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The role of investment-specific technological change in the business cycle

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Abstract

This is a quantitative investigation of the importance of technological change specific to new investment goods for postwar US aggregate fluctuations. A growth model that incorporates this form of technological change is calibrated to US data and simulated, using the relative price of new equipment to identify the process driving investment-specific technology shocks. The analysis suggests that this form of technological change is the source of about 30% of output fluctuations. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The role of technological change in business cycle fluctuations has attracted the attention of macroeconomists, particularly since the seminal work of Kydland and Prescott (1982) and Long and Plosser (1983). In these studies and

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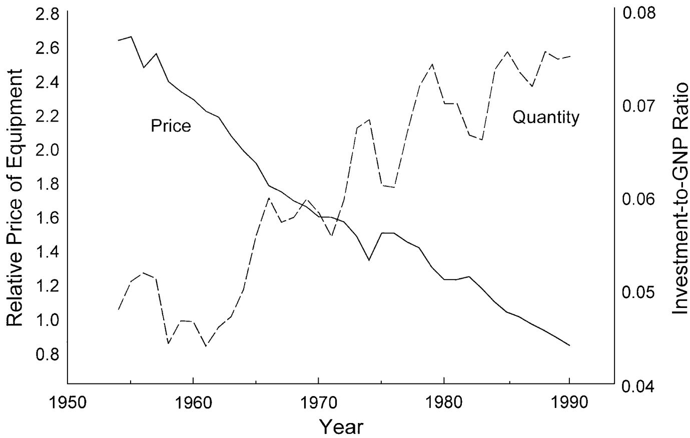

Fig. 1. Investment in equipment.

the literature that followed, technological change is modelled as an aggregate, sector-neutral, productivity shock. The main result is the surprisingly high degree to which this type of shock, when incorporated into a stochastic growth model, can explain a set of business cycle phenomena. A characteristic of this setup, with sector-neutral productivity change, however, is that relative prices of different uses of output are assumed to be fixed. Hence, this setup is not equipped to address the following evidence from the postwar US period, which suggests an important link between relative prices and technology:

- Low frequency: as shown in Fig. 1, the relative price of new equipment declined at an annual average rate of more than 3%, while the equipment investment-to-GNP ratio increased substantially.
- High frequency: there is a negative correlation (− 0.46) between the de-trended relative price of new equipment and new equipment investment. This is shown in Fig. 2.[1]

This negative comovement between price and quantity of new equipment at both frequencies suggests the presence of *investment-specific* technological change – in contrast to the sector-neutral form referred to above – affecting the production of new equipment. Examples of this type of technological change are

[1] In Fig. 2, NBER contractions are indicated by the shadowed intervals. The relative price of equipment has a countercyclical pattern which is modest but discernable; most contractions are associated with a rising relative price of equipment relative to its trend. However, the pattern is not very strong. The correlation between HP-detrended output and the relative price is − 0.21.

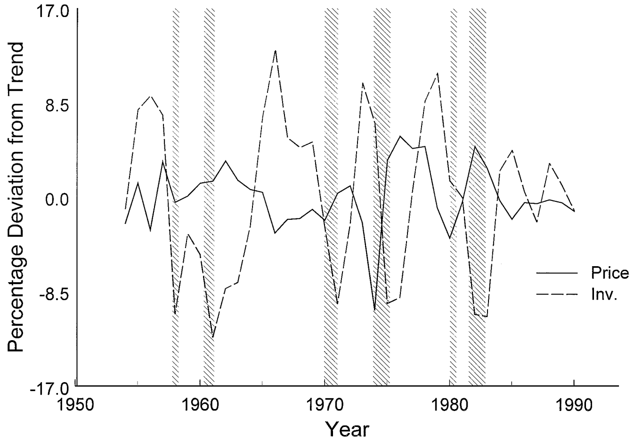

Fig. 2. Investment in equipment. HP detrended.

well known: more powerful computers, faster and more efficient means of telecommunication and transportation, etc. The story seems to be that technological advances have made equipment less expensive, triggering increases in the accumulation of equipment both in the short and long run. One may visually interpret the observed negative comovement as shifts of the supply schedule of equipment along the equipment demand curve. Given this interpretation, the fall in the relative price of new equipment is a direct, micro-based measure of investment-specific technological change.

The long-run implications of this type of technological change were analyzed in Greenwood et al. (1997), who concluded that it explains about 60% of US postwar growth in output per man-hour. In the present paper the focus is on the short run, i.e., on the quantitative role of investment-specific technological change in the generation of business cycles. The model used to address this question is the general equilibrium vintage capital setup developed in Greenwood et al. (1997), adapted for the short-run analysis conducted here. In that model the main feature is that the production of capital goods becomes increasingly more efficient over time.

The present version also includes an endogenous utilization rate of equipment, which is important for the short-run propagation of the shocks. Then, the contribution of investment-specific technological change for US postwar business cycles is assessed by simulating the model. The present analysis concludes that close to 30% of GNP variability can be accounted for by investment-specific technology shocks. Given that investment in new equipment is only 7% of GNP, these results indicate that investment-specific technology shocks have a powerful effect on the economy.

The paper is organized as follows: Section 2 presents the model and in Section 3 the model is calibrated to National Income and Products Accounts (NIPA). An investigation of its business cycle properties is then undertaken in Section 4 and Section 5 discusses further the structure of the model and its implications. Finally, Section 6 concludes the paper.

2. The model

2.1. The economic environment

The economy is inhabited by a representative agent who maximizes the expected value of lifetime utility as given by

$$E\left[\sum_{t=0}^{\infty} \beta^t U(c_t, l_t)\right], \tag{2.1}$$

with

$$U(c_t, l_t) = \theta \ln c_t + (1-\theta)\ln(1-l_t), \quad 0<\theta<1, \tag{2.2}$$

where c_t and l_t represent period-t consumption and labor. The production of final output y requires the services of labor, l, and two types of capital: equipment, k_e, and structures, k_s.[2] Equipment is utilized at the varying rate h, and thus the service flow from equipment is hk_e. The production technology is described by

$$y = F(hk_e, k_s, l, z) = z(hk_e)^{\alpha_e} k_s^{\alpha_s} l^{1-\alpha_e-\alpha_s}, \quad 0<\alpha_e, \alpha_s, \ \alpha_e+\alpha_s<1, \tag{2.3}$$

where z is a measure of total-factor, or sector-neutral, productivity.

Final output, less adjustment costs, a (to be discussed below), can be used for three purposes: consumption, c, investment in structures, i_s, and investment in equipment, i_e:

$$y - a = c + i_e + i_s\,. \tag{2.4}$$

Note that all variables in this resource constraint, and investments in particular, are expressed in units of consumption. This will be relevant later.

Structures can be produced from final output on a one-to-one basis. The stock of structures evolves according to

$$k_s' = (1-\delta_s)\,k_s + i_s, \quad \text{where } 0<\delta_s<1. \tag{2.5}$$

[2] Time subscripts are omitted whenever there is no risk of ambiguity.

The accumulation equation for equipment is

$$k'_e = (1 - \delta_e(h))k_e + i_e q. \tag{2.6}$$

The treatment of equipment in Eqs. (2.3) and (2.6) differs from that of structures in two respects:

1. The inclusion of the factor q, representing the current state of the technology for producing equipment. Here, changes in q represent investment-specific technological change, which is assumed to affect equipment only. Casual observation suggests that technological change specific to equipment is far more dramatic than for structures. Given that i_e is expressed in consumption units, q determines the amount of equipment in efficiency units that can be purchased for one unit of consumption.
2. The rate of depreciation on equipment depends on the utilization rate, reflecting a 'user-cost'. The specific functional form is[3]

$$\delta_e(h) = \frac{b}{\omega} h^{\omega}, \quad \omega > 1. \tag{2.7}$$

   Thus, equipment, unlike structures, has variable rates of utilization and depreciation. This is due to the more active role equipment plays in production, which is precisely why it is less durable than structures. It is natural, then, to model the depreciation on equipment as an increasing, convex function of its rate of utilization.

This formulation of the production function and the evolution of equipment has an important implication for the cyclical behavior of the model. A higher realization of q directly affects the stock of new equipment that will be active in production next period. However, it also increases the *current* flow of equipment services endogenously, since it lowers the replacement value (in consumption units) of old equipment and thus its utilization cost. Hence, investment-specific technological change translates immediately into a higher service flow from old equipment.

Both z and q are stochastic, with average gross growth rates of γ_z and γ_q, respectively. The process for z is

$$z_{t+1} = \gamma_z^{t+1} e^{\zeta_{t+1}}, \tag{2.8}$$

[3] This formulation is used in Greenwood et al. (1988). The role of a variable rate of factor utilization in business cycle fluctuations has been studied by Lucas (1970), Greenwood et al. (1988), Kydland and Prescott (1988), Bils and Cho (1994), Finn (1995), Burnside and Eichenbaum (1996), and Cooley et al. (1995).

where ζ_{t+1} is governed by the distribution function $Z(\zeta' \mid \zeta) = \Pr\{\zeta_{t+1} = \zeta' \mid \zeta_t = \zeta\}$. Investment-specific technological change follows the process

$$q_{t+1} = \gamma_q^{t+1} e^{\eta_{t+1}}, \tag{2.9}$$

where η_{t+1} is drawn from the distribution function $H(\eta' \mid \eta) = \Pr\{\eta_{t+1} = \eta' \mid \eta_t = \eta\}$.

Installing new capital involves adjustment costs $a = a_e + a_s$, where a_e and a_s are the costs for equipment and structures, respectively. These costs are assumed to be quadratic:

$$\begin{aligned} a_e &= A_e(k_e'/q, k_e/q; \eta) \\ &= e^{\eta}\phi_e(k_e'/q - \kappa_e k_e/q)^2/(k_e/q) \quad \text{with } \phi_e, \kappa_e > 0, \end{aligned} \tag{2.10}$$

and

$$a_s = A_s(k_s', k_s) = \phi_s(k_s' - \kappa_s k_s)^2/k_s \quad \text{with } \phi_s, \kappa_s > 0. \tag{2.11}$$

This parameterization of the functions A_e and A_s is convenient because it allows for balanced growth.

Finally, there is a government in the economy, which levies taxes on labor and capital income at the rates τ_l and τ_k. The inclusion of income taxation is important for the quantitative analysis because of the significant effect that it has on equilibrium capital formation. The revenue raised by the government in each period is rebated back to agents in the form of lump-sum transfer payments in the amount τ. The government's budget constraint is then

$$\tau = \tau_k(r_e h k_e + r_s k_s) + \tau_l w l, \tag{2.12}$$

where r_e, r_s, and w represent the market returns for the services provided by equipment, structures and labor.

A key variable is the equilibrium price for an efficiency unit of newly produced equipment, using consumption goods as the numéraire. This price corresponds, on the one hand, to the inverse of the investment-specific technology shock, q, and, on the other, it is a direct theoretical counterpart to the ratio between a price index of quality-adjusted equipment constructed by Gordon (1990) and a price index for consumption. Hence, investment-specific technological change can be identified here using Gordon's price series.

2.2. Competitive equilibrium

The competitive equilibrium under study is now formulated. The present section will use a decentralization with two key features. First, consumers save by purchasing capital; in the following period they then rent capital services to firms and sell the undepreciated capital. Second, production of consumption and investment goods (equipment and structures) is joint, with $1/q$ representing the relative marginal cost, and therefore the relative price, of equipment in terms of either consumption or structures. Equivalently, it is possible to think of the production of investment goods as occurring in two stages: in the first stage, consumption/structures goods are produced, using the production function F, and in the second stage some of these goods are used as intermediate goods in the production of investment goods, using the technology $k'_e - [1-\delta_e(h)]k_e = q(y-c-i_s-a)$. The latter formulation makes clear how pq has to equal one in equilibrium, where p is the relative price of the investment good.[4] In Section 5 below, an alternative decentralization which builds on a two-sector interpretation will be discussed.

The aggregate state of the world is described by $\lambda = (s, z, q)$, where $s \equiv (k_e, k_s)$. Assume that the equilibrium wage and rental rates w, r_e and r_s, and individual transfer payments τ can all be expressed as functions of the state of the world λ as follows: $w = W(\lambda)$, $r_e = R_e(\lambda)$, $r_s = R_s(\lambda)$, $\tau = T(\lambda)$. Also, suppose that the two aggregate capital stocks evolve according to $k'_e = K_e(\lambda)$ and $k'_s = K_s(\lambda)$. Hence, the law of motion for s is $s' = S(\lambda) \equiv (K_e(\lambda), K_s(\lambda))$. The optimization problems facing households and firms can now be cast. Of course, all agents take the evolution of s, as governed by $s' = S(s, z, q)$, to be exogenously given.

2.2.1. The household

The dynamic program problem facing the representative household is

$$V(k_e, k_s; s, z, q) = \max_{c, k'_e, k'_s, l, h} \{U(c, l) + \beta \mathrm{E}\,[V(k'_e, k'_s; s', z', q')]\} \tag{P.1}$$

subject to

$$\begin{aligned} c + k'_e/q + k'_s = {} & (1-\tau_k)[R_e(\lambda)hk_e + R_s(\lambda)k_s] + (1-\tau_l)W(\lambda)l \\ & + (1-\delta_e(h))k_e/q + (1-\delta_s)k_s + T(\lambda) \\ & - A_s(k'_s, k_s) - A_e(k'_e/q, k_e/q; \eta), \end{aligned}$$

and $s' = S(\lambda)$.

2.2.2. The firm

The maximization problem of the firm is

$$\max_{\tilde{k}_e, \tilde{k}_s, l, h} \pi_y = F(h\tilde{k}_e, \tilde{k}_s, l, z) - R_e(\lambda)h\tilde{k}_e - R_s(\lambda)\tilde{k}_s - W(\lambda)l. \tag{P.2}$$

[4] In equilibrium the profits made by equipment producers will be $p\{k'_e - [1-\delta_e(h)]k_e - q(y-c-i_s-a)\}$, which can be written more as $i_e - pqi_e$. Zero profits necessitate that $p = 1/q$.

Due to the constant-returns-to-scale assumption, the firm makes zero profits in each period; i.e., $\pi_y = 0$.

2.2.3. Definition of equilibrium

A competitive equilibrium is a set of allocation rules $c = C(\lambda)$, $k'_e = K_e(\lambda)$, $k'_s = K_s(\lambda)$, $l = L(\lambda)$ and $h = H(\lambda)$, a set of pricing and transfer functions $w = W(\lambda)$, $r_e = R_e(\lambda)$, $r_s = R_s(\lambda)$, and $\tau = T(\lambda)$, and an aggregate law of motion for the capital stocks $s' = S(\lambda)$, such that

1. Households solve problem (P.1), taking as given the aggregate state of the world $\lambda = (s, z, q)$ and the form of the functions $W(\cdot)$, $R_e(\cdot)$, $R_s(\cdot)$, $T(\cdot)$ and $S(\cdot)$, with the equilibrium solution to this problem satisfying $c = C(\lambda)$, $k'_e = K_e(\lambda)$, $k'_s = K_s(\lambda)$, $l = L(\lambda)$, and $h = H(\lambda)$.
2. Firms solve the problem (P.2), given λ and the functions $R_e(\cdot)$, $R_s(\cdot)$, and $W(\cdot)$, with the equilibrium solution to this problem satisfying $\tilde{k}_e = k_e$, $\tilde{k}_s = k_s$, $l = L(\lambda)$ and $h = H(\lambda)$.
3. The economy-wide resource constraint (2.4) holds each period so that

$$c + i_e + i_s = F(hk_e, k_s, l, z) - a_s - a_e,$$

where

$$i_s = k'_s - (1 - \delta_s)k_s\,,$$

$$i_e = [k'_e - (1 - \delta_e(h))k_e]/q\,,$$

$$a_s = A_s(k'_s, k_s)\,,$$

and

$$a_e = A_e(k'_e/q, k_e/q; \eta)\,.$$

2.3. Balanced growth

The growth rates of the different variables along the balanced growth path can be derived as follows. First, the exogenous variables z and q grow at the (gross) rates γ_z and γ_q, respectively. The amount of labor employed, l, and the utilization rate for equipment, h, remain constant in balanced growth. From the resource constraint (2.4) and the accumulation equation (2.5) for structures it follows that y, c, i_e, i_s, a_e, a_s, and k_s all have to grow at the same rate, say g. Equipment, however, grows faster: from Eq. (2.6) its rate of growth, g_e, equals $g\gamma_q$. Finally, the production function (2.3) implies that $g = \gamma_z g_e^{\alpha_e} g^{\alpha_s}$. Thus, the following conditions hold for balanced growth:

$$g = \gamma_z^{1/(1-\alpha_e-\alpha_s)}\,\gamma_q^{\alpha_e/(1-\alpha_e-\alpha_s)}, \tag{2.13}$$

and

$$g_e = \gamma_z^{1/(1-\alpha_e-\alpha_s)}\,\gamma_q^{(1-\alpha_s)/(1-\alpha_e-\alpha_s)}. \tag{2.14}$$

3. Calibration

Before simulating the model, values must be assigned to its parameters:
Preferences: β, θ.
Technology: $\alpha_e, \alpha_s, \delta_s, b, \omega, \gamma_q, g, \phi_e, \kappa_e, \phi_s, \kappa_s$.[5]
Tax rates: τ_k, τ_l.

The procedure adopted is the following: (a) as many parameters as possible are set in advance based upon a priori information; (b) given the parameters in (a), as many additional parameters as possible are set so that model's balanced-growth variables match the average values in the US data for the 1954–1990 sample; and (c) remaining parameters values are chosen so that the model's cyclical behavior matches alternative actual cyclical observations – other than the variability of output which is the main variable of interest.[6] Appendix A provides the definitions of the data used in the calibration.

3.1. Parameter values based on a priori information

The following parameters were selected on the basis of a priori information:

(i) $\gamma_q = 1.032$. This number corresponds to the average annual rate of decline in the relative price of equipment prices–measured dividing the equipment price index by the deflator of consumer nondurables and nonhousing services. The equipment price index is from Gordon (1990), for the period 1954–1983 (Gordon constructed his index through 1983), linked to a corrected NIPA index for the 1984–1990 period. (See footnote 11 for details.)

(ii) $\delta_s = 0.056$. This depreciation rate is constructed from NIPA and standard capital stock data as follows: using the accumulation equation for structures from the model and data on real investment and stocks of capital it is possible to back out a series on the implied depreciation rates $1-(k_{s,t+1}-i_{st})/k_{st}$. The value reported above is an average over the sample.

(iii) $\tau_l = 0.40$. This value is taken from Lucas (1990).

3.2. Parameter values based on average US data

The values for the parameters $\beta, \theta, \alpha_e, \alpha_s, \omega, g$, and τ_k are set so that the model's balanced-growth path displays seven features that are observed over the long run in the US data. As explained below, the parameter b does not have to be identified.

[5] Note that from Eq. (2.13) it follows that g and γ_q imply a value for γ_z. For convenience, hence, g is included instead of γ_z.

[6] The classic reference on calibration is Prescott (1986).

The balanced growth path should satisfy the following seven equations, under the restriction that the adjustments costs are zero along this path (see below):

$$\gamma_q = (\beta/g)[(1-\tau_k)\alpha_e yq/k_e + (1 - bh^{\omega}/\omega)], \tag{3.1}$$

$$1 = (\beta/g)[(1-\tau_k)\alpha_s y/k_s + (1-\delta_s)], \tag{3.2}$$

$$i_e/y = (k_e/yq)[g\gamma_q - (1 - bh^{\omega}/\omega)], \tag{3.3}$$

$$i_s/y = (k_s/y)[g - (1-\delta_s)], \tag{3.4}$$

$$(1-\tau_l)(1-\alpha_e-\alpha_s)\frac{\theta(1-l)}{(1-\theta)(c/y)} = l, \tag{3.5}$$

$$(1-\tau_k)\alpha_e(yq/k_e) = bh^{\omega}, \tag{3.6}$$

and

$$c/y + i_e/y + i_s/y = 1. \tag{3.7}$$

Eqs. (3.1) and (3.2) are the Euler equations for equipment and structures, while Eqs. (3.3) and (3.4) define the corresponding investment/output ratios. The efficiency conditions for labor and utilization are given by Eqs. (3.5) and (3.6), and Eq. (3.7) is the resource constraint.

The relevant averages of US data over the 1954–1990 sample are: (i) an annual growth rate of GNP per hour worked of 1.24%; (ii) a ratio of total hours worked to non-sleeping hours of the working-age population of 24%; (iii) a capital share of income of 30%; (iv) a ratio of investment in equipment to GNP of 7.3%; (v) a ratio of investment in structures to GNP of 4.1%; (vi) a depreciation rate on equipment of 12.4%; and (vii) an after-tax return on capital of 4%. These restrictions imply the additional seven equations:

$$g = 1.0124, \tag{3.8}$$

$$l = 0.24, \tag{3.9}$$

$$\alpha_e + \alpha_s = 0.30, \tag{3.10}$$

$$i_e/y = 0.073, \tag{3.11}$$

$$i_s/y = 0.041, \tag{3.12}$$

$$bh^{\omega}/\omega = 0.124, \tag{3.13}$$

and

$$(\beta/g) = 1/1.04. \tag{3.14}$$

The systems (3.1)–(3.14) contains 14 equations in 14 unknowns, viz. k_e/yq, k_s/y, i_e/y, i_s/y, l, c/y, θ, α_e, α_s, ω, bh^{ω}, τ_k, β, and g. Note that b and h appear in the

Table 1

Parameter	Calibrated value	Parameter	Calibrated value
α_e	0.18	θ	0.40
α_s	0.12	ω	1.59
β	0.97	g	1.0124
γ_q	1.032	bh^{ω}	0.20
ϕ	2.32 or 1.50	δ_s	0.056
τ_k	0.53	ρ	0.64
τ_l	0.40	σ	0.035

system only in the form bh^{ω}, and hence one cannot (and there is no need to) identify b and h separately.[7] The parameter values obtained solving this system are $\theta = 0.40$, $\alpha_e = 0.18$, $\alpha_s = 0.12$, $\omega = 1.59$, $\tau_k = 0.53$, $\beta = 0.97$, $g = 1.0124$, and $bh^{\omega} = 0.20$.[8]

3.3. Remaining parameters

Selecting values for the adjustment cost parameters, ϕ_s, κ_s, ϕ_e, and κ_e, is more problematic. First, the restriction made above of zero adjustment costs in balanced growth (but positive elsewhere) is achieved by setting $\kappa_s = g$ and $\kappa_e = g_e$ [see Eqs. (2.10) and (2.11)]. This restriction has to be imposed because there is no data on these costs, and hence balanced growth adjustment costs cannot be matched to data. Additionally, the model predicts that for reasonable parameter values the adjustments costs are very small relative to output (although the *marginal* costs are important relative to the marginal productivity of capital). Further, the symmetry condition $\phi_e = (g/g_e)^2\phi_s \equiv \phi$ was imposed, after which only one adjustment cost parameter ϕ remains to be determined. Given that long-run facts cannot be used to pin down ϕ, its value will be picked so that the model's cyclical behavior for investment matches one of two alternative observations from the US data in an attempt to provide a lower and an upper bound for the contribution of the q shock to output fluctuations – more on this later.

A list of the calibrated parameter values is contained in Table 1.

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[7] See Burnside and Eichenbaum (1996) for a discussion of this point in a similar context.

[8] Note that the value of τ_k, which is the tax rate on capital income before depreciation allowance, turns out to be quite high. Given that the calibration requires satisfying the investment/output ratios [Eqs. (3.11) and (3.12)], τ_k may reflect other costs of capital beyond the depreciation rate and the interest rate of 4%.

4. Simulation of the model

The quantitative importance of investment-specific technological change for business fluctuations is now gauged by simulating the model. The model without investment-specific technological change has been extensively explored in other studies (e.g., Kydland and Prescott, 1982; Hansen, 1985; King et al., 1988), so in order to isolate the effects of this form of technological change, only the q shock is allowed to operate. The stochastic structure that governs the evolution of this shock is taken from the time series properties of the relative price of equipment in the postwar US period.

The analysis consists of comparing a set of summary statistics characterizing the cyclical movements of the variables in the model with the corresponding set describing the behavior of US data for the 1954–1990 sample period. All statistics are compiled using data that is logged and Hodrick–Prescott filtered. The model's statistics are generated by simulating the artificial economy developed above for 100 samples of 37 observations – the number of years in the 1954–1990 sample. The statistics reported for the model are the averages of the statistics computed from the individual samples. The question is: how much of the fluctuations in US GNP can be accounted for by investment-specific technological change?

Note that unlike the standard real business cycle model, the technology shock here does not directly affect the production function in the current period. Current output is affected only to the extent that the shock can elicit increased employment of capital and labor in response to changed investment opportunities. The transmission mechanism to current output is the following. A positive shock raises the return on equipment investment. This entices equipment investment and hence a higher equipment stock next period. The resulting decline in equipment's replacement value implies a lower marginal utilization cost. This promotes more intensive utilization of the existing equipment, which leads to increased employment of labor and to output expansion. Note, though, that equipment investment is only 7% of GNP (on average over the sample), with only 18% of the value of output being derived from the use of equipment in production. Hence, unlike the standard model, the fraction of GNP directly affected by the shock is quite small. Significant movements in GNP may take place only if the transmission mechanism described above is quantitatively important.

The increases in the rate of return on equipment investment that stimulate production, however, operate at the same time to dissuade consumption. Hence, it is a priori uncertain whether consumption is procyclical in the model, as it is in the actual data.

To simulate the model, the stochastic process for q in Eq. (2.9) must first be fully specified and estimated. As discussed above, the identification of

q with the inverse of the relative price of new equipment is used for this purpose.[9]

The process for q to be estimated is:[10]

$$\ln q_t = \text{constant} + t \ln \gamma_q + \eta_t,$$

where

$$\eta_t = \rho\eta_{t-1} + \xi_t \quad \text{with } 0 < \rho < 1 \text{ and } \xi_t \sim \text{N}(0, \sigma). \tag{4.1}$$

Using the annual 1954–1990 sample, the estimated parameters are:

$$\ln \gamma_q = \underset{(24.16)}{0.032}, \quad \rho = \underset{(4.94)}{0.64}, \quad \sigma = 0.035 \text{ with DW} = 1.90,$$

where the numbers in parentheses are t statistics.[11]

An important aspect of the present analysis is that the process for investment-specific technological change is estimated directly using Gordon's equipment price series. This has an advantage over the real business cycle literature, which emphasizes the 'Solow residual' as the driving force underlying the business cycle. This imputed residual may include other influences, besides technological change, which affect rates of capacity utilization. Government spending, for instance, tends to be positively related with the Solow residual and energy prices negatively so. Finn (1995) has explained these correlations by modelling the effect that such factors have on capacity utilization. Those issues

[9] Of course, this identification is model dependent, and other interpretations of the movements in the relative price (and its negative correlation with the quantity of new equipment) are not inconceivable. For example, increasing returns in equipment production, monopoly power and time-varying (relative) markups for equipment, or other shocks in combination with differences in equipment shares across sectors (see Section 5 below) could potentially produce this correlation.

[10] The relative price of equipment shows evidence of a more rapid fall in the second part of the period (the mid-1970s and on) over which data is available (see Greenwood and Yorukoglu, 1997; Hornstein and Krusell, 1996). A correction for a structural break may lead to a somewhat lower estimate of the serial correlation for *q conditional on regime*. The present analysis can be viewed as a shortcut to estimating a q process with stochastic regime shifts and solving and simulating the model with the resulting process.

[11] The estimates for the parameters were obtained using data for the sample period 1954 to 1990. Gordon's price index was used for the 1954–1983 subperiod and a correction of NIPA price measures for the 1984–1990 subperiod. The correction to the NIPA measures involved adjusting downwards the growth rates for the indexes in the producer durable equipment (PDE) categories by 1.5%. An exception was the computers category, which already incorporates the quality adjustment used in Gordon (1990). This adjustment to the NIPA numbers was suggested by Robert Gordon. Moreover, the new index for 1984–1990 was constructed by taking an average of the implicit PDE price deflator (IPD) and the fixed-weight price index (PPI) for PDE. This average reflects the desire to replicate the more elaborate Tornquist index used in Gordon (1990).

are partially avoided here given the use of more direct evidence on technological change.

In principle, it is still true that the price of investment goods is an endogenous variable determined by the supply and demand for them. These supplies and demands may be influenced by factors such as government purchases, the price of energy, monetary policy, etc. In the model these effects do not take place because of the assumptions that (a) the marginal cost curve of investment in efficiency units is flat at the level $1/q$, and hence p reflects q only, and (b) technology evolves exogenously. An attempt to test these two assumptions was carried out by regressing η from Eq. (4.1) on its own lagged value and lagged values of government purchases changes, energy prices, T-bill rates and money growth.[12] All the four additional variables were found to be statistically insignificant. That is, they are not useful in forecasting the course of q, and hence from this test one cannot reject the exogeneity of q. It should be noted that various authors, such as Evans (1992), have noted that standard measures of the Solow residual do not pass such a test (although this may be due to failure to take account of factors such as capacity utilization, as mentioned above).

There is no good guide available for choosing an appropriate value for ϕ, which is obviously an important parameter for evaluating the cyclical properties of the model. When ϕ is relatively small, a given q shock will generate more investment and output than when ϕ is relatively high. This link is exploited, as elaborated on next, by selecting two values for ϕ that are likely to provide a lower bound and an upper bound on the contribution of q shocks to business cycles.

The value of ϕ that is likely to result in a conservative estimate is set by equalizing the output/consumption correlation in the model to that in the data (the resulting ϕ is 2.32). This choice of ϕ should produce a conservative estimate of the contribution of q shocks to output fluctuations for the following reason: with investment-specific shocks the mechanism that stimulates capital accumulation works at the same time to retard consumption. This substitution away from consumption toward investment, in response to a good realization of the q shock, can be weakened by increasing the adjustment-costs parameter ϕ, because then investment increases by less. As mentioned above, however, a higher ϕ value also reduces output's reaction to the shock. Therefore, increasing

[12] Using the sample 1961–1990, the results are:

$$\eta' = \underset{(1.2)}{0.088} + \underset{(2.8)}{0.55\eta} - \underset{(1.01)}{0.0010e} + \underset{(0.46)}{0.09\Delta g} + \underset{(0.13)}{0.0006r} + \underset{(0.33)}{0.08\Delta m},$$

where the numbers in parenthesis are t statistics. Here Δ denotes the rate of change, e is the relative price of energy, g represents total real government purchases (federal, state and local), r is the real return on three month Treasury bills, and m is M1. The F test on all the four additional variables yields the statistic 0.6, while the 5% F value for 4 and 24 degrees of freedom is 2.78.

ϕ strengthens the procyclicality of consumption and reduces the variability of output. This criterion (of fitting the consumption/output correlation) is likely to produce too high a value for ϕ. This is because, in reality, disturbances other than the q shock are also at work – such as the factors underlying the z shock. The omitted z shocks tend to generate strongly procyclical movements in consumption, and thus, if these shocks were included, a lower value for ϕ would be called for. Correspondingly, the upshot of choosing too high a value for ϕ is too low a value for output volatility, and thus the results can be interpreted as providing a lower bound on the contribution of q shocks to the business cycle.

The ϕ value that corresponds to an upper bound for the contribution of q is chosen by equalizing the percentage standard deviation of investment in the model to that found in the data (the resulting value here is 1.50). This procedure should provide an upper bound because all the variability of investment is forced to be generated by the only shock operating, q, while in reality also the z shocks contribute to investment volatility.

In Table 2 key statistics characterizing the behavior of economic fluctuations for the postwar US economy are presented, along with the corresponding

Table 2

Variable	Standard deviation (%)	Cross-correlation with output	Autocorrelation
US Annual data, 1954–1990			
Output	2.32	1.00	0.42
Consumption	1.25	0.85	0.61
Investment	5.96	0.79	0.45
Hours	1.71	0.89	0.47
Relative price	3.00	− 0.21	0.25
Model [$\phi = 2.32$]			
Output	0.65	1.00	0.28
Consumption	0.23	0.85	0.51
Investment	4.36	0.97	0.25
Hours	0.35	0.97	0.25
Utilization	2.67	0.89	0.26
Model [$\phi = 1.50$]			
Output	0.75	1.00	0.29
Consumption	0.23	0.57	0.69
Investment	5.92	0.96	0.24
Hours	0.49	0.96	0.24
Utilization	2.89	0.84	0.26

Note: Data definitions are given in Appendix A. The statistics are calculated using data that was logged and Hodrick–Prescott filtered.

statistics for the model (for $\phi = 2.32$ and $\phi = 1.50$). Observe that for the US economy, the standard deviation of GNP around its Hodrick–Prescott trend is about 2.3%. When $\phi = 2.32$, the figure for the model is 0.65%. By this accounting, 28% of business cycle fluctuations can be explained by investment-specific technological change. When $\phi = 1.50$ the standard deviation of output is 0.75%, which corresponds to 32% of the actual figure. These results suggest that investment-specific technological shocks contribute to the generation of business cycles, but they are not the main factor. Note, however, that the figures above are likely to be underestimates, because the model does not include mechanisms, analyzed in the real business cycle literature, which would amplify the responsiveness of the economy to q shocks. Examples of these mechanisms are Rogerson (1988)/Hansen (1985) indivisible labor and a utility function that is nonseparable in leisure across time as in Kydland and Prescott (1982).

Regarding other aspects of Table 2, in the US data investment is more volatile than output, and consumption and hours less so. The model exhibits this behavior, but greatly exaggerates the variability in investment relative to output. This is to be expected given the nature of the shock. Additionally, all variables in the model are strongly procyclical, as well as in the data.

The relative price of equipment (which corresponds to $1/q$) is countercyclical in the US data, although not strongly so; the correlation with output is -0.21. This correlation is consistent with the results above of a positive but partial contribution of q shocks to output fluctuations. In the model, the relative price/output correlation is, obviously, close to one, given that it is the only shock included in the simulations.

The dynamic behavior of the model can also be illustrated by the impulse responses it generates. Figs. 3 and 4 portray the impulse responses of y, c, i_e and i_s to a shock to q of one standard deviation, 3.5%, and a serial correlation of 0.64. These figures correspond to $\phi = 1.50$. As mentioned below, the results are similar when $\phi = 2.32$ is used.

In Fig. 3, output has a typical response. The highest impact occurs during the first year, and is declining thereafter. The consumption response, however, has a hump shape: c increases in the first year, and reaches its maximum in the fourth year. This illustrates the point mentioned previously: the same mechanism motivating equipment investment also tends to retard consumption.

The behavior of investment is shown in Fig. 4. The immediate response of i_e is strongly positive, and it remains positive, but is declining, for five years. Then it becomes negative, showing that the optimal timing of equipment investment shifts towards periods in which q is high. Structures investment has a similar hump shape as consumption: the impact effect is positive, indicating that complementarity in production between k_s and k_e is more important in the short run than is the rivalry for resources between the two types of investment. This

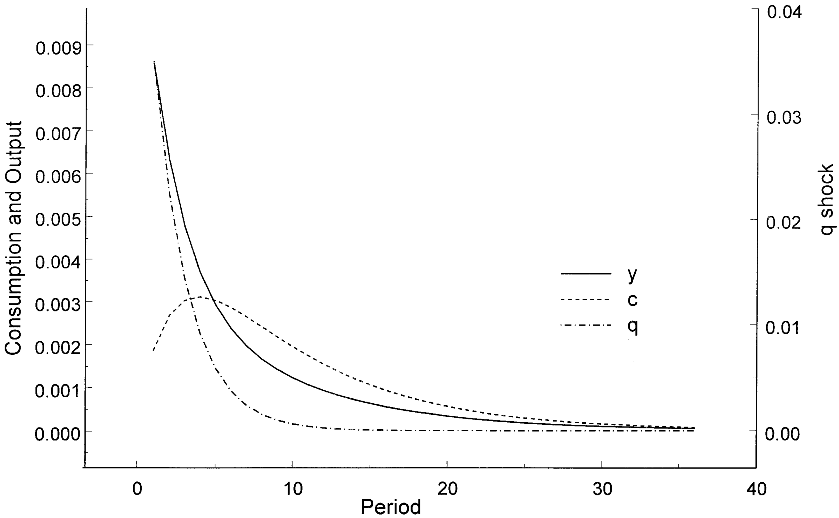

Fig. 3. Impulse responses. Deviation from steady state.

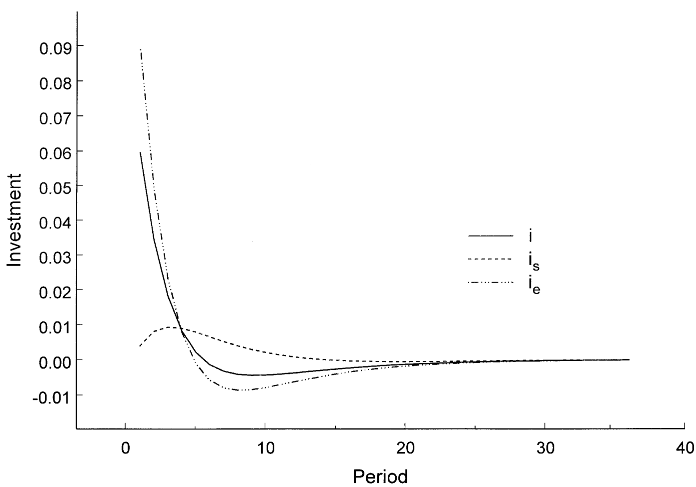

Fig. 4. Impulse responses. Deviation from steady state.

rivalry tends to retard investment in structures in a similar way as it retards consumption.

The impulse responses when $\phi = 2.32$, which are not shown, are fairly similar, but differ in expected ways. The immediate response of investment in equipment is smaller (6.4% compared to 9%), it remains positive for 6 years, instead of 5, and becomes less negative thereafter. The weaker response of i_e implies less competition for resources with i_s and c. This explains why investment in structures does not have a hump shape here – it has the highest response in the first year, and declines thereafter. Consumption now has a much flatter hump shape. The response of output is, as expected, weaker than before, but has a similar shape as in Fig. 3.

To conclude, it appears that investment-specific technological change may account for a sizable fraction of business cycle fluctuations, without being the dominant force. By the simple accounting undertaken here, about 30% of output fluctuations can be attributed to this type of shock. This implies that investment-specific technological shocks have a powerful effect, given that investment in equipment amounts to only 7% of GNP.

5. A two-sector interpretation of the model

The discussion here of a two-sector interpretation of the model has two purposes: (a) to make clear under what conditions on sectoral production functions and factor mobility the equilibrium allocations in a two-sector model are identical to those studied in the previous section, and (b) to discuss comovement of inputs and outputs across the two sectors.

5.1. Characterization of the two-sector economy

The two sectors are defined as follows. One sector produces equipment – the equipment sector – and the other produces consumption, structures, and adjustment costs – the consumption sector.

Suppose that there is a continuum of firms, identified with their stocks of equipment and structures. The firms, owned by consumers, are long-lived and manage the replenishing of their capital stocks. Assume that at the beginning of a given period all firms have the same amount of each type of capital. After all current shocks are realized, each firm decides whether to produce in the consumption or in the equipment sector. Production in the consumption sector takes place according to the production function F, and production in the equipment sector according to qF. After production has taken place, the firms can sell their undepreciated capital and/or buy new capital for next period. They also bear adjustment costs for changes in the capital stock in the form expressed by Eqs. (2.10) and (2.11). There is no cost for firms to switch between sectors over time.[13]

[13] In fact, it would be sufficient to assume that only a subset of firms can switch their product types costlessly.

A firm which chooses to produce in the consumption sector has net profits (before investments are made and adjustment costs are incurred) given by

$$F(\tilde{h}_c \tilde{k}_{ec}, \tilde{k}_{sc}, \tilde{l}_c, z) - w\tilde{l}_c - \delta_e(\tilde{h}_c)\tilde{k}_{ec} - \delta_s \tilde{k}_{sc}, \tag{5.1}$$

where the $\tilde{}$'s are used to denote the variables of the given firm (as before, variables without $\tilde{}$'s are economywide). The variables $\tilde{k}_{ec}$ and $\tilde{l}_c$ denote the quantities of equipment and labor employed by a firm in the consumption sector, and so forth. Similarly, the profits of a firm in the equipment sector equal

$$pqF(\tilde{h}_e \tilde{k}_{ee}, \tilde{k}_{se}, \tilde{l}_e, z) - w\tilde{l}_e - \delta_e(\tilde{h}_e)\tilde{k}_{ee} - \delta_s \tilde{k}_{se}. \tag{5.2}$$

In an equilibrium with production taking place in both sectors, the relative price p has to adjust so that firms are indifferent between sectors. It is straightforward to verify that $pq = 1$ is an equilibrium. If all the firms have the same initial amounts of capital, the profit functions are identical for firms in different sectors, and all firms will make the same labor hiring, utilization, and investment decisions: $\tilde{l}_c = \tilde{l}_e$, $\tilde{h}_c = \tilde{h}_e$, $\tilde{i}_{ec} = \tilde{i}_{ee}$, and $\tilde{i}_{sc} = \tilde{i}_{se}$. The firms thus start with the same amount of capital, utilize it, invest identically, and carry the same stocks into the next period. This means that firms are also ex ante indifferent between which sector to join, and the allocation of firms across sectors will thus be dictated by the consumer's savings decisions. As a result, the aggregate economy corresponds exactly to that studied in the previous section.

Another way of illustrating that aggregation holds in this environment is the following. Since labor is freely mobile across firms, and since firms are free to move across sectors from one period to another, the capital inputs are de facto freely mobile across sectors. This mobility will imply that capital/labor ratios are the same across firms, and thus across sectors. Therefore, it follows that

$$\begin{aligned} c + i_s + i_e &= \varsigma\left[lF\left(\frac{hk_e}{l}, \frac{k_s}{l}, 1, z\right) - a\right] \\ &\quad + (1-\varsigma)\left[plqF\left(\frac{hk_e}{l}, \frac{k_s}{l}, 1, z\right) - a\right] \\ &= F(hk_e, k_s, l, z) - a, \end{aligned}$$

where as in the previous sections i_e is the equipment output measured in consumption units, and ς is the fraction of the total labor hours l allocated in equilibrium to the consumption firms. Hence, Eq. (2.4) is reproduced.

Two assumptions are key for the two-sector interpretation to go through. First, it is necessary that the production function be the same for consumption and equipment production, save the productivity parameter q. With different production functions, the relative price would no longer satisfy $pq = 1$.[14] Second, it is important that inputs be freely mobile across consumption and equipment production. Without this assumption, input ratios would not always be equal, and $pq = 1$ would not hold in general.

5.2. Comovements of inputs and outputs across sectors

To know how inputs behave across sectors it is sufficient to study l_c and l_e, i.e., the amount of labor allocated to each sector, since the other inputs will move together with each of these variables due to input-ratio equalization across all firms. In other words, once the correlation between l_c and l_e is known, then so are the correlations between k_{ec} and k_{ee}, k_{sc} and k_{se}, and h_c and h_e. Since total labor supply varies, the sign of the correlation is not clear a priori. The comovement of sectoral outputs is given by the comovement of zl_c and qzl_e, again due to the equalization of input ratios and the Cobb–Douglas structure of production.

As done in a similar context by Christiano and Fisher (1995), it is possible to reach some theoretical insights about the correlation between l_c and l_e by studying the first-order condition resulting from the labor/leisure choice:

$$\frac{\theta}{c} w = \frac{1-\theta}{1-l_c-l_e}, \tag{5.3}$$

which, because of the Cobb–Douglas production function, can be written as

$$\frac{\theta}{1-\theta}(1-\alpha_e-\alpha_s)\left(1+\frac{i_s+a}{c}\right) = \frac{l_c}{1-l_c-l_e}. \tag{5.4}$$

If $(i_s + a)/c$ is constant, the left-hand side of Eq. (5.4) is constant over time, and an increase in l_c unambiguously forces l_e to decrease. In the present calibration, as in the data, $(i_s + a)/c$ is small, implying that the left-hand side is close to being constant. Thus, l_c and l_e (as well as the capital inputs in the two sectors) tend to move in opposite directions. Christiano and Fisher do not separate equipment and structures nor do they have adjustment costs [so that $(i_s + a)/c = 0$]. They therefore find that l_c and l_e have to satisfy a deterministic, negative (nonlinear) relation. Although the sectoral inputs comove negatively, the results above show that this does not imply that the sectoral outputs have to move in opposite directions.

[14] For instance, Greenwood et al. (1997) and Hornstein and Krusell (1996) use Cobb–Douglas production functions to illustrate how changes in the relative price p may come about due to changes in z (without q movements) when equipment shares differ across sectors.

What does the data say about the cross-sectoral correlations, and how do these correlations compare with those of the model? Note that it is not entirely clear what variables in the data are the relevant counterparts of the sectoral variables in the model. This is because firms in the model switch between sectors over time, sometimes producing consumption and sometimes equipment goods, whereas the data is constructed on the basis of firms which are allocated to the same sector over time. To the extent a given firm either produces multiple goods, or produces goods which can be used both as consumption and investment goods, it is not clear how to define sectors.

The input and output movements across the consumption and investment sectors have been examined recently in the context of stochastic, dynamic equilibrium models by Christiano and Fisher (1995), Hornstein and Praschnik (1997), and Huffman and Wynne (1999). In each of these papers a different consumption/investment breakdown is used, but a common finding is that hours worked and employment in the two sectors comove positively, contrary to what is implied by Eq. (5.4). Each of these papers then goes on to amend the basic framework in order to produce a positive comovement across the sectoral inputs. The following discussion briefly summarizes the findings in these papers.

5.2.1. Christiano and Fisher (1995): Habit persistence and factor immobility

They consider a framework with habit formation and costs of adjusting labor across sectors. In particular, they assume that labor has to be committed to sectors before the current shocks are realized, i.e., that it is completely immobile within the period once shocks are realized. In their framework, Eq. (5.4) has a much more complicated left-hand side, since the marginal utility of current consumption involves all future consumption levels through the habit factor; moreover, the equation only holds in expectation as of the previous period, due to the commitment of labor to sectors. Having broken the theoretical negative relationship between l_c and l_e, they go on to show that their particular parameterization indeed produces a positive correlation between l_c and l_e. In addition, they also show that the model does display a negative correlation between p and total output.

5.2.2. Huffman and Wynne (1999): Intratemporal adjustment costs on investment

A different kind of factor immobility is considered in Huffman and Wynne (1999). They assume that investment goods going into the consumption and investment sectors are joint, imperfectly substitutable outputs. This idea is operationalized by

$$[\kappa i_c^{-\nu} + (1-\kappa)\, i_e^{-\upsilon}]^{-1/\upsilon} = z k_e^{\alpha_e} l_e^{1-\alpha_e} \quad \text{for } \kappa \in (0,1) \text{ and } \nu < -1,$$

where the right-hand side represents the production function for the investment goods sector. The idea is that it costly to switch capital goods production between the consumption and investment goods sectors and this is captured by the left-hand side of the above equation. Perhaps there is some immobility of factors across these lines of production. Relative to Eq. (5.4), again, these changes are sufficient to produce positive comovement in labor hours across sectors.

5.2.3. Hornstein and Praschnik (1997): Intermediate inputs

A different route is taken in Hornstein and Praschnik (1997), who argue, in a way similar to that of Long and Plosser (1983), that the use of intermediate inputs in all sectors can induce positive comovement of inputs across the durable and the nondurable goods sectors. In their framework, where productivity shocks in durable goods sector are quantitatively more important than shocks to nondurable production, the relative price of durable goods is countercyclical.

To sum up, although the model presented in this paper can produce positive comovement of sectoral outputs, it does imply that sectoral inputs covary negatively. The latter fact also characterizes the two-sector interpretation of the model with neutral technological change, i.e., the standard real-business-cycle model. As demonstrated in the papers reviewed above, however, there are several amendments of the present framework that would produce positive comovements and most likely would not invalidate the general insights reached here.[15]

6. Conclusions

The analysis in this paper was motivated by the negative comovement between the relative price of new equipment and equipment investment. This evidence suggests that investment-specific technological change may trigger equipment investment and be a source of economic fluctuations. The kind of technological change considered here is embodied in the form of new equipment. It represents phenomena such as advances in computer technology, robotization of assembly lines, faster and richer means of telecommunications, etc. Given the sector-specific nature of this type of technological change, the relative price of new equipment can be used to identify the stochastic process driving the technological change.

[15] Benhabib et al. (1992) use a home production structure to produce comovement.

A simple vintage-capital model was constructed with the property that the equipment-to-GNP ratio increases stochastically over time as the relative price of new capital goods declines. The standard features of the neoclassical growth model were otherwise preserved.

Greenwood et al. (1997) found that about 60% of postwar growth in output per man-hour can be explained by investment-specific technological change. The present paper is an attempt to complete the macroeconomic picture by looking at the cyclical frequency, which is of key interest to macroeconomists. The present analysis suggests investment-specific technological change contributes relatively less to the business cycle than to long-term growth. The estimate obtained here is about 30%.

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Appendix A. Data

A.1. Sample: Annual data 1954–1990.

The variables in the model's resource constraint, namely y, c, i_e and i_s, are matched with the corresponding nominal variables from the NIPA divided through by a *common* price deflator. A natural such price in this context is the consumption deflator for nondurable goods and nonhousing services, base year 1987 – so as to avoid the issue of accounting for quality improvement in consumer durables. Hence, y, c, i_e and i_s are measured in consumption units. The nominal data used to construct these series are:

y: nominal GNP net of gross housing product – since only capital in the business sector is used to produce output in the model,

c: nominal consumption expenditure on nondurables and nonhousing services,

i_e: nominal investment in producer durable equipment,

i_s: nominal investment in producer structures,

i: total investment: $i_e + i_s$.

A.2. Other data

l: total hours employed per week – Household Survey data.

q: implicit price deflator for nondurable consumption goods and non-housing services divided by Gordon's (1990, Chapter 12, 12.4) index of nominal prices for producer durable equipment. Since Gordon's index is only computed through 1983, a correction of the NIPA measures for producer durable equipment was used for the remainder of the sample. See footnote 11 for the details.

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