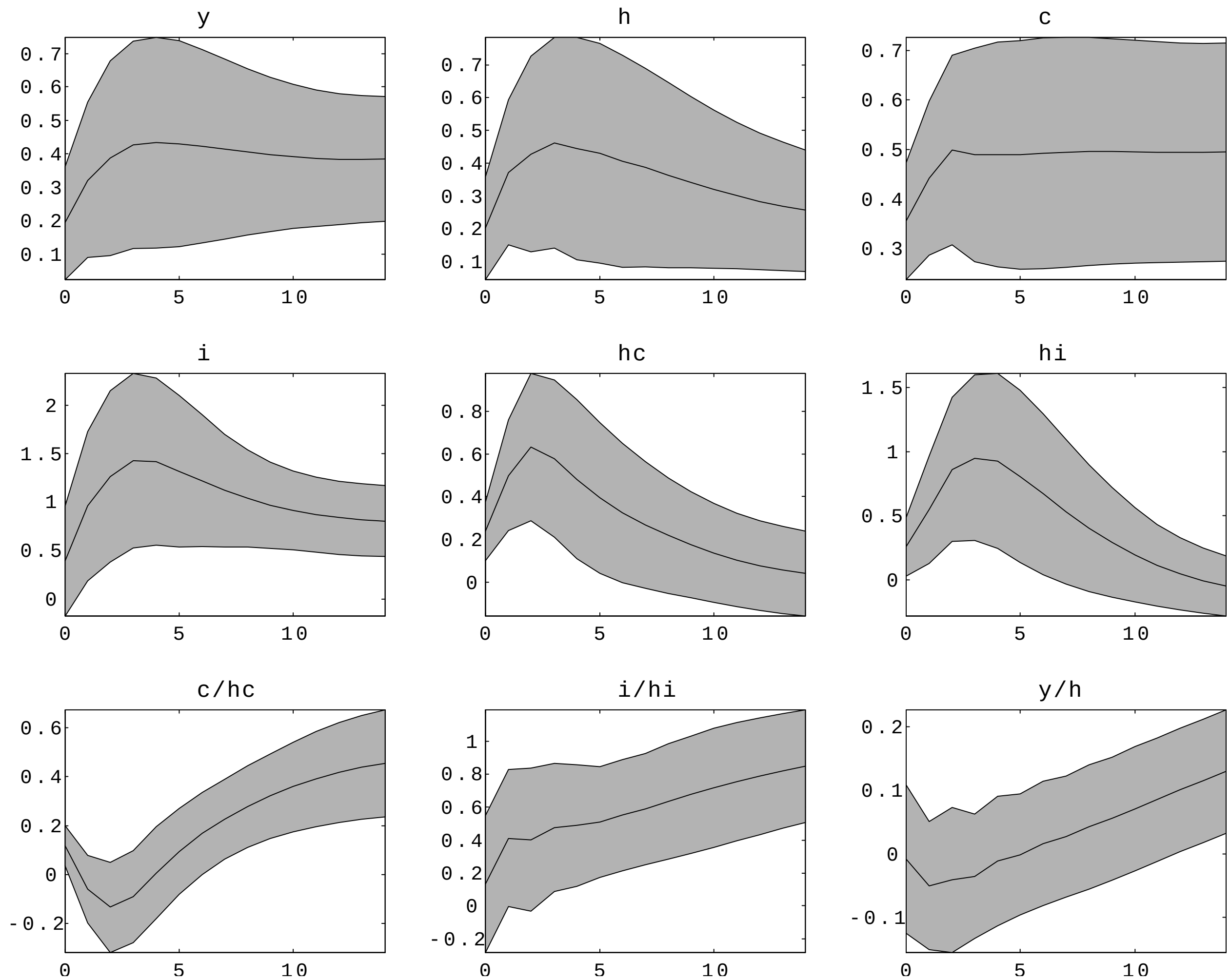


Figure 1: The Impact of a Neutral Technology Shock



The Impact of an Investment Specific Technology Shock

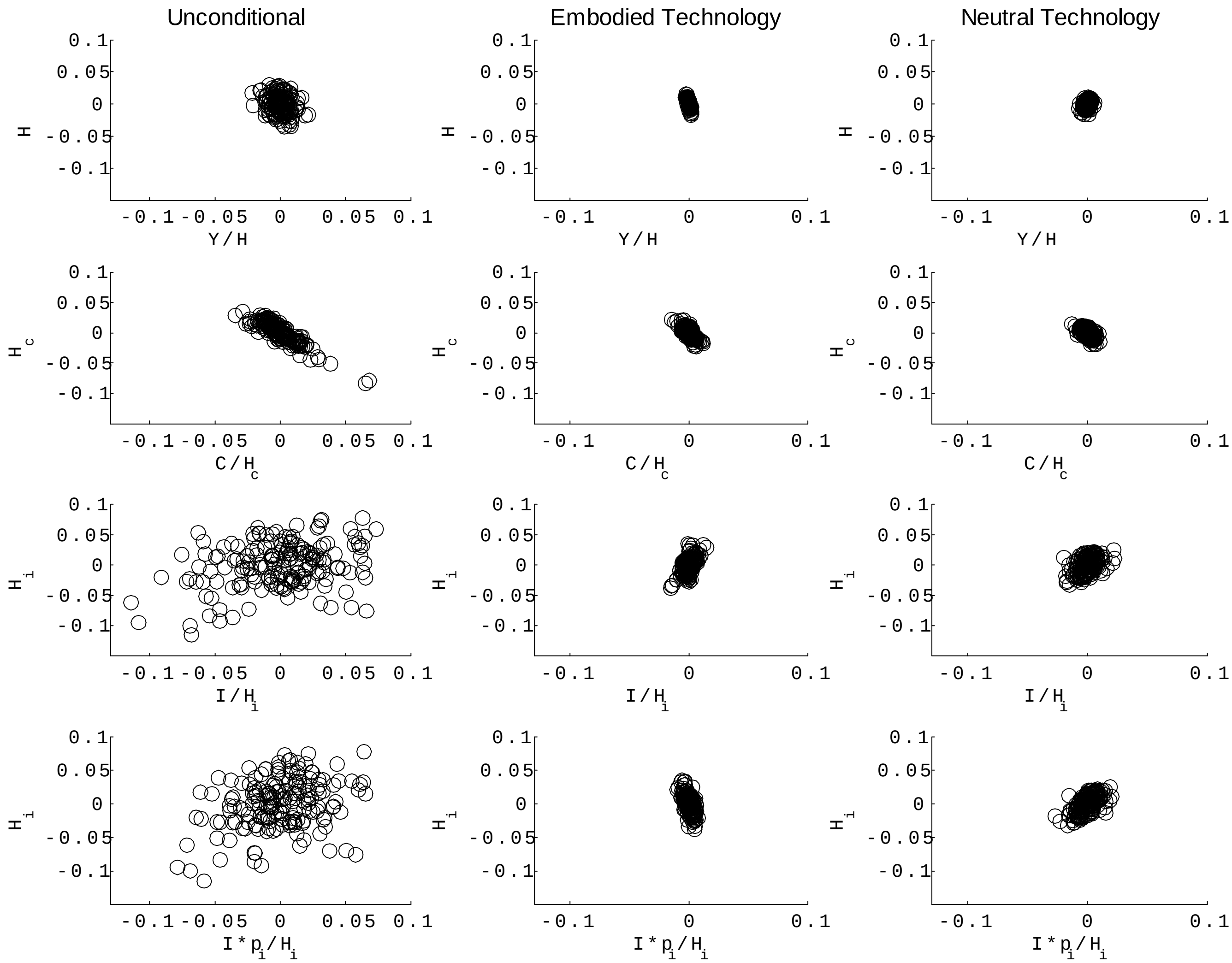


Figure 3: The Relationship Between Hours and Productivity

Neutral Technology Shock

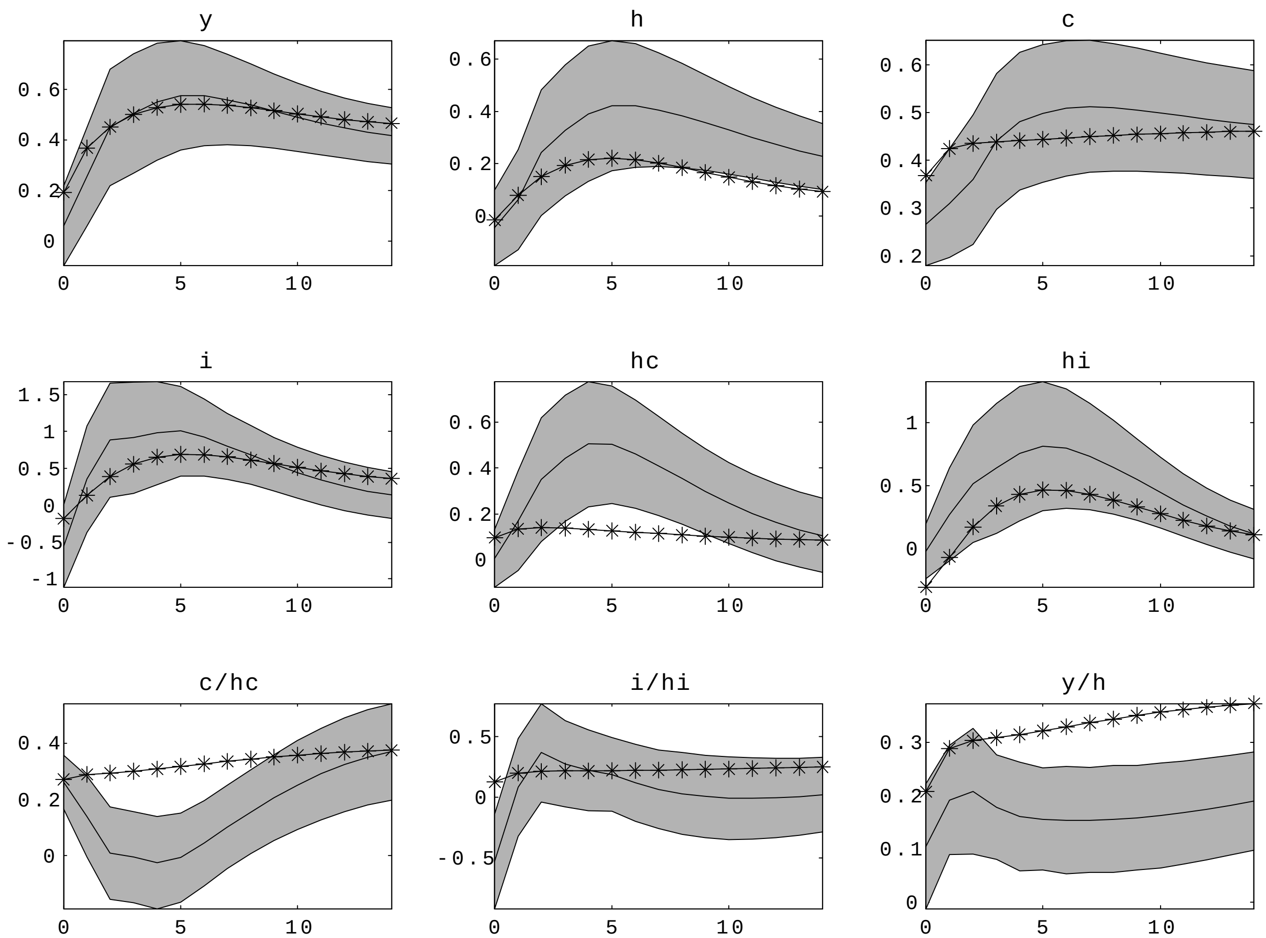


Figure 4: Impulse Responses of Benchmark Model to a Neutral Technology Shock
(full lines: empirical estimates; lines with starts: Model)

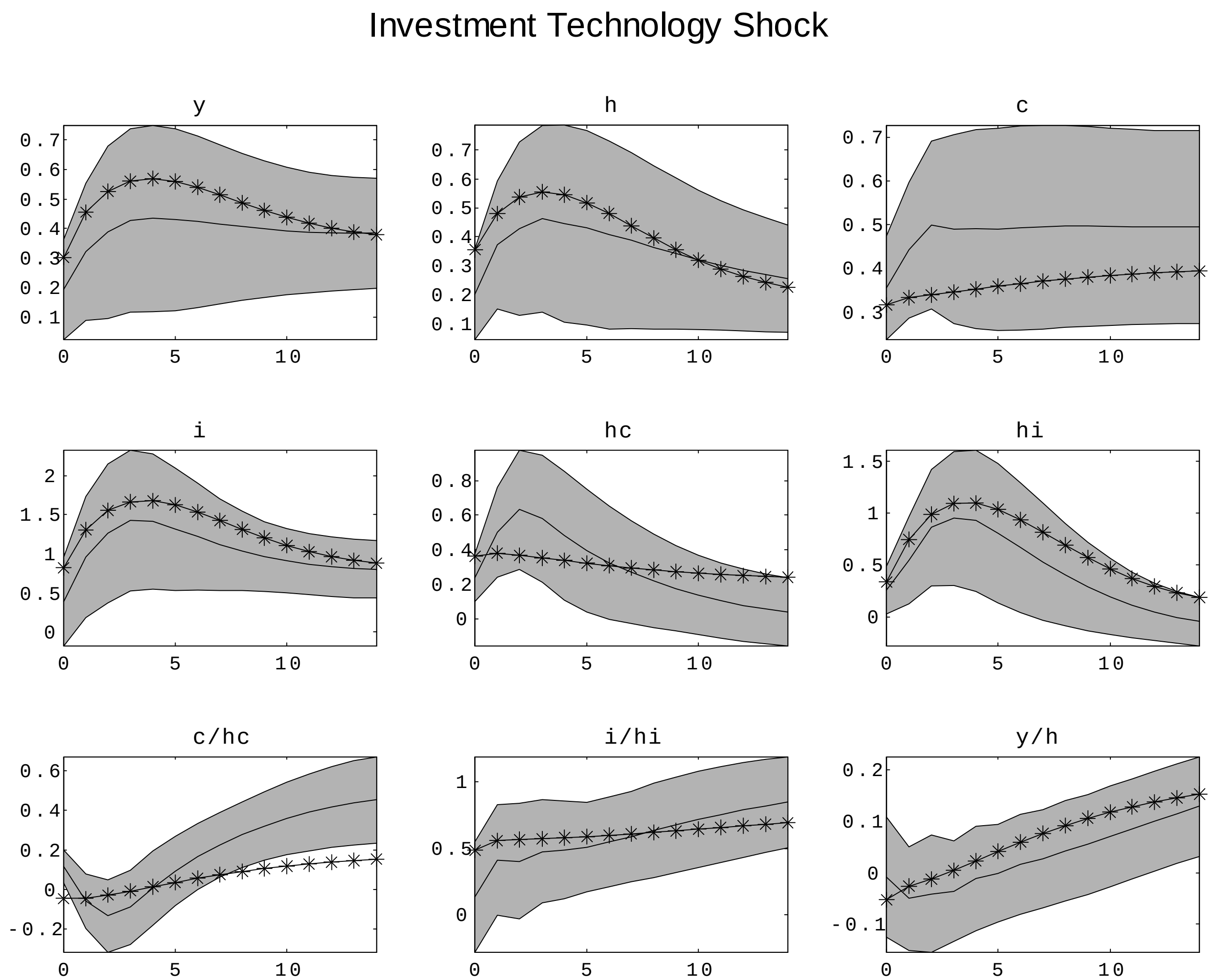


Figure 5: Impulse Responses of Benchmark Model to an Investment Specific Technology Shock (full lines: empirical estimates; lines with starts: Model)