Investment frictions and the relative price of investment goods in an open economy model

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Abstract

Is the relative price of investment goods a good proxy for investment frictions? We analyze investment frictions in an open economy, flexible price, two-country model and show that when the relative price of investment goods is endogenously determined in such a model, the relative price of investment can actually rise in response to a reduction in investment frictions. Only when the model is driven by TFP shocks do we observe a data congruent negative correlation between investment and the relative price of investment goods.

JEL classification: E22, E32, F41

Keywords: Investment frictions, investment specific technological progress, total factor productivity, relative price of investment goods terms of trade.

1 Introduction

The relative price of investment goods with respect to consumption goods has shown a remarkable decline during the 1980s in the United States. This also coincides with a period of a remarkable boom in total factor productivity (see Figure 1). A number of papers interpret this decline in the relative price of investment goods as evidence of investment specific technological progress and a consequent decline in capital market friction. Greenwood et al (2000) use the relative price of equipment as a driver of investment specific technological (IST for short) change in their calibrated

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1The relative price of investment is the ratio of the equipment price deflator to the CPI of nondurable and services obtained from Bureau of Economic Analysis. The TFP is measured by a Solow residual from the regression of nonfarm output on capital stock and hours worked.

In this paper, we argue that this price-based approach to understanding investment friction has its merits and demerits. We ask a simple question: how does the relative price of investment goods respond to an IST shock - does it decline, as postulated in models that treat this relative price as exogenous? To answer this question, we put forward a model that shows that when the relative price of investment goods is endogenously determined, a reduction in investment frictions results in an increase in the relative price of investment goods. This finding is at odds with the literature that interprets an investment friction shock as the inverse of the relative price of investment goods. As in Fisher (2006), an investment friction is modelled as an investment specific technology (IST) shock which impacts the relative price of investment goods via its effects on (i) the demand for consumption and investment goods, and therefore (ii) the terms of trade. In addition to this IST shock our model also has a Hicks-neutral total factor productivity shock (TFP) shock. In our model, it is the TFP shock, originating either in the intermediate goods sector or the investment goods sector, that can account for the negative correlation between the investment rate and the relative price of investment.

Thus, the central message of our paper is that the fundamental driver of the observed negative correlation between the investment rate and the relative price of investment goods is the TFP boom in the 1980s not the IST change. This contrasting result from Fisher (2006) is due to the fact that ours is an open economy model in which the relative price of investment goods is linked to the endogenously determined terms of trade.

The remainder of this paper is organized as follows. In the following section, we describe the basic intuition of our model in terms of a simple arbitrage condition. Section 3 lays out the formal model. Sections 4 and 5 report the calibration and the results of our impulse response analysis of the relative price of investment goods with respect to TFP and investment specific technology shocks. Section 6 analyses the business cycle properties of our model driven by TFP and IST shocks. In Section 7, we perform sensitivity analysis to check the robustness of our findings. In Section 8, we analyse the model when the IST shock enters as a productivity shock specific to the investment goods sector. In Section 9 we put forward some empirical evidence in support of our findings. Finally section 10 concludes.
2 A Simple Model for Intuition

Cummins and Violante (2002) argue that a comparison of constant-quality investment prices with a constant-quality consumption price is an informative measure of technological change in the investment goods sector. To illustrate their intuition, we follow Cummins and Violante and set up a simple two-sector model, where the two sectors produce investment and final goods respectively. Let the final good, $z_t$, be produced competitively with a constant returns to scale combination of capital and labour. Final goods can be used for consumption or in the production of investment goods. Investment goods, $x_t$, are produced according to the following linear investment technology.

$$ x_t = \varepsilon_t^x z_t $$  

(1)

where $\varepsilon_t^x$ is a multiplicative shock to investment specific technology. Competition in the consumption and investment goods sectors implies the following arbitrage condition

$$ P_t^x x_t = P_t^C z_t $$

(2)

where $P_t^C$ is the price of the consumption good. Combining equations (1) and (2) allows us to express investment specific technology in terms of the relative price of investment goods to final consumption goods:

$$ \frac{P_t^x}{P_t^C} = \frac{1}{\varepsilon_t^x} $$

In the setting of Cummins and Violante (2002), Greenwood, et al (2000) and Fisher (2006), the relative price of investment is just the reciprocal of the investment specific technology shock $\varepsilon_t^x$. A higher investment friction (lower $\varepsilon_t^x$) means a higher relative price of investment goods. The relative price of investment goods, therefore, mirrors the underlying investment friction.

In this paper, we argue that in economies where not all final goods can or are being alternatively used as investment goods, say because of differences in the composition of the investment and the consumption baskets, the relative price of investment goods to final consumption goods may be a misleading measure of investment technology. Assume that only a subset of final goods can be used for both consumption and investment, say $z$, whose price index is $P_t^C$, then following the steps above, we get:

$$ \frac{P_t^x}{P_t^C} = \frac{1}{\varepsilon_t^x} $$

which relates to Cummins and Violante’s measure as follows:

$$ \frac{P_t^x}{P_t^C} = \frac{1}{\varepsilon_t^x} \frac{P_t^C}{P_t^C} $$

where $\frac{P_t^C}{P_t^C}$ is endogenous to the model and determined by general equilibrium considerations. In the following section we outline a formal open economy model where the final goods basket consists
of home and foreign-produced goods produced with a certain technology that differs from the technology used to produce investment goods. As a result, the ratio $\frac{P_C}{P_I}$ will be shown to depend on the relative price of foreign to home-produced traded goods, i.e. on the terms of trade. This relative price is a function of the exogenous shocks hitting the model, such as changes in $\varepsilon^*_t$.

3 The model

We propose, what is essentially an international real business cycle model with incomplete financial markets, modified to incorporate some of recent modelling features put forward in Smets and Wouters (2003) and Christiano, Eichenbaum and Evans (2005). The basic structure of our model is also similar to related work by Boileau (2002).

3.1 Consumer behavior

The world economy is populated by a continuum of agents on the interval $[0, 1]$. The population on the segment $[0, n)$ belongs to the country $H$ (Home), while the segment $[n, 1]$ belongs to $F$ (Foreign). Preferences for a generic Home-consumer are described by the following utility function:

$$U^j_t = \mathbb{E}_t \sum_{s=t}^{\infty} \beta^{s-t} U(C^j_s, (1 - h^j_s))$$

(3)

where $\mathbb{E}_t$ denotes the expectation conditional on the information set at date $t$, while $\beta$ is the intertemporal discount factor, with $0 < \beta < 1$. The Home consumer obtains utility from consumption, $C^j$, and receives dis-utility from supplying labour, $h^j$.

In our model, we assume that international asset markets are incomplete. The asset market structure in the model is relatively standard in the literature. We assume that home residents are able to trade two nominal risk-less bonds denominated in the domestic and foreign currency. These bonds are issued by residents in both countries in order to finance their consumption expenditure. Among these two nominal bonds, we assume that home bonds are only traded nationally. On the other hand, foreign residents can allocate their wealth only in bonds denominated in the foreign currency. This asymmetry in the financial market structure is made for simplicity. The results would not change if we allow home bonds to be traded internationally. We would, however, need to consider a further arbitrage condition. Home households face a cost (i.e. transaction cost) when they take a position in the foreign bond market. This cost depends on the net foreign asset position of the home economy as in Benigno (2001). Domestic firms are assumed to be wholly owned by domestic residents, and profits are distributed equally across households. Consumer $j$ faces the

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\footnote{We have also analysed a complete markets version, and have found that our results are not affected by the asset market structure. Smidt-Grohe and Uribe (2003) describe other ways of eliminating the unit root in bond holding problem.}
following budget constraint in each period $t$:

$$
PtC^j_t + \frac{B^j_{H,t}}{(1 + i_t)} + \frac{S_tB^j_{F,t}}{(1 + i^*_t)}\Theta\left(\frac{S_tB^j_{F,t}}{P_t}\right) = B^j_{H,t-1} + S_tB^j_{F,t-1} + P_tw_t h^j_t + \Pi^j_t
$$

where $B^j_{H,t}$ and $B^j_{F,t}$ are the individual's holdings of domestic and foreign nominal risk-less bonds denominated in the local currency. $i_t$ is the Home country nominal interest rate and $i^*_t$ is the Foreign country nominal interest rate. $S_t$ is the nominal exchange rate expressed as units of domestic currency needed to buy one unit of foreign currency, $P_t$ is the consumer price level and $w_t$ is the real wage. $\Pi^j_t$ are dividends from holding a share in the equity of domestic firms obtained by agent $j$. All domestic firms are wholly owned by domestic agents and equity holding within these firms is evenly divided between domestic agents.

The cost function $\Theta(.)$ drives a wedge between the return on foreign-currency denominated bonds received by domestic and by foreign residents. We follow Benigno, P. (2001) in rationalizing this cost by assuming the existence of foreign-owned intermediaries in the foreign asset market who apply a spread over the risk-free rate of interest when borrowing or lending to home agents in foreign currency. This spread depends on the net foreign asset position of the home economy. We assume that profits from this activity in the foreign asset market are distributed equally among foreign residents (see P. Benigno (2001)).

As in P. Benigno (2001), we assume that all individuals belonging to the same country have the same level of initial wealth. This assumption, along with the fact that all individuals face the same labour demand and own an equal share of all firms, implies that within the same country all individuals face the same budget constraint. Thus they will choose identical paths for consumption. As a result, we can drop the $j$ superscript and focus on a representative individual for each country.

The maximization problem of the Home individual consists of maximizing (3) subject to (4) in determining the optimal profile of consumption and bond holdings and the labour supply schedule.

Agent $j$’s maximisation problem:

$$
L = \mathbb{E}_t \sum_{s = t}^{\infty} \beta^{s-t} \left\{ \mu_s \left[ \frac{B^j_{H,s-1}}{P_s} + \frac{S_s B^j_{F,s-1}}{P_s} + w_s h_s^j + \frac{\Pi^j_s}{P_s} - C_s^j - \frac{B^j_{H,s}}{P_s (1+i_s)} - \frac{S_s B^j_{F,s}}{P_s (1+i^*_s) \Theta\left(\frac{S_s B^j_{F,s}}{P_s}\right)} \right] \right\}
$$

The domestic households’ first order conditions are described by the following equations:

$$
K = \frac{B^j_{F,t}}{r^j_t (1+i_t)} \left[ \frac{\beta S_t}{\Theta\left(\frac{S_t B^j_{F,t}}{P_t}\right)} - 1 \right].
$$
\[
\frac{\partial L_t}{\partial C_t^j} : UC(C_t^j, (1 - h_t^j)) - \mu_t = 0 \\
\frac{\partial L_t}{\partial h_t^j} : \frac{U_t(C_t^j, (1 - h_t^j))}{UC(C_t^j, (1 - h_t^j))} = w_t \\
\frac{\partial L_t}{\partial B_{H,t}^j} : -\mu_t \frac{1}{P_t(1 + i_t)} + \beta E_t \mu_{t+1} \frac{1}{P_{t+1}} = 0 \\
\frac{\partial L_t}{\partial B_{F,t}^j} : -\mu_t \frac{S_t}{P_t(1 + i_t) \Theta \left( \frac{S_t B_{F,t}}{P_t} \right)} + \beta E_t \mu_{t+1} S_{t+1} \frac{1}{P_{t+1}} = 0
\]

where (8) is the optimality condition for the Home country’s holdings of foreign-currency denominated bonds.

### 3.2 Final consumption goods sector

Home final consumption goods \((C)\) are produced with the aid of home and foreign-produced intermediate goods \((c_H \text{ and } c_F)\) in the following manner:

\[
C = \left[ \frac{1}{v} \frac{\theta + 1}{\alpha} c_H^{\frac{\theta + 1}{\alpha}} + (1 - v) \frac{1}{\alpha} c_F^{\frac{\theta + 1}{\alpha}} \right]^{\frac{\alpha}{\theta + 1}}
\]

where \(\theta\) is the elasticity of intratemporal substitution between home and foreign-produced intermediate goods. Final goods producers maximize (10) subject to (9).

\[
\max_{c_H, c_F} PC - P_H c_H - P_F c_F
\]

This maximization yields the following input demand functions for the home economy (similar conditions hold for Foreign producers)

\[
c_H = v \left( \frac{P_H}{P} \right)^{-\theta} C, \quad c_F = (1 - v) \left( \frac{P_F}{P} \right)^{-\theta} C
\]

The price index that corresponds to the previous demand function is defined as:

\[
P^{1-\theta} = [v P_H^{1-\theta} + (1 - v) P_F^{1-\theta}]^{\frac{\theta}{\theta + 1}}
\]
3.3 Investment goods sector

Similar to final consumption goods, investment goods \((x)\) are produced with the aid of home and foreign-produced intermediate goods \((x_H \text{ and } x_F)\) in the following manner:

\[
x = \left[ \varphi^\tau x_H + (1 - \varphi)^\tau x_F \right]^{1/\tau}
\]

Investment goods producers maximize (14) subject to (13).

\[
\max_{x_H, x_F} P_x x - P_H x_H - P_F x_F
\]

The investment goods producer’s maximization yields the following investment demand functions and price index:

\[
x_H = \varphi \left( \frac{P_H}{P_x} \right)^{-\tau} x, \quad x_F = (1 - \varphi) \left( \frac{P_F}{P_x} \right)^{-\tau} x
\]

\[
P^{1-\tau}_{x,t} = \left[ \varphi P^{1-\tau}_{H,t} + (1 - \varphi) P^{1-\tau}_{F,t} \right]
\]

The investment goods price index is a function of the price of home and foreign-produced intermediate goods prices. It differs from the consumption goods price index due to different substitution elasticities and different degrees of consumption and investment home biases. Specifically, \(\varphi\), the share of home-produced intermediate goods in the home final investment good can differ from \(v\), the share of home-produced intermediate goods in the final consumption good. Unlike in Greenwood, et al (2000) \(\frac{P_H}{P_x}\), the relative price of investment goods in terms of the consumption goods basket is an endogenous relative price that responds to exogenous shocks such as changes in total factor productivity (TFP) or investment specific technology shocks, \(\varepsilon^x_t\).

3.4 Intermediate goods sectors

Firms in the intermediate goods sector produce output, \(y_t\), that is used in the production of the final consumption and investment goods at home and abroad using capital and labour services employing the following constant returns to scale production function:

\[
y_t = A_t F(k_{t-1}, h_t)
\]

where \(A_t\) is total factor productivity. The cash flow of this typical firm in the intermediate goods producing sector is:

\[
\Pi_t = P_H A_t F(k_{t-1}, h_t) - P_t w_t h_t - P_{x,t} x_t
\]

where \(w\) is the real wage, \(P_H\) is the price of home-produced intermediate goods and \(P_t\) and \(P_{x,t}\) are the consumption and investment goods deflators, respectively. The firm faces the following capital accumulation constraint:

\[
k_t = (1 - \delta)k_{t-1} + \varepsilon^x_t F(x_t, x_{t-1})
\]
where $\delta$ is the rate of depreciation of the capital stock and $F(x_t, x_{t-1})$ captures investment adjustment costs as proposed by Christiano et al (2005), i.e. it summarizes the technology which transforms current and past investment into installed capital for use in the following period. Specifically, we assume that $F(x_t, x_{t-1}) = (1 - s(\frac{x_t}{x_{t-1}}))x_t$ and that the function $s$ has the following properties: $s(1) = s'(1) = 0$ and $s''(1) > 0$. Finally, $\varepsilon_t^x$ is a multiplicative shock to $F(x_t, x_{t-1})$ that increases (or decreases) the amount of installed capital available next period for any given value of current or past investment.

The firm maximizes shareholder’s value using the household’s intertemporal marginal rate of substitution as the stochastic discount factor. The maximization problem of the representative domestic intermediate goods firm is thus:

$$J = E_t \sum_{s=t}^{\infty} \beta^{s-t} \mu_s \left\{ \Pi_s \left( \frac{P_s}{P_t} \right) \right\} + E_t \sum_{s=t}^{\infty} \beta^{s-t} \lambda_s \left[ (1 - \delta)k_{s-1} + \varepsilon_t^x (1 - s(\frac{x_s}{x_{s-1}})))x_s - k_s \right]$$

The first-order conditions for the choice of labour input, investment and capital stock in period $t$ are:

$$\frac{\partial J_t}{\partial h_t} : \frac{P_{H,t}}{P_t} A_t F_h(k_{t-1}, h_t) - w = 0$$

$$\frac{\partial J_t}{\partial x_t} : q_t (1 - s(\frac{x_t}{x_{t-1}}))\varepsilon_t^x = q_t s'(\frac{x_t}{x_{t-1}}) \frac{x_t}{x_{t-1}} - \beta E_t q_{t+1} \frac{\mu_{t+1}}{\mu_t} s'(\frac{x_{t+1}}{x_t}) \frac{x_{t+1}}{x_t} + \frac{P_{x,t}}{P_t}$$

$$\frac{\partial J_t}{\partial k_t} : \beta E_t \frac{\mu_{t+1}}{\mu_t} \left( \frac{P_{H,t+1}}{P_{t+1}} A_t F_{k_t}(k_t, h_{t+1}) + q_{t+1} (1 - \delta) \right) = q_t$$

where we define Tobin’s q as: $q_t = \frac{\lambda_t}{\mu_t}$.

### 3.5 The relative price of investment goods

In this two-country model, the price of investment goods, relative to the price of consumption goods, $\frac{P_{x,t}}{P_t}$, is a function of the terms of trade. We can illustrate this by taking a log-linear approximation of the price index

$$\frac{P_{x,t}}{P_t} = \frac{P_{x,t}}{P_{H,t}} \frac{P_{H,t}}{P_t}$$
around its steady state value making use of the investment and consumption goods price indices.\footnote{We make use of the consumption and investment goods price indices and normalise the price of home-produced traded goods such that in the steady state \( P_H = P_F \). Because the law of one price holds, we can define the terms of trade as \( T = P_F / P_H \)}

\[
\frac{\tilde{P}_{x,t}}{P_t} = \frac{\tilde{P}_{x,t}}{\tilde{P}_{H,t}} + \frac{\tilde{P}_{H,t}}{P_t} = (1 - \varphi) \frac{\tilde{P}_{F,t}}{\tilde{P}_{H,t}} + (v - 1) \frac{\tilde{P}_{F,t}}{\tilde{P}_{H,t}} = (1 - \varphi) \hat{T}_t + (v - 1) \hat{T}_t = (v - \varphi) \hat{T}_t \tag{25}\n\]

This shows that the log-deviation of the price of investment goods from its steady state value is a linear function of the log-deviation of the terms of trade from its steady state value. If home-bias for investment goods is stronger (weaker) than for consumption goods \( v < \varphi \) (\( v > \varphi \)) then the price of investment goods is negatively (positively) related to the terms of trade.

### 3.6 Tobin’s q and the Relative Price of Capital

In this section, we analyse the link between Tobin’s q and the relative price of investment goods. Taking a log-linear approximation of the first-order condition of the intermediate goods firm (22) yields the following relationship between deviations in Tobin’s q and the relative price of investment goods:

\[
\hat{q}_t = [(1 + \beta)s''(\hat{x}_t - s''(\hat{x}_{t-1} - s''(\hat{x}_{t+1} - \tilde{\varepsilon}_t + \frac{\tilde{P}_{x,t}}{\tilde{P}_t}) \right)\tag{26}\n\]

Alternatively, if we abstract from adjustment costs, i.e. if \( s''(\hat{x}_t) = 0 \)

\[
\hat{q}_t = -\tilde{\varepsilon}_t + \frac{\tilde{P}_{x,t}}{\tilde{P}_t} = -\tilde{\varepsilon}_t + (v - \varphi) \hat{T}_t \tag{27}\n\]

From equation (27), it is easy to see that if we do not allow for a separate investment goods sector, or if the share of home produced intermediate goods is the same in investment than in consumption then the relative price of capital is unity and therefore, the Tobin’s q is just the reciprocal of the investment shock \( \tilde{\varepsilon}_t \). In the present context, the investment shock \( \tilde{\varepsilon}_t \) drives a wedge between Tobin’s q and the relative price of capital. Therefore we can refer to our investment shock as an investment friction. Even in the absence of any adjustment cost, Tobin’s q may not necessarily be the inverse of the investment shock \( \tilde{\varepsilon}_t \). The reason is that a positive investment shock may increase the demand for investment goods thus driving up the the relative price of investment goods, partially offsetting the the negative effect on \( q \).
Two special cases deserve attention: (i) One sector closed economy case: Here $v = \varphi = 1$. In this case using (12) and (16) one can immediately verify that $P = P_x$. In other words, the relative price of investment goods is unity. In this case, Tobin’s $q$ varies inversely with the investment friction shock $\varepsilon^*_t$. (ii) Same home-bias in consumption as in investment case: Here $v = \varphi$. This is still a two sector scenario but the Tobin’s $q$ varies inversely with the investment friction shock. Chari et al. (2005), Greenwood et al. (2000) and Fisher (2005) basically refer to the first special case of our model. In an open economy context, the Tobin’s $q$ is not just the reciprocal of the investment friction shock. It is related to the function of the terms of trade which depend not only on the investment shock $\varepsilon^*_t$ but also on the TFP shock $A_t$.

3.7 Monetary policy

Since we are characterizing a nominal model we need to specify a monetary policy rule. In what follows we simply assume that the monetary authorities in both countries follow a strategy of setting producer price inflation equal to zero.

3.8 Market Equilibrium

The solution to our model satisfies the following market equilibrium conditions must hold for the home and foreign country:

1. Home-produced intermediate goods market clears:

$$y_t = c_{H_t} + c^*_{H_t} + x_{H_t} + x^*_{H_t}$$

2. Foreign-produced intermediate goods market clears:

$$y^*_t = c_{F_t} + c^*_{F_t} + x_{F_t} + x^*_{F_t}$$

3. Bond Market clears:

$$\frac{S_t B_{F,t}}{P_t (1 + i^*_t) \Theta \left( \frac{S_t B_{F,t}}{P_t} \right)} - \frac{S_t B_{F,t-1}}{P_t} = \frac{P_{H,t}}{P_t} \left( c^*_{H,t} + x^*_{H,t} \right) - \frac{P_{F,t}}{P_t} \left( c_{F,t} + x_{F,t} \right)$$

3.9 Solution technique

Before solving our model, we log-linearize around the steady state to obtain a set of equations describing the equilibrium fluctuations of the model. The log-linearization yields a system of linear difference equations which can be expressed as a singular dynamic system of the following form:

$$A_{E_t} y(t + 1 | t) = B y(t) + C x(t)$$
where $y(t)$ is ordered so that the non-predetermined variables appear first and the predetermined variables appear last, and $x(t)$ is a martingale difference sequence. There are four shocks in $C$: shocks to the home intermediate goods sectors’ productivity, shocks to the foreign intermediate goods sectors’ productivity, and shocks to home and foreign investment frictions. The variance-covariance as well as the autocorrelation matrices associated with these shocks are described in table 1. Given the parameters of the model, which we describe in the next section, we solve this system using the King and Watson (1998) solution algorithm. The linearized equations of the model are listed in the appendix.

4 Calibration

In this Section, we outline our baseline calibration. Our calibration assumes that countries Home and Foreign are of the same size, and that both countries are symmetric in terms of their deep structural parameters. For our calibration, we specify the following functional form for the utility function:

$$U_t = E_t \sum_{s=t}^{\infty} \beta^{s-t} \left[ \frac{(C_j)^{1-\rho}}{1-\rho} + \chi \frac{(1-h_j)^{1-\eta}}{1-\eta} \right]$$

where $\beta$ is the subjective discount factor, $\rho$ and $\eta$ are the constant relative risk aversion parameters (inverse of the intertemporal elasticity of substitution) associated with work and leisure, respectively. For our baseline calibration, we assume moderate amounts of consumption home-bias, $v = (1 - v^*) = 0.75$ and complete specialization in the production of the final investment good, $\varphi = (1 - \varphi^*) = 1$. In our sensitivity analysis below, we allow $\varphi$ to differ from unity. The intratemporal elasticity of substitution between home and foreign-produced intermediate goods in consumption, $\theta$, is set to 2, whereas $\tau$, the intertemporal elasticity of substitution between home and foreign intermediate goods in investment goods is set to 1. As is common in the literature, we set the share of labour in production to 0.64 and assume a 2.5% depreciation rate of capital per quarter. Following Benigno, P. (2001), we introduce a bond holding cost to eliminate the otherwise arising unit root in foreign bond holdings. This cost can be very small, and thus we choose a 10 basis point spread of the domestic interest rate on foreign assets over the foreign rate, such that $\varepsilon \equiv -\Theta'(b)C = 0.001$. The curvature of the investment adjustment cost function $s''(.)$ is set so as to allow the calibrated model to match the relative volatility of investment to GDP.

The stochastic processes for total factor productivity and investment specific technological change are taken from Boileau (2002), whose model structure is similar to ours. Specifically, the stochastic process for TFP is taken from the seminal work of Backus et al (1994) on international real business cycles. The investment specific productivity shock calculated by Boileau (2002) is price based and calculated using G7 data on the relative price of a new unit of equipment relative to final goods output. The home country in this calibration is assumed to be the United States. Matrix $V[\mu]$ in table 1 above shows the variance-covariance matrix of our shock processes, and
Table 1: Baseline calibration

| Preferences | $\beta = 1/1.01, \rho = 1, \eta = 0.25, \bar{h} = 1/3, \gamma = 0$ |
| Final goods tech | $v = (1 - v^*) = 0.75, \theta = 2, \tau = 1, \varphi = (1 - \varphi^*) = 1$ |
| Intermediate goods tech | $\alpha = 0.64, \delta = 0.025, s''(.) = 0.5, \phi''(.) = -7.5$ |
| Financial markets | $\varepsilon = 0.001$ |

| Shocks | $\Omega = \begin{bmatrix} 0.906 & 0.088 & 0 & 0 \\ 0.088 & 0.906 & 0 & 0 \\ 0 & 0 & 0.553 & 0.027 \\ 0 & 0 & 0.027 & 0.553 \end{bmatrix}$ |

$V[\mu] = 10^{-4} \begin{bmatrix} 0.726 & 0.187 & 0 & 0 \\ 0.187 & 0.726 & 0 & 0 \\ 0 & 0 & 1.687 & 0.582 \\ 0 & 0 & 0.582 & 1.687 \end{bmatrix}$

matrix $\Omega$ their first-order autocorrelation coefficients. The upper left hand quadrant of matrices $V[\mu]$ and $\Omega$ contain the TFP shocks, while the lower right hand quadrant contain the investment specific technology shocks.

5 Impulse Response Analysis

Having described the model and its calibration, we now proceed to use impulse response analysis to examine the effect of investment specific technology (IST) shocks and total factor productivity (TFP) shocks on investment, its relative price, the terms of trade and Tobin’s q. Figure 1 shows the response of the model economy to a unit IST shock. For this shock, we observe that the investment rate and the relative price of investment goods are positively correlated. An investment specific shock is initially similar to a demand shock. Such a shock increases demand for investment goods without, initially at least, increasing the output capacity of the economy. In order for the market for home-produced investment goods to clear following a domestic investment shock, resources must be diverted from domestic and foreign consumers to domestic producers of intermediate goods. To achieve this reallocation of resources, the relative price of investment goods must rise. In our baseline calibration, the share of home-produced investment goods in final investment goods spending exceeds the share of home-produced consumption goods in final consumption goods spending, i.e. $v < \varphi$. Therefore, the relative price of investment goods is a negative function of the terms of

\footnote{For our impulse response analysis, we ignore the cross-country spillovers present in the shock processess.}
trade. A rise in the price of investment goods is thus associated with a decline, or appreciation, of the terms of trade. An appreciation of the terms of trade transfers purchasing power from the foreign to the home consumer. This reduces the demand for home-produced intermediate goods coming from foreign consumers. Within the home economy, an appreciation of the terms of trade also shifts demand away from home to foreign-produced goods. Both of these re-allocations of resources allow the producers of investment goods to meet the increased demand from the home intermediate goods sector.

A unit total factor productivity shock, on the other hand, induce a negative correlation between the investment rate and the relative price of investment goods, as figure 2 illustrates. In order for the market for home-produced intermediate goods to clear their relative price must fall which causes the terms of trade to depreciate. This depreciation leads to a positive wealth effect abroad, raising foreign demand for home-produced intermediate goods. Since, for this calibration, the relative price of investment goods is a negative function of the terms of trade, the relative price falls.

[Figures 2 and 3 here]

Our impulse response analysis suggests that in our model, where we have explicitly modelled the relative price of investment goods, a shock that exogenously increases the amount of installed capital available next period for any given value of current or past investment, will raise investment along with its relative price. Our analysis suggest that the observed negative correlation between investment and its relative price comes about through TFP shocks. In the next section, we examine a selection of second moments generated by our model economy when driven by IST and TFP shocks.

6 Second Moments

Following our impulse response analysis, we now analyse a selection of second moments generated by our calibrated model. The purpose of this section is to analyse if IST shocks can help our international real business cycle model match some of the salient features of the international business cycle. Our selected second moments presented in table 2 are constructed using actual data, as well as artificial model economy data. Both data are of quarterly frequency, logged and Hodrick-Prescott filtered with a smoothing parameter set to 1600. The sample period for the data is 1960:1 - 2003:4. We refer the reader to the appendix for details of data sources.

The key finding of our impulse response analysis is reflected in the second moments generated by our model, as reported in table 2. Investment specific technology shocks (column 4) induce a positive correlation between the relative price of investment and the investment output ratio. TFP shocks (column 5), on the other hand, induce a strong negative correlation between the investment ratio and its relative price. When our model is driven by both types of shocks (column 3), the correlation is small but positive.
Table 2: Second moments: baseline model

<table>
<thead>
<tr>
<th>Correlations</th>
<th>Data</th>
<th>Model both shocks</th>
<th>Model IST shocks</th>
<th>Model TFP shocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corr((\frac{P_x}{P_y}), (\frac{z}{y}))</td>
<td>-0.25</td>
<td>0.12</td>
<td>0.58</td>
<td>-0.33</td>
</tr>
<tr>
<td>Corr(c, y)</td>
<td>0.84</td>
<td>0.56</td>
<td>-0.85</td>
<td>0.86</td>
</tr>
<tr>
<td>Corr(x, y)</td>
<td>0.89</td>
<td>0.86</td>
<td>0.97</td>
<td>0.95</td>
</tr>
<tr>
<td>Corr(h, y)</td>
<td>0.88</td>
<td>0.81</td>
<td>0.98</td>
<td>0.91</td>
</tr>
<tr>
<td>Corr(w, y)</td>
<td>0.26</td>
<td>0.69</td>
<td>-0.78</td>
<td>0.90</td>
</tr>
<tr>
<td>Corr(t, y)</td>
<td>-0.50</td>
<td>0.35</td>
<td>-0.42</td>
<td>0.56</td>
</tr>
<tr>
<td>Corr((\frac{w}{c}), y)</td>
<td>-0.42</td>
<td>0.30</td>
<td>-0.43</td>
<td>0.54</td>
</tr>
<tr>
<td>Corr(c, c*)</td>
<td>0.51</td>
<td>0.83</td>
<td>0.86</td>
<td>0.82</td>
</tr>
<tr>
<td>Corr(y, y*)</td>
<td>0.66</td>
<td>0.18</td>
<td>0.51</td>
<td>0.13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Standard deviations</th>
<th>(\sigma_y)</th>
<th>(\sigma_c/\sigma_y)</th>
<th>(\sigma_x/\sigma_y)</th>
<th>(\sigma_t/\sigma_y)</th>
<th>(\sigma_{rs}/\sigma_y)</th>
<th>(\sigma_{ca}/\sigma_y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>1.57</td>
<td>0.78</td>
<td>3.18</td>
<td>1.71</td>
<td>3.04</td>
<td>0.22</td>
</tr>
<tr>
<td>Model both shocks</td>
<td>1.57</td>
<td>0.53</td>
<td>3.18</td>
<td>0.50</td>
<td>0.25</td>
<td>0.17</td>
</tr>
<tr>
<td>Model IST shocks</td>
<td>0.56</td>
<td>0.71</td>
<td>6.43</td>
<td>0.79</td>
<td>0.39</td>
<td>0.30</td>
</tr>
<tr>
<td>Model TFP shocks</td>
<td>1.47</td>
<td>0.50</td>
<td>2.36</td>
<td>0.44</td>
<td>0.22</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Notation: \(P_x\)=relative price of investment goods, \(x\)=investment, \(c\)=consumption, \(y\)=GDP, \(h\)=hours worked, \(w\)=real wage, \(t\)=terms of trade, \(ca\)=current account, \(rs\)=real exchange rate

Column 3 shows our selection of second moments generated by our model when driven by both IST and TFP shocks. This model matches the standard deviation of GDP, \(\sigma_y\), and investment, \(\sigma_x/\sigma_y\), (the latter by choice of adjustment cost parameter), but in common with this type of model, fails to match the standard deviation of the terms of trade and the real exchange rate relative to GDP (\(\sigma_t/\sigma_y\) and \(\sigma_{rs}/\sigma_y\)). As is common with this type of international business cycle model, our model driven by both shocks generates a pro-cyclical current account and suggests that consumption is more highly correlated across countries than is GDP, both of these features are at odds with the data.

When we solve the model for the case where IST shocks are the only source of variation (column 4), we find GDP in our model is about 1/3 as volatile as the data, a finding that corresponds to the results of Greenwood et al (2002), whereas investment is more than twice as volatile as the data. The relative volatility of the terms of trade is still below the value suggested in the data, but almost twice as volatile than in the model driven only by TFP shocks. This version of the model departs from the data in terms of the cross-correlations between consumption and GDP and the real wage.
and GDP. In both cases, the model predicts negative correlations. Counter-cyclical consumption following IST shocks is also noted in Boileau (2002) in a two-country model and Ejarque (1999), who for a closed economy suggests that this feature could be overcome by introducing variable capital utilization. Where IST shocks help bring the model closer to the data is the correlation between home and foreign GDP. This correlation is higher than in the model with TFP shocks, but still less than the cross-country correlation between home and foreign consumption. Unlike TFP shocks, IST shocks also generate a counter-cyclical current account.

7 Sensitivity Analysis

In this section we analyse how changing the share of home-produced intermediate goods in final investment goods, \( \phi \) affects our key finding that IST shocks induce a positive correlation between investment and its relative price. When \( \phi > \psi \) as in our baseline calibration, the relative price of investment is a negative function of the terms of trade. In this case, a rise in the relative price of investment goods is associated with an appreciation of the terms of trade. When \( \phi < \psi \), i.e. when producers of final investment goods display less home-bias than producers of final consumption goods, then the relative price of investment goods becomes a positive function of the terms of trade. Does this change to our baseline calibration change our results?

\[
\frac{\bar{P}_{x,t}}{P_t} = (v - \phi)\bar{T}_t
\]

In figures 4 and 5, we analyse impulse response functions for IST and TFP shocks for the case where \( \phi = 0.5 \), with the remainder of the deep parameters remaining unchanged. Following an IST shock, we find that as in the previous case, investment rises, as does its relative price, but to a smaller extent. Since the relative price of investment goods is now a positive function of terms of trade, we observe a terms of trade depreciation. The terms of trade depreciate (rises) because the IST shock raises demand for final investment goods relative to final consumption goods. Since \( \psi < \phi \), the final investment good contains a higher proportion of foreign-produced intermediate goods than does the final consumption good. Market clearing requires the relative price of foreign-produced intermediate goods, the terms of trade, to rise. Figure 4 suggests that for this calibration the terms of trade depreciation is prolonged and ‘hump’ shaped. Figure 5 shows the response of the model to a unit TFP shock. In this case, the terms of trade depreciate, as in our baseline model, but the relative price of investment goods now rises. This rise is again attributed to the greater share of foreign-produced intermediate goods investment than in consumption goods.

Next, we examine if any of our findings are driven by our choice of the investment adjustment cost function. In the appendix, we report the selected second moments for our model when adjustment costs take the more conventional form:

\[
k_t = (1 - \delta)k_{t-1} + \varepsilon_t^x\phi(\frac{x_t}{k_{t-1}})k_{t-1}
\]

15
We find that our results are robust to changes in the specification of adjustment costs.

In summary, our impulse responses suggest that when $\varphi = 0.5$ the relative price of investment is positively correlated with investment for both IST and TFP shocks. Setting $v > \varphi$ implies that the relative price of investment goods becomes a positive function of the terms of trade, but this change in our model also changes the response of the terms of trade to IST shocks. Instead of appreciating, as in our baseline model, the terms of trade now depreciate following a shock to home country IST. We also examined the effect of different adjustment cost specifications and found our results to be robust. Having found that our result that IST shocks cause the relative price of investment goods to rise is relatively robust, we now proceed to put forward an alternative way to model investment specific technological progress that results in a negative correlation between investment and its relative price.

[Figures 4 and 5 here]

8 An alternative model

In this section, we explore the characteristics of our model if we introduce investment specific technical progress, not as a shock to the capital accumulation equation (19), but as a shock the production function of investment goods (13). Specifically, we assume the following production function for investment goods:

$$x_t = \varepsilon_t^x \left[ \varphi H x_t^{r-1} + (1 - \varphi) F x_t^{r-1} \right]^{\frac{r}{r-1}}$$

(28)

Whereas in our original specification, an investment specific shock raises the amount of capital stock that is accumulated for a given level of investment, this specification assumes that the shock raises the amount of final investment goods that is obtained from a given amount of intermediate inputs. Whereas in the initial model the investment shock behaves like a demand shock, in this case the investment shock affects the model like a supply shock. A positive IST shock will now free up intermediate goods for consumption. The supply of investment goods will rise following a positive shock and therefore, to clear the market for investment goods, the relative price of investment goods will decline as investment rises, resulting in a negative correlation between investment and its relative price.

We can see from the linearized $q$ equation that an investment specific TFP shock does not enter the expression for Tobin’s $q$, so the shock does not drive a wedge between Tobin’s $q$ and the relative price of investment goods, and as such should not be interpreted as a shock to investment frictions.

$$\dot{q}_t = \left[ (1 + \beta) s''(\hat{x}_t - s''(\hat{x}_{t-1} - s''(\hat{x}_{t-1}) \beta \hat{x}_{t+1} + \frac{P_{x,t}}{P_t}) \right]$$

(29)
Without adjustment costs, we see the direct relationship between Tobins’ q and the relative price of investment goods (linearized).

\[ \hat{q}_t = \frac{\bar{P}_{x,t}}{P_t} \]  

(30)

In table 3, we use the calibration of our baseline model to illustrate the second moments generated by our alternative model.\(^6\)

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>Alt. Model both shocks</th>
<th>Alt. Model IST shocks</th>
<th>Alt. Model TFP shocks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Correlations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{Corr}(\frac{P_{x,t}}{P_t}, \hat{z}_y) )</td>
<td>-0.25</td>
<td>-0.33</td>
<td>-0.42</td>
<td>-0.33</td>
</tr>
<tr>
<td>( \text{Corr}(c, y) )</td>
<td>0.86</td>
<td>0.83</td>
<td>-0.96</td>
<td>0.86</td>
</tr>
<tr>
<td>( \text{Corr}(x, y) )</td>
<td>0.89</td>
<td>0.93</td>
<td>-0.70</td>
<td>0.95</td>
</tr>
<tr>
<td>( \text{Corr}(h, y) )</td>
<td>0.88</td>
<td>0.89</td>
<td>0.99</td>
<td>0.91</td>
</tr>
<tr>
<td>( \text{Corr}(w, y) )</td>
<td>0.26</td>
<td>0.88</td>
<td>-0.93</td>
<td>0.90</td>
</tr>
<tr>
<td>( \text{Corr}(t, y) )</td>
<td>-0.50</td>
<td>0.54</td>
<td>-0.50</td>
<td>0.56</td>
</tr>
<tr>
<td>( \text{Corr}(\bar{w}, y) )</td>
<td>-0.42</td>
<td>0.51</td>
<td>-0.50</td>
<td>0.54</td>
</tr>
<tr>
<td>( \text{Corr}(c, c^*) )</td>
<td>0.51</td>
<td>0.82</td>
<td>0.83</td>
<td>0.82</td>
</tr>
<tr>
<td>( \text{Corr}(y, y^*) )</td>
<td>0.66</td>
<td>0.13</td>
<td>0.50</td>
<td>0.13</td>
</tr>
<tr>
<td><strong>Standard Deviations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \sigma_y )</td>
<td>1.57</td>
<td>1.48</td>
<td>0.17</td>
<td>1.47</td>
</tr>
<tr>
<td>( \sigma_c / \sigma_y )</td>
<td>0.78</td>
<td>0.50</td>
<td>0.65</td>
<td>0.50</td>
</tr>
<tr>
<td>( \sigma_x / \sigma_y )</td>
<td>3.18</td>
<td>2.36</td>
<td>2.30</td>
<td>2.36</td>
</tr>
<tr>
<td>( \sigma_t / \sigma_y )</td>
<td>1.71</td>
<td>0.44</td>
<td>0.69</td>
<td>0.44</td>
</tr>
<tr>
<td>( \sigma_{rs} / \sigma_y )</td>
<td>3.04</td>
<td>0.22</td>
<td>0.34</td>
<td>0.22</td>
</tr>
<tr>
<td>( \sigma_{ca} / \sigma_y )</td>
<td>0.22</td>
<td>0.15</td>
<td>0.25</td>
<td>0.15</td>
</tr>
</tbody>
</table>

When the model is driven by only investment specific TFP (column 4), the correlation between the investment to GDP ratio and the relative price of investment is negative. On the other hand, the model predicts a number of counterfactual correlations. Notably, both consumption and investment are negatively correlated with intermediate goods production. An investment specific TFP shock raises investment and consumption, but lowers output of the intermediate goods sector (actual investment rises by less than the shock, so the amount of intermediate goods demanded by the investment goods sector declines), thus consumption and investment are negatively correlated with intermediate goods production. When the model is driven by both TFP and investment specific

\(^6\)Note that for a meaningful interpretation of the second moments we ought to calculate investment specific TFP shocks - as a result these moments should be taken only as a guide to how this model performs under investment specific TFP shocks.
TFP shocks, the model behaves qualitatively similar to our baseline model with investment friction shocks.

9 Empirical evidence

A key prediction of our open economy model is that the observed negative correlation between the investment to GDP ratio and the relative price of investment goods is driven primarily by the TFP shock not by the IST shock. In fact, a pure IST shock gives rise to a positive correlation between the investment rate and the relative price of capital. In this section, we look for empirical evidence for these results. Given the reservations regarding price based measures of IST that our work raises, we propose to construct an alternative measure of IST shocks. Based on (19) we use a simple linear depreciation rule (ignoring adjustment cost) as follows:

\[ \varepsilon_t = \frac{k_t - (1 - \delta)k_{t-1}}{x_t} \] (31)

Using quarterly data for capital stock and investment and assuming a 2.5% quarterly rate of depreciation of the capital stock, we generate a series for this IST shock, \( \varepsilon_t \) over the sample period 1980:1-2003:4. Figure 6 plots the log of both series. Our measure of IST shows significant volatility as opposed to TFP. The IST series shows a decline starting from mid 1980s and then a remarkable growth starting from the early 1990s which approximately coincides with the information technology revolution phase.

Tables 4 and 5 present the correlation matrices for the log Hodrick-Prescott filtered series for TFP, IST, and the relative price of investment goods and the investment to GDP ratio for two sample periods, 1980:1-2003:4 and 1990:1-2003:4. The correlations between the cyclical components of TFP and the relative price of investment goods are -0.33 and -0.31, for the two sample periods, respectively, while the correlation between TFP and the investment to GDP ratio are 0.29 and 0.4. The picture is different when one looks at the correlation matrix for the cyclical components of IST, relative price of investment goods, and the investment to GDP ratio. The correlation between IST and the relative price of investment goods is 0.09 and 0.15 for the two respective periods.

Tables 6 and 7 report least squares regressions of the relative price of investment goods as well as the investment to GDP ratio on TFP and IST. These regressions show the individual effects of these two technology shocks on the relevant endogenous variables. A positive TFP shock impacts the relative price of capital negatively and investment to GDP ratio positively. Both effects are significant at the 5% level. On the other hand, a IST shock impacts both relative price of investment goods and investment to GDP ratio positively but the effects are insignificant at the 5% level for both sample periods. These results are consistent with our theoretical prediction that the negative correlation between investment and the relative price of investment goods is driven primarily by the TFP shocks and not by IST shock.
Table 4: Empirical correlations: 1980:1 to 2003:4

<table>
<thead>
<tr>
<th></th>
<th>$\ln \varepsilon_t^2$</th>
<th>$\ln A_t$</th>
<th>$\ln (P_{x/P})$</th>
<th>$\ln (x/y)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ln \varepsilon_t^2$</td>
<td>1.00</td>
<td>-0.01</td>
<td>0.09</td>
<td>0.10</td>
</tr>
<tr>
<td>$\ln A_t$</td>
<td>-0.01</td>
<td>1.00</td>
<td>-0.33</td>
<td>0.29</td>
</tr>
<tr>
<td>$\ln (P_{x/P})$</td>
<td>0.09</td>
<td>-0.33</td>
<td>1.00</td>
<td>-0.22</td>
</tr>
<tr>
<td>$\ln (x/y)$</td>
<td>0.10</td>
<td>0.29</td>
<td>-0.22</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Table 5: Empirical correlations: 1990:1 to 2003:4

<table>
<thead>
<tr>
<th></th>
<th>$\ln \varepsilon_t^2$</th>
<th>$\ln A_t$</th>
<th>$\ln (P_{x/P})$</th>
<th>$\ln (x/y)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ln \varepsilon_t^2$</td>
<td>1.00</td>
<td>0.11</td>
<td>0.15</td>
<td>0.23</td>
</tr>
<tr>
<td>$\ln A_t$</td>
<td>0.11</td>
<td>1.00</td>
<td>-0.31</td>
<td>0.40</td>
</tr>
<tr>
<td>$\ln (P_{x/P})$</td>
<td>0.15</td>
<td>-0.31</td>
<td>1.00</td>
<td>-0.12</td>
</tr>
<tr>
<td>$\ln (x/y)$</td>
<td>0.23</td>
<td>0.40</td>
<td>-0.12</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Table 6: LS regression of relative price of investment goods

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>constant</td>
<td>-0.000473</td>
<td>0.000612</td>
</tr>
<tr>
<td>Std Error</td>
<td>0.000814</td>
<td>0.001032</td>
</tr>
<tr>
<td>( \ln x_t )</td>
<td>0.006518</td>
<td>0.009068</td>
</tr>
<tr>
<td>Std Error</td>
<td>0.00714</td>
<td>0.006231</td>
</tr>
<tr>
<td>( \ln A_t )</td>
<td>-0.281856*</td>
<td>-0.309945*</td>
</tr>
<tr>
<td>Std Error</td>
<td>0.08478</td>
<td>0.122666</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.114079</td>
<td>0.128306</td>
</tr>
</tbody>
</table>

Note: an asterix (*) denotes significance at the 5% level

Table 7: LS regression of the investment to GDP ratio

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>constant</td>
<td>-0.003277</td>
<td>0.00000</td>
</tr>
<tr>
<td>Std Error</td>
<td>0.00307</td>
<td>0.003276</td>
</tr>
<tr>
<td>( \ln x_t )</td>
<td>0.028895</td>
<td>0.030894</td>
</tr>
<tr>
<td>Std Error</td>
<td>0.026925</td>
<td>0.019777</td>
</tr>
<tr>
<td>( \ln A_t )</td>
<td>0.94908*</td>
<td>1.194032*</td>
</tr>
<tr>
<td>Std Error</td>
<td>0.319701</td>
<td>0.389349</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.095993</td>
<td>0.1973</td>
</tr>
</tbody>
</table>

Note: an asterix (*) denotes significance at the 5% level

10 Conclusion

The central message of this paper is that in an open economy context, the relative price of investment goods is a misleading proxy for investment friction. Our calibrated model suggests that a lower investment friction identified by a positive shock to the investment technology instead of lowering the relative price of investment goods actually raises it. This gives rise to the question: What really explains the observed decline in the relative price of investment goods during the 1980s? Our theoretical and empirical impulse responses point to the fact that this decline is driven by a positive...
TFP shock which lowers the relative price of investment goods. In our model, the relative price of investment goods, being essentially the relative price of two internationally tradable goods baskets, is a linear function of the terms of trade. A shock that causes the terms of trade to depreciate is associated with a decline in the relative price of investment goods. Thus if one seriously wants to investigate the main driver of technological change during the 1980s, our open economy model suggests that it is indeed the TFP boom not investment boom alluded by some recent authors.

References


A Quadratic adjustment costs

In this appendix, we show that our results are robust to changes in the specification of investment adjustment costs. If adjustment costs take on the following form:

\[ k_t = (1 - \delta)k_{t-1} + \varepsilon_t^i \phi\left(\frac{x_t}{k_{t-1}}\right)k_{t-1} \]

where we make the usual assumption that in the steady state \( \phi\left(\frac{x}{k}\right) = \frac{x}{k} = \delta, \phi'(\frac{x}{k}) = 1 \) and \( \phi''(\frac{x}{k}) < 0 \), then repeating our calibration exercise above, we find the following:

\[ \hat{q}_t = E_t \hat{q}_{t+1} (1 - \delta) + E_t \mu_{t+1} - \hat{\mu}_t + (v - 1) E_t \delta T_{t+1} (1 - \beta (1 - \delta)) + E_t \delta \beta \phi''(\delta) (\delta - 1) \]

\[ \hat{q}_t + \varepsilon_t^i + \hat{x}_t \phi''(\delta) - \hat{k}_{t-1} \phi''(\delta) = (v - \varphi) \hat{T}_t \]

The second moments generated by this model are reported in table 4. We find the same pattern of correlations and relative volatilities as in the baseline model.
Table 8: Second moments: model with quadratic adjustment costs

<table>
<thead>
<tr>
<th>Correlations</th>
<th>Data</th>
<th>Model both shocks</th>
<th>Model IST shocks</th>
<th>Model TFP shocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corr((\frac{P_x}{P_y}, \frac{y}{x}))</td>
<td>-0.25</td>
<td>0.11</td>
<td>0.61</td>
<td>-0.58</td>
</tr>
<tr>
<td>Corr(c, y)</td>
<td>0.86</td>
<td>0.54</td>
<td>-0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Corr(x, y)</td>
<td>0.89</td>
<td>0.83</td>
<td>0.98</td>
<td>0.99</td>
</tr>
<tr>
<td>Corr(h, y)</td>
<td>0.88</td>
<td>0.77</td>
<td>0.98</td>
<td>0.94</td>
</tr>
<tr>
<td>Corr(w, y)</td>
<td>0.26</td>
<td>0.66</td>
<td>-0.84</td>
<td>0.93</td>
</tr>
<tr>
<td>Corr(t, y)</td>
<td>-0.50</td>
<td>0.37</td>
<td>-0.47</td>
<td>0.67</td>
</tr>
<tr>
<td>Corr((\frac{w}{y}), y)</td>
<td>-0.42</td>
<td>0.33</td>
<td>-0.47</td>
<td>0.67</td>
</tr>
<tr>
<td>Corr(c, c*)</td>
<td>0.51</td>
<td>0.83</td>
<td>0.85</td>
<td>0.82</td>
</tr>
<tr>
<td>Corr(y, y*)</td>
<td>0.66</td>
<td>0.17</td>
<td>0.49</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Standard Deviations

- \(\sigma_y\): 1.57, 1.54, 0.62, 1.41
- \(\sigma_c / \sigma_y\): 0.78, 0.53, 0.74, 0.55
- \(\sigma_x / \sigma_y\): 3.18, 3.19, 6.66, 1.90
- \(\sigma_t / \sigma_y\): 1.71, 0.56, 0.85, 0.48
- \(\sigma_{rs} / \sigma_y\): 3.04, 0.28, 0.42, 0.24
- \(\sigma_{ca} / \sigma_y\): 0.22, 0.20, 0.32, 0.16

B Log-linearized model

Home and foreign marginal utilities of consumption

\[-\rho \frac{1}{1 - \gamma} \hat{C}_t + \rho \frac{\gamma}{1 - \gamma} C_{t-1} = \hat{\mu}_t \]  
\[-\rho \frac{1}{1 - \gamma} C_{t}^* + \rho \frac{\gamma}{1 - \gamma} C_{t-1}^* = \hat{\mu}_t^* \]  

Euler equations for home and foreign bonds

\[\hat{\mu}_t = \hat{\mu}_{t+1} + \hat{\pi}_t - \hat{E}_t \pi_{t+1} \]  
\[\hat{\mu}_t^* = \hat{\mu}_{t+1}^* + \hat{\pi}_t^* - \hat{E}_t \pi_{t+1}^* \]

Euler equations for home and foreign labour supply

\[\hat{\pi}_t \frac{l}{(1 - l)} \eta = \hat{\mu}_t + \hat{\omega}_t \]
\[
\tilde{I}_t^* \frac{l^*}{(1 - l^*)} \eta = \tilde{\mu}_t^* + \tilde{w}_t^* \quad \text{(A6)}
\]

UIP condition
\[
E_t \Delta s_t+1 = \tilde{i}_t - \tilde{i}_t^* + \varsigma \dot{b}_t \quad \text{(A7)}
\]

Current account equation
\[
\beta \dot{b}_t - \dot{b}_{t-1} = (1 - \nu) \left( (\theta - 1) \tilde{T}_t + \theta \tilde{R}S_t - \tilde{C}_t + \tilde{C}_t^* \right) \quad \text{(A8)}
\]

Home and Foreign q equations
\[
\dot{q}_t = \dot{q}_{t+1}^* \beta (1 - \delta) + \dot{\mu}_{t+1} - \dot{\mu}_t + (v - 1) \tilde{T}_{t+1} (1 - \beta (1 - \delta)) + \tilde{\rho}_{t+1} (1 - \beta (1 - \delta)) \quad \text{(A9)}
\]
\[
\dot{q}_t^* = \dot{q}_{t+1}^* \beta (1 - \delta) + \dot{\mu}_{t+1}^* - \dot{\mu}_t^* + (v^* \tilde{T}_{t+1} - \tilde{R}S_{t+1}) (1 - \beta (1 - \delta)) + \tilde{\rho}_{t+1}^* (1 - \beta (1 - \delta)) \quad \text{(A10)}
\]

Home and Foreign MPK equations
\[
\dot{\rho}_t = \dot{A}_t - \alpha \dot{k}_{t-1} + \alpha \hat{l}_t \quad \text{(A11)}
\]
\[
\dot{\rho}_t^* = \dot{A}_t^* - \alpha \dot{k}_{t-1}^* + \alpha \hat{l}_t^* \quad \text{(A12)}
\]

Optimal capital accumulation equations
\[
\frac{\dot{q}_t}{(1 + \beta) s''} + \frac{\hat{\tilde{z}}_t^i}{(1 + \beta) s''} + \frac{1}{(1 + \beta)} \hat{x}_{t-1} + \frac{\beta}{(1 + \beta)} \hat{x}_{t+1} - (v - \varphi) \tilde{T}_t \frac{1}{(1 + \beta) s''} = \hat{x}_t \quad \text{(A13)}
\]
\[
\frac{\dot{q}_t^*}{(1 + \beta) s''} + \frac{\hat{\tilde{z}}_t^i}{(1 + \beta) s''} + \frac{1}{(1 + \beta)} \hat{x}_{t-1}^* + \frac{\beta}{(1 + \beta)} \hat{x}_{t+1}^* - (v^* - \varphi^*) \tilde{T}_t \frac{1}{(1 + \beta) s''} = \hat{x}_t^* \quad \text{(A14)}
\]

Home and Foreign MPL equations
\[
(v - 1) \tilde{T}_t + \dot{A}_t + (\alpha - 1) \hat{l}_t + (1 - \alpha) \dot{k}_{t-1} = \dot{w}_t \quad \text{(A15)}
\]
\[
v \tilde{T}_t - \tilde{R}S_t + \dot{A}_t^* + (\alpha - 1) \hat{l}_t^* + (1 - \alpha) \dot{k}_{t-1}^* = \dot{w}_t^* \quad \text{(A16)}
\]

Home and Foreign capital accumulation constraints
\[
\dot{k}_t = \dot{k}_{t-1} (1 - \delta) + \delta \dot{x}_t + \delta \hat{\tilde{z}}_t^i \quad \text{(A17)}
\]
\[
\dot{k}_t^* = \dot{k}_{t-1}^* (1 - \delta) + \delta \dot{x}_t^* + \delta \hat{\tilde{z}}_t^i \quad \text{(A18)}
\]

Home and Foreign production functions
\[
\hat{y}_{H,t} = \dot{A}_t + (1 - \alpha) \dot{k}_{t-1} + \alpha \hat{l}_t \quad \text{(A19)}
\]
\[
\hat{y}_{F,t} = \dot{A}_t^* + (1 - \alpha) \dot{k}_{t-1}^* + \alpha \hat{l}_t^* \quad \text{(A20)}
\]
Home and Foreign economy-wide constraints

\[ \dot{y}_{H,t} = \frac{c_{H}}{y_{H}} \dot{c}_{H} + \frac{c_{H}^{*}}{y_{H}} \dot{c}_{H}^{*} + \frac{x_{H}}{y_{H}} \dot{x}_{H} + \frac{x_{H}^{*}}{y_{H}} \dot{x}_{H}^{*} \]  
(A21)

\[ \dot{y}_{F,t}^{*} = \frac{c_{F}}{y_{F}^{*}} \dot{c}_{F} + \frac{c_{F}^{*}}{y_{F}^{*}} \dot{c}_{F}^{*} + \frac{x_{F}}{y_{F}^{*}} \dot{x}_{F} + \frac{x_{F}^{*}}{y_{F}^{*}} \dot{x}_{F}^{*} \]  
(A22)

Terms of trade based on zero PPI inflation monetary policy

\[ \hat{T}_{t} = \hat{T}_{t-1} + \Delta s_{t} \]  
(A23)

Real exchange rate

\[ \hat{R}S_{t} = (v - v^{*})\hat{T}_{t} \]  
(A24)

Home and Foreign input demand functions

\[ \dot{c}_{H} = -\theta(v - 1)\hat{T}_{t} + \dot{C}_{t} \]  
(A25)

\[ \dot{c}_{H}^{*} = -\theta(v - 1)\hat{T}_{t} + \theta \hat{R}S_{t} + \dot{C}_{t}^{*} \]  
(A26)

\[ \dot{c}_{F} = -\theta v\hat{T}_{t} + \dot{C}_{t} \]  
(A27)

\[ \dot{c}_{F}^{*} = -\theta v\hat{T}_{t} + \theta \hat{R}S_{t} + \dot{C}_{t}^{*} \]  
(A28)

\[ \dot{x}_{H,t} = -\tau(\varphi - 1)\hat{T}_{t} + \dot{x}_{t} \]  
(A29)

\[ \dot{x}_{F,t} = -\tau\varphi\hat{T}_{t} + \dot{x}_{t} \]  
(A30)

\[ \dot{x}_{H,t}^{*} = -\tau(\varphi^{*} - 1)\hat{T}_{t} + \dot{x}_{t}^{*} \]  
(A31)

\[ \dot{x}_{F,t}^{*} = -\tau\varphi^{*}\hat{T}_{t} + \dot{x}_{t}^{*} \]  
(A32)

Relative price of investment based on CES price indexes

\[ \frac{\hat{P}_{x_{t}}}{\hat{P}_{t}} = (v - \varphi)\hat{T}_{t} \]  
(A33)

\[ \frac{\hat{P}_{x_{t}^{*}}}{\hat{P}_{t}^{*}} = (v^{*} - \varphi^{*})\hat{T}_{t} \]  
(A34)
B.1 Steady-state ratios

\[
\frac{x_H}{y_H} = \frac{x}{k y} = \delta \left( \frac{i + \delta}{1 - \alpha} \right)^{-1} \tag{B1}
\]

\[
\frac{x_H}{y_H} = \frac{\varphi}{y_H} \tag{B2}
\]

\[
\frac{x_{H^*}}{y_H} = \frac{\varphi^*}{y_H} \tag{B3}
\]

\[
\frac{y_H}{c_H} = \frac{1}{\nu} \left( 1 - \frac{x_H}{y_H} \right)^{-1} \tag{B4}
\]

\[
\frac{c_H^*}{y_H} = 1 - \frac{c_H}{y_H} - \frac{x_H}{y_H} - \frac{x_{H^*}}{y_H} \tag{B5}
\]

\[
\frac{x_F}{y_{F^*}} = \delta \left( \frac{i + \delta}{1 - \alpha} \right)^{-1} \tag{B6}
\]

\[
\frac{x_F^*}{y^*} = (1 - \varphi^*) \frac{x_F}{y_{F^*}} \tag{B7}
\]

\[
\frac{x_F}{y^*} = (1 - \varphi) \frac{x_F}{y_{F^*}} \tag{B8}
\]

\[
\frac{y_F}{c_{F^*}} = \frac{1}{(1 - \nu^*)} \left( 1 - \frac{x_F^*}{y^*} \right)^{-1} \tag{B9}
\]

\[
\frac{c_F}{y^*} = 1 - \frac{c_{F^*}}{y^*} - \frac{x_F^*}{y^*} - \frac{x_F}{y^*} \tag{B10}
\]
C The data

Our data are of quarterly frequency and come from two main sources: the *US Department of Commerce: Bureau of Economic Analysis* (BEA) and *US Department of Labor: Bureau of Labor Statistics* (BLS) and span the sample period 1960:1 to 2003:4.

1. GDP referred to in tables 2, 3 and 8 is real GDP per capita from BEA’s NIPA table 7.1. ‘Selected Per Capita Product and Income Series in Current and Chained Dollars’, seasonally adjusted. The series was logged and H-P filtered.

2. Consumption referred to in tables 2, 3 and 8 is total consumption expenditures deflated by the relevant GDP deflator, both from BEA’s NIPA tables 2.3.5 and 1.1.9.

3. Investment referred to in tables 2, 3 and 8 is real fixed investment per capita from BEA’s NIPA table 5.3.3. Real Private Fixed Investment by Type. Population is from NIPA table 7.1.

4. Hours referred to in tables 2, 3 and 8 is per capita hours worked in non-farm businesses, from BLS, series code PRS85006033. Population is from NIPA table 7.1.

5. Real wage referred to in tables 2, 3 and 8 is real hourly compensation from BLS, series code PRS85006153.

6. The Solow residual used in the empirical analysis of section 9 is constructed as follows:

\[ A_t = y_{nfb_t} - s_k \log(K_t) - (1 - s_k) \log(N_t) \]

where \(y_{nfb}\) is the log of real GDP in the non-farm business sector, series PRS85006043 from BLS. \(N_t\) is aggregate hours worked, as above, but not deflated by the population. \(K\) is real non-residential fixed assets, constructed following Stock and Watson (1999)

7. Exchange rate, terms of trade and current account data are taken from OECD.
Figure 1: Total factor productivity and the relative price of investment goods.
Figure 2: Investment rate, Tobin’s q, the relative price of investment and terms of trade following a unit IST shock
Figure 3: Investment rate, Tobin’s q, the relative price of investment and terms of trade following a unit TFP shock
Figure 4: Investment rate, Tobin’s q, the relative price of investment and terms of trade following a unit IST shock when $\varphi < v$
Figure 5: Investment rate, Tobin’s q, the relative price of investment and terms of trade following a unit TFP shock when \( \varphi < v \)
Figure 6: Total factor productivity and IST, defined as $\varepsilon^x$ expressed in logs.