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by

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This paper investigates the relevance of capital-adjustment costs in the theory of investment of a small open economy. A dynamic stochastic model is numerically analyzed to compare the neoclassical theory with the adjustment-cost framework. When adjustment costs are introduced, the model mimics closely some of the stylized facts of Canadian investment and other macro-aggregates of interest. These results indicate that small and transitory shocks to productivity or the terms of trade can explain the observed fluctuations in the balance of trade and the correlation between savings and investment.

* I would like to thank David Backus, Martin Eichenbaum, Jeremy Greenwood, Zvi Hercowitz, Greg Huffman, Maurice Obstfeld and Bruce Smith for helpful suggestions and comments. Financial support from the Alfred P. Sloan workshop in international economics at the University of Western Ontario is gratefully acknowledged. All remaining errors are my own.
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IN A SMALL OPEN ECONOMY.

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This paper investigates the relevance of capital-adjustment costs in the theory of investment of a small open economy. A dynamic stochastic model is numerically analyzed to compare the neoclassical theory with the adjustment-cost framework. When adjustment costs are introduced, the model mimics closely some of the stylized facts of Canadian investment and other macro-aggregates of interest. These results indicate that small and transitory shocks to productivity or the terms of trade can explain the observed fluctuations in the balance of trade and the correlation between savings and investment.

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1. Introduction.

This paper investigates the role played by capital-adjustment costs in the theory of investment of a small open economy. The main reason for undertaking this research is to produce a model that can successfully extend the existing work on closed-economy real business cycles to the international arena. The pioneering work of Kydland and Prescott (1982) and Long and Plosser (1983) preceded the development of a wide variety of closed-economy models capable of replicating some of the observed stylized facts of the U.S. economy\(^1\). Therefore, an extension of this theory to a small open-economy environment, where foreign financial assets are allowed to play a role in the dynamics of savings and investment, appears to be interesting.

The development of open-economy real business cycle models is complicated by the fact that they postulate a significantly different theory of investment behavior than the closed-economy models. With the exception of models like that of Kydland and Prescott (1982), where time-to-build restrictions in the process of investment are considered, most real business cycle models developed to date assume that capital accumulation is not affected by explicit costs or frictions. The only cost associated to additional investment is the marginal utility of the current consumption sacrificed in order to augment the future capital stock. Thus, as King, Plosser and Rebelo (1988) point out, most of the existing real business cycle prototypes are stochastic extensions of the free-adjustment neoclassical model of investment for a closed economy.

In the closed-economy neoclassical model of investment, optimal capital accumulation decisions are equivalent to optimal savings choices because the capital stock is the only existing vehicle of savings. Optimal investment is determined by equating the intertemporal marginal rate of substitution with
the marginal productivity of future capital, which occurs at a tangency point like A in Figure 1. Consequently, the adjustments in investment, and in the intertemporal allocation of consumption, that follow a productivity disturbance are governed by intertemporal consumption-smoothing and consumption-substitution effects. These effects play an important role in determining the ability that real business cycle models possess to reproduce the observed stylized facts. When a favorable, serially correlated productivity disturbance occurs, the desire to smooth consumption causes consumption, investment and output to exhibit positive comovement and persistence. Because investment is equivalent to savings and savings are planned so as to smooth consumption, investment is likely to be more volatile than output and output is likely to be more volatile than consumption. Furthermore, persistent disturbances can also cause the equilibrium interest rate to rise, generating an intertemporal consumption-substitution effect away of current consumption\(^2\). This consumption-substitution effect dominates the consumption-smoothing effect in certain states of nature where the latter is particularly weak, and hence it generates positive but less-than-perfect correlation between consumption and output - as observed in the actual data.

It has been known for some time that the theory of investment described in the previous paragraph is significantly modified when the neoclassical model is applied to a small open economy. Following the writings of Fisher (1907) and (1930), Hirshleifer (1958) illustrated how a different theory of investment is obtained when economic agents have access to financial markets from which they can borrow or lend in order to support consumption planning. The essential difference between the neoclassical investment models for the closed economy and the small open economy is that in the latter savings and
THE NEOClassICAL MODEL OF INVESTMENT

FIGURE 1.
investment decisions are separated. Individuals have access to a perfectly competitive world capital market where they can borrow or save by trading foreign assets that pay or charge the real interest rate $r^*$. Optimal savings are chosen so as to equalize the intertemporal marginal rate of substitution with the world's intertemporal relative price of consumption $1+r^*$, as in point B of Figure 1. Whereas optimal investment is solely decided on the basis of portfolio considerations that equate the marginal rates of return on domestic capital and foreign assets, as in point C of Figure 1. In this environment, productivity shocks affect investment only to the extent that they alter the marginal productivity of domestic capital relative to the world's real interest rate. Thus, investment is not regulated by either consumption-smoothing or consumption-substitution effects. The former are still present, but operating through the accumulation of foreign financial assets, and the latter are eliminated, because the world rate of interest is exogenously determined in the international financial market.

Quantitative research in open-economy real business cycles has revealed that the neoclassical model of investment in its original form is not capable of replicating the observed stylized facts. Using a two-country model, Backus, Kehoe and Kydland (1989) noted that, unless time-to-build restrictions and international spill-overs of technological disturbances are considered, the variability of investment is largely exaggerated by the model. Mendoza (1989) observed that a model of a small open economy exaggerates the variability of private investment and underestimates its first-order serial autocorrelation, its correlation with domestic output and its correlation with aggregate savings. Consequently, in order to postulate a solution for this problem, this paper proposes to modify the neoclassical model of investment
for a small open economy by adopting a different view of the technology. An explicit capital-adjustment cost is introduced here to force optimizing agents to undertake changes in capital accumulation in a gradual manner, so that random productivity disturbances may generate a relatively less volatile pattern of investment behavior$^4$.

The present work has also two empirical motivations. First, since the intertemporal reallocation of consumption in a real-world economy is achieved not only by changes in investment, but also by accumulating or depleting foreign financial assets to finance a trade deficit or surplus, it is important for real business cycle theory to explain the behavior of both investment and the balance of trade. In fact, the empirical evidence indicates that trade-balance movements are large and countercyclical, suggesting that they may play as much as an important role as changes in private investment do. The second empirical motivation follows from the debate on the meaning of the high degree of correlation between savings and investment observed in industrialized economies. This debate started with the empirical work of Feldstein and Horioka (1980), whom considered these high correlations as evidence indicating that the degree of international capital mobility is very low. In contrast, numerical experiments performed with overlapping-generations models by Obstfeld (1985) and Finn (1988) indicate that, considering productivity disturbances with the right intensity of persistence, a high degree of correlation between savings and investment can be theoretically consistent with the assumption of perfect capital mobility. In this context, the numerical investigation undertaken in this paper studies the ability of a dynamic stochastic model to match the correlation between savings and investment when restricted to employ the kind of disturbances
required to replicate actual business cycles.

Technically, the artificial economy studied here is an extension of theoretical developments made by Obstfeld (1981a) and (1981b) and Epstein (1983) to an environment where investment is costly to adjust. The work of Obstfeld utilizes an endogenous rate of time preference to obtain a well-behaved deterministic stationary equilibrium for the holdings of international assets. Such a deterministic stationary equilibrium is produced when the world's real interest rate and the rate of time preference are equalized. It is a well-established fact, documented among others by Helpman and Razin (1982) and Frenkel and Razin (1987), that as long as the world's interest rate is greater (smaller) than the rate of time preference, individuals will rationally choose to accumulate (deplete) foreign assets so as to finance an increasing (decreasing) consumption stream\(^5\). The usual constant-discount formulation of preferences cannot explain the process by which this long-run equilibrium is reached; in this framework either (a) there is no steady state, because the rate of time preference is not preset at the level of the world interest rate, or (b), when the two are equal, the economy starts out in a stationary equilibrium, which is contingent on the agents' initial level of asset holdings, and will never be displaced from it. In an economy with uncertainty, the endogenous rate of time preference is utilized in a similar manner to determine a stable stochastic stationary state. Epstein (1983) extended the endogenous time-preference framework to an uncertain environment and determined sufficient conditions to obtain a stationary joint limiting distribution of the state variables in the stochastic steady-state. His analysis also showed that this formulation of preferences does not imply a radical departure from the standard time-separable setup. The costs of
adjusting investment are introduced in accordance with the principles summarized in Brechling (1975), adopting the convex, quadratic specification employed by Gould (1968), Craine (1975) and Eichenbaum (1984).

The model is numerically analyzed using an extension of the solution method employed by Sargent (1980) and Greenwood, Hercowitz and Huffman (1988). This procedure computes the exact joint limiting distribution of the state variables in the stochastic stationary equilibrium of the economy, making use of an algorithm that solves numerically the functional equation problem for a discretized version of the state space. The statistical moments that characterize the random processes of the model's endogenous variables are calculated using this limiting distribution, and are then compared with the actual sample moments from detrended, Canadian data.

The rest of the paper is ordered as follows: Section 2 describes the structure of the artificial economy to be studied here and comments on the strategy used to implement the model empirically. Section 3 presents the results of the numerical experiments, stressing the differences between the model with adjustment costs and the free-adjustment neoclassical model and comparing the results with those obtained for some closed-economy prototypes. Some concluding remarks are presented in the last section.

2.- The Structure of the Model and the Solution Technique.

The analysis starts with the description of the artificial economy and an explanation of the numerical solution method employed to analyze it. This section presents first a dynamic stochastic model of a small open economy that incorporates explicit costs of adjustment in the capital stock and an endogenous rate of time preference. The analysis of the model is then
simplified by applying dynamic programming techniques that are used later to calculate numerically the equilibrium stochastic process of the economy.

2.1 Structure of the Model.

Preferences: All agents are identical and infinitely-lived, with preferences described by the Stationary Cardinal Utility function formulated by Epstein (1983)\textsuperscript{5}:

\[
E_0 \left[ \sum_{t=0}^{\infty} \left( u(C_t - G(L_t)) \exp \left\{ -\sum_{r=0}^{t-1} v(C_r - G(L_r)) \right\} \right) \right].
\] (1)

Here, \( C_t \) is private consumption and \( L_t \) are labor services. The Stationary Cardinal Utility is assumed to embody the following instantaneous utility and time-preference functions:

\[
u(C_t - G(L_t)) = (1 - \gamma)^{-1} \left[ (C_t - L_t^{\omega/\omega})^{1 - \gamma} - 1 \right], \quad \omega > 1, \quad \gamma > 1, \quad (2)
\]

\[
u(C_t - G(L_t)) = \beta \ln \left[ 1 + C_t - L_t^{\omega/\omega} \right], \quad \beta > 0. \quad (3)
\]

Which satisfy the following conditions:

\[
u(\cdot) > 0, \quad \nu'(\cdot) > 0, \quad \nu''(\cdot) < 0, \quad (4.2)
\]

\[
u'(\cdot) \exp[\nu(\cdot)] \text{ non-increasing,} \quad (4.3)
\]

\[
\text{Log}[-u(\cdot)] \text{ convex.} \quad (4.4)
\]

The formulation of preferences presented in (1) ensures the existence of a well-behaved stationary equilibrium for the holdings of international assets by assuming that the rate of time preference is an increasing function of past consumption levels. As in the work by Obstfeld (1981), the deterministic
long-run equilibrium of foreign-asset holdings is determined by equating the rate of time preference with the world's real interest rate. According to the specific functional forms adopted in (2) and (3), lifetime utility is studied in terms of the composite commodity defined by consumption minus the disutility of labor. This allows the model to focus expressly on the dynamic interaction of domestic capital and foreign financial assets as alternative vehicles of savings. The cost of this simplification, however, is that the intratemporal marginal rate of substitution between consumption and labor is forced to depend on the latter only, and hence the wealth effect affecting the supply of labor is eliminated. Finally, conditions (4.1)-(4.4) are sufficiency conditions identified by Epstein (1983) to satisfy the requirements of dynamic programming, to ensure that consumption in any given period is a normal good and to prove the existence of a stationary probability distribution that characterizes the stochastic steady-state of the economy\(^6\).

**Technology and Financial Structure:** The mechanism by which resources for consumption or investment are made available has two components. First, the domestic production technology is described as follows:

\[
G(K_t, L_t, K_{t+1}) = \exp(e_t) K_t^{\alpha L_t^{1-\alpha}} - (\phi/2)(K_{t+1} - K_t)^2, \tag{5}
\]

\[0 < \alpha < 1, \quad \phi > 0,\]

where \(e_t\) is a random technological shock to be discussed in more detail later, \(K_t^{\alpha L_t^{1-\alpha}}\) is a neoclassical constant-returns-to-scale production function, \(K_t\) is the domestic capital stock currently productive and \((\phi/2)(K_{t+1} - K_t)^2\) is the cost of adjusting the capital stock as a function of net investment \(I_{t+1} - K_{t+1} - K_t\). The capital evolution equation is given by
\[ K_{t+1} = (1-\delta)K_t + I_{gt}, \quad 0 \leq \delta \leq 1, \quad (6) \]

where \( \delta \) is a constant rate of depreciation and \( I_{gt} \) is gross investment.

Individuals also have access to a perfectly competitive, international capital market where foreign financial assets \( A_t \) paying, or charging, the real rate of return \( r^* \) are exchanged with the rest of the world. The holdings of foreign financial assets evolve according to

\[ A_{t+1} = TB_t + A_t(1+r^*), \quad (7) \]

where \( TB_t \) is the balance of trade.

By combining domestic production with foreign borrowing or savings, the aggregate resource constraint dictates that domestic absorption plus the balance of trade cannot exceed GDP net of adjustment costs\(^7\):

\[ C_t + I_{gt} + TB_t \leq \exp(e_t) K_t^\alpha L_t^{1-\alpha} - (\phi/2)(K_{t+1} - K_t)^2. \quad (8) \]

Domestic absorption is defined here as the sum of private consumption and gross investment\(^8\).

The convex quadratic formulation of the adjustment cost included in (5) ensures that the total cost of changing the capital stock by a fixed amount is larger the faster the adjustment. Hence, optimizing agents are motivated to adjust investment in a gradual manner in order to avoid large adjustment costs\(^9\). Also, the domestic economy is assumed to be small relative to the size of the international capital market, so that individuals take \( r^* \) as given when formulating their optimal intertemporal plans. For simplicity, worldwide productivity disturbances are assumed to cancel each other on the average and thus \( r^* \) is considered to be non-random\(^10\).
2.2 The Dynamic Programming Problem and the Solution Technique.

The intertemporal equilibrium of the artificial economy described above is characterized by a set of state-contingent decision rules for consumption, domestic capital, labor supply and foreign financial assets that maximize (1), given $K_0$, $A_0$, $e_0$ and the stochastic process governing the disturbances, subject to (5)-(8), the non-negativity restrictions $K_t \geq 0$, $L_t \geq 0$ and $C_t \geq 0$, and the condition of intertemporal solvency\textsuperscript{11}. The same problem can be studied and numerically solved in a more tractable manner by applying Bellman's optimality principle.

At any given date, the optimal intertemporal choices of rational agents involve selecting $K_{t+1}$, $A_{t+1}$, $C_t$ and $L_t$ given the state of the economy as described by $K_t$, $A_t$ and $e_t$. By taking advantage of the time-recursive structure of the Stationary Cardinal Utility, and by simplifying the stochastic process of the disturbances in the manner discussed below, the optimal decision rules that characterize the equilibrium stochastic process of the economy can be obtained as the solutions of the following dynamic programming problem:

$$V(K_t, A_t, C_t) = \max \left\{ (1-\gamma)^{-1} \left[ (C_t - \frac{C_t}{K_t})^{\gamma} - 1 \right] + \exp[-\beta \ln(1+C_t - \frac{C_t}{K_t})] \left[ \sum_{s=1}^{2} V(K_{t+1}, A_{t+1}, C_{t+1}) \right] \right\},$$

s.t.

$$C_t = \exp(e_t^s) K_t^{\alpha} L_t^{1-\alpha} - K_{t+1} + K_t (1-\delta) - \frac{\theta}{2} (K_{t+1} - K_t)^2 + (1+r)x A_t - A_{t+1},$$

$$L_t = \arg\max_{L_t} \left\{ \exp(e_t^s) K_t^{\alpha} L_t^{1-\alpha} - L_t \frac{\omega}{\omega} \right\}.$$
Here, \( \pi_{sr} \) for \( s,r=1,2 \) denotes the transition probability of the next-period's technological disturbance conditional on its observed value in the current period. Accordingly, the usual properties that \( 0 \leq \pi_{sr} \leq 1 \) and \( \pi_{s1} + \pi_{s2} = 1 \) for \( s,r=1,2 \) must be satisfied. Note that the stochastic structure of the problem has been simplified by assuming that the disturbances follow a two-point Markov process, so that in any given period the productivity shock takes one of two values

\[
\varepsilon_t \in \mathbb{E} = \{ \varepsilon^1, \varepsilon^2 \}. \tag{10}
\]

Then the assumptions that \( \pi_{11} = \pi_{22} = \pi \) and \( \varepsilon^1 = \varepsilon^2 = \varepsilon \) are adopted. These symmetry conditions imply that the asymptotic standard deviation, \( \sigma_\varepsilon \), and the first-order autocorrelation coefficient, \( \rho_\varepsilon \), that characterize the stochastic shocks are given by \( \sigma_\varepsilon = \varepsilon \) and \( \rho_\varepsilon = 2\pi - 1 \) respectively.

The particular values of the parameters \( \gamma \) (coefficient of relative risk aversion), \( \omega \) (1 plus the inverse of the intertemporal elasticity of substitution in labor supply), \( \alpha \) (capital's share in output), \( \delta \) (depreciation rate) and \( \beta \) (the consumption elasticity of the rate of time preference), are selected using long-run averages of actual data and the restrictions imposed by the theoretical structure of the model, and also by considering some estimates obtained in the relevant empirical literature. Accordingly, these structural parameters are assigned the following values:

\[
\alpha = 0.32, \quad \beta = 0.11, \quad \gamma = 1.001 \text{ or } 2.0, \quad \delta = 0.1, \quad \omega = 1.455 \quad \text{and} \quad \sigma^* = 0.04. \tag{11}
\]

The model is calibrated by adjusting the parameters \( \Phi \) (the rate of change of the marginal adjustment cost), \( \varepsilon \) and \( \pi \). The first parameter is selected so as to mimic the observed volatility of private investment, and the second
and third are set so as to replicate the variability and first-order serial autocorrelation of Canadian post-war, detrended GDP$^{13}$.

The dynamic programming problem is solved following a procedure suggested in Bertsekas (1976) and employed by Sargent (1980) and Greenwood, Hercowitz and Huffman (1988). This methodology starts by specifying a discrete grid of points to approximate the state space. In this case, two evenly-spaced grids containing the admissible values of domestic capital \( K = \{K_1, \ldots, K_M\} \) and foreign assets \( A = \{A_1, \ldots, A_N\} \) need to be defined. Thus, the state space of this artificial economy is given by the set \( K \times A \times E \) that contains \( 2MN \) elements.

The next step in the solution process is to construct an algorithm that performs successive iterations in the functional equation (9). The algorithm iterates on (9) using the set of numbers included in \( K \times A \times E \) until the sequences of optimal, state-contingent decision rules for domestic capital and foreign assets converge. The decision rules obtained in this way are combined with the conditional probabilities \( \pi_{sr} \), for \( s, r = 1, 2 \), to define the one-step transition probabilities of moving from any initial triple of domestic capital, foreign assets and the technological disturbances to any other such triple in one period. These transition probabilities are condensed in a matrix \( P \) of dimensions \( (2MN \times 2MN) \), which is used to calculate the stationary probabilities of each triple of \( K, A \) and \( e \). The long-run probabilities are calculated by iterating on the sequence \( \rho^1 = \rho^0 P \), where \( \rho^0 \) is an initial-guess vector of dimensions \( (1 \times 2MN) \) and \( \rho^1 \) is a vector of identical dimensions that is used as the new guess in the following iteration. These iterations eventually converge to a unique fixed point \( \rho^* \), which is the joint limiting probability distribution of \( K, A \) and \( e \) that characterizes the stochastic
steady-state of the economy. This probability distribution is used to compute population moments of variability, comovement and persistence of all endogenous variables in the model.

3.- Calibration and Analysis of the Results.

In this section of the paper, the quantitative performance of the model described in the previous section is evaluated by comparing its own statistical moments with those obtained from the original neoclassical model, where investment does not bear explicit adjustment costs, and with the actual moments from the Canadian economy. This is done for two sets of calibration exercises, one for each value of the risk aversion parameter. The sample moments calculated from the Canadian data are listed in panel A of tables 1 and 2^{14}.

3.1 The Neoclassical Model without Adjustment Costs.

The statistical moments calculated for the neoclassical model are listed in panel B of tables 1 and 2. Panel B of Table 1 presents the results for the case where \( \gamma = 2.0 \) and the same panel in Table 2 lists the moments for \( \gamma = 1.001 \), the marginal probability distribution of domestic capital and foreign assets that corresponds to the first case is plotted in Figure 2. These two artificial economies were calibrated to replicate the observed percentage variability and first-order serial autocorrelation of GDP.

In the case where \( \gamma = 2.0 \), the technological disturbances are set to exhibit 1.18\% volatility and 0.36 first-order autocorrelation. As panels A and B of Table 1 indicate, the neoclassical model exaggerates the volatility
Table 1
Statistical Moments: Canadian Data and Artificial Economiesa.
(γ=2.0)

<table>
<thead>
<tr>
<th>Variables</th>
<th>A Canadian Data 1946-1985</th>
<th>B Artificial Economy Free Adjustment σe=1.18% ρe=0.36 Φ=0.0</th>
<th>C Artificial Economy Costly Adjustment σe=1.29% ρe=0.42 Φ=0.028</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(I)b</td>
<td>(II)c (III)d</td>
<td>(I)b (II)c (III)d</td>
</tr>
<tr>
<td>1) GDP</td>
<td>2.810</td>
<td>0.615 1.000</td>
<td>2.810 0.615 1.000</td>
</tr>
<tr>
<td>2) GNP</td>
<td>2.950</td>
<td>0.643 0.995</td>
<td>2.821 0.619 0.990</td>
</tr>
<tr>
<td>3) C</td>
<td>2.460</td>
<td>0.701 0.586</td>
<td>2.086 0.693 0.944</td>
</tr>
<tr>
<td>4) S</td>
<td>7.306</td>
<td>0.542 0.662</td>
<td>5.772 0.599 0.932</td>
</tr>
<tr>
<td>5) I</td>
<td>9.820</td>
<td>0.314 0.639</td>
<td>21.056 -0.319 0.235</td>
</tr>
<tr>
<td>6) K</td>
<td>1.380</td>
<td>0.649 -0.384</td>
<td>1.980 0.377 0.669</td>
</tr>
<tr>
<td>7) L</td>
<td>2.020</td>
<td>0.541 0.799</td>
<td>1.936 0.615 1.000</td>
</tr>
<tr>
<td>8) rA</td>
<td>15.250</td>
<td>0.727 -0.175</td>
<td>19.566 0.886 -0.198</td>
</tr>
<tr>
<td>9) TB/Y</td>
<td>0.019</td>
<td>0.623 -0.129</td>
<td>0.046 -0.312 0.032</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CORR(S,I) = 0.434</td>
<td>CORR(S,I) = 0.251</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CORR(S,I) = 0.501</td>
<td></td>
</tr>
</tbody>
</table>

aThe data are measured in per-capita terms of the 15+ population, logged and detrended with a linear quadratic time trend. 1)-3), 5) and 8) are the totals from the national income accounts in 1981 dollars. 6) was obtained from the end-of-period net stocks of fixed non-residential capital in manufacturing and non-manufacturing industries, in 1981 prices. The labor data is an index of man hours worked by paid workers with 1981=100.0. Savings in 4) is generated as investment plus the trade balance surplus. The source of all is the CANSIM data retrieval.

bPercentage standard deviation, except 9 which is not in percent.

cFirst-order autocorrelation coefficient.

dCoefficient of correlation with GDP.
MARGINAL PROBABILITY DENSITY OF CAPITAL AND FOREIGN ASSETS IN THE ECONOMY WITHOUT ADJUSTMENT COSTS

Figure 2
<table>
<thead>
<tr>
<th>Variables</th>
<th>A Canadian Data 1946-1985</th>
<th>B Artificial Economy Free Adjustment $\sigma_e=1.18%$ $\rho_e=0.34$ $\Phi=0.0$</th>
<th>C Artificial Economy Costly Adjustment $\sigma_e=1.29%$ $\rho_e=0.41$ $\Phi=0.023$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(I)&lt;sup&gt;b&lt;/sup&gt; (II)&lt;sup&gt;c&lt;/sup&gt; (III)&lt;sup&gt;d&lt;/sup&gt;</td>
<td>(I)&lt;sup&gt;b&lt;/sup&gt; (II)&lt;sup&gt;c&lt;/sup&gt; (III)&lt;sup&gt;d&lt;/sup&gt;</td>
<td>(I)&lt;sup&gt;b&lt;/sup&gt; (II)&lt;sup&gt;c&lt;/sup&gt; (III)&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
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<td>1) GDP</td>
<td>2.810 0.615 1.000</td>
<td>2.810 0.615 1.000</td>
<td>2.810 0.615 1.000</td>
</tr>
<tr>
<td>2) GNP</td>
<td>2.950 0.643 0.995</td>
<td>2.795 0.611 0.997</td>
<td>2.849 0.613 0.998</td>
</tr>
<tr>
<td>3) G</td>
<td>2.460 0.701 0.586</td>
<td>2.105 0.669 0.961</td>
<td>2.234 0.689 0.957</td>
</tr>
<tr>
<td>4) S</td>
<td>7.306 0.542 0.662</td>
<td>5.483 0.590 0.947</td>
<td>5.209 0.568 0.926</td>
</tr>
<tr>
<td>5) I</td>
<td>9.820 0.314 0.639</td>
<td>21.050 -0.343 0.266</td>
<td>9.837 -0.052 0.571</td>
</tr>
<tr>
<td>6) K</td>
<td>1.380 0.649 -0.384</td>
<td>1.913 0.322 0.669</td>
<td>1.347 0.792 0.595</td>
</tr>
<tr>
<td>7) L</td>
<td>2.020 0.541 0.799</td>
<td>1.931 0.615 1.000</td>
<td>1.927 0.615 1.000</td>
</tr>
<tr>
<td>8) $r^A$</td>
<td>15.250 0.727 -0.175</td>
<td>11.064 0.632 -0.354</td>
<td>9.551 0.929 -0.085</td>
</tr>
<tr>
<td>9) TB/Y</td>
<td>0.019 0.623 -0.129</td>
<td>0.046 -0.338 -0.013</td>
<td>0.017 -0.045 -0.080</td>
</tr>
</tbody>
</table>

\[ \text{CORR}(S,I) = 0.434 \quad \text{CORR}(S,I) = 0.268 \quad \text{CORR}(S,I) = 0.616 \]

*See note "a" in Table 1 for sources and calculations.

<sup>b</sup>Percentage standard deviation, except 9 which is not in percent.

<sup>c</sup>First-order autocorrelation coefficient.

<sup>d</sup>GDP correlation coefficient.
of private investment (21.0% instead of 9.8%) and underestimates its first-order autocorrelation (-0.32 v. 0.31), its correlation with GDP (0.24 v. 0.64) and its correlation with aggregate savings (0.25 v. 0.43)\textsuperscript{15}. Furthermore, it also exhibits too much positive comovement between consumption and GDP (0.94 instead of 0.59) and results in negative persistence in the trade-balance-output ratio (-0.31 instead of 0.62). The neoclassical model with $\gamma=1.001$ is calibrated using a 1.18% shock with 0.34 first-order serial autocorrelation. Comparing the results in panel B of tables 1 and 2, it transpires that changes in the degree of risk aversion only have sizeable effects on the stochastic process of foreign-asset holdings. The model still misrepresents the moments that characterize investment in the actual data in approximately the same manner as before.

The process of capital accumulation is badly reproduced by the free-adjustment neoclassical model of investment because of the frictionless manner in which it can be undertaken. Since this is a small open economy, individuals choose separately the optimal amount of savings and the optimal portfolio allocation of those savings across domestic capital and foreign assets. The portfolio decision is made so as to equalize the expected marginal returns, in utility terms, of both vehicles of savings. Optimal savings, on the other hand, are determined by equating the stochastic intertemporal marginal rate of substitution with the real rate of return on foreign assets. When a productivity shock hits this economy, the domestic capital stock is rapidly and freely adjusted to maintain the equality of expected returns, and the optimal alterations in the dynamic path of savings are mainly achieved through changes in foreign-asset accumulation. As discussed in the introduction, investment is not as volatile in closed-economy
real business cycle models, which are also based on the neoclassical framework, because there the optimal savings and investment decisions are the same. Hence, in closed-economy models the accumulation of the capital stock responds to both consumption-smoothing and consumption-substitution effects and faces an increasing supply price. In contrast, in the small open-economy framework the consumption-smoothing effect operates mainly through the current account, the intertemporal consumption-substitution effect is eliminated, and investment faces a constant supply price of the capital stock given by $r^*$. Given that a real business cycle prototype based on the neoclassical model of investment for a small open economy is not capable of mimicking the stylized facts of Canadian private investment, it is reasonable to deduce that the actual savings mechanism operating in the economy is not as flexible as this framework indicates. The ability that agents in this model have to equalize returns across alternative vehicles of savings can be limited in various ways. It is possible to introduce capital market imperfections or to impose controls on international capital flows. However, the Canadian economy has been historically characterized by the absence of capital controls and a high degree of integration with the U.S. financial markets. Thus, it is more likely that the frictions affecting optimal portfolio allocation are located in the process of domestic investment instead of the current account.

One possible friction affecting the accumulation of domestic capital is the irreversibility of investment studied in Sargent (1980). However, gross and net investment in the simulations of the free-adjustment model resulted always positive in every state of nature. Hence, investment irreversibility is not a binding constraint for this particular model. Another friction that complicates investment, which has been largely studied in the closed-economy
context, are adjustment costs in the process of accumulating capital. The role of such adjustment costs in the present model is thoroughly analyzed next.

3.2 The Model with Adjustment Costs.

When the costs of adjusting the capital stock take the form introduced in (5), the marginal cost of altering investment is increasing with the absolute size of the adjustment. Firms will then have to consider both current and future marginal adjustment costs when formulating their optimal intertemporal plans. As a result, the reaction of the capital stock to a given change in domestic productivity will be more gradual and the overall behavior of the investment process will be less volatile.

The statistical moments that characterize the equilibrium stochastic process of the artificial economy with investment-adjustment costs are listed in panel C of tables 1 and 2. Panel C of Table 1 presents the results for the case where \( \gamma = 2.0 \), and the corresponding marginal probability density of \( K \) and \( A \) is depicted in Figure 3. Panel C of Table 2 lists the results for \( \gamma = 1.001 \).

In the case where the risk aversion parameter is given a value of 2.0, the artificial economy with adjustment costs is calibrated setting \( \Phi = 0.028 \), \( \sigma_e = 1.29 \) and \( \rho_e = 0.42 \). The value of \( \Phi \) was not predetermined as the other parameter values because of the partial-equilibrium, non-structural nature of most of the existing empirical work on adjustment cost models of investment. However, the value \( \Phi = 0.028 \) is consistent with the findings of Craine (1975) for the U.S. economy. Using a ratio of price indices to approximate the relative price of capital goods in terms of output, Craine (1975) estimated that the coefficient of the quadratic adjustment cost function is 0.025.
MARGINAL PROBABILITY DENSITY OF CAPITAL AND FOREIGN ASSETS IN THE ECONOMY WITH ADJUSTMENT COSTS
Figure 3
Furthermore, the fact that the average adjustment cost in the artificial economy is only about 0.1% of GDP is also consistent with the findings of Brechling (1975) and Eichenbaum (1984), in the sense that investment-adjustment costs are statistically significant but relatively small in size. Thus, the numerical investigation performed here indicates that modest adjustment costs are sufficient to induce a less volatile pattern of investment behavior.

The analysis of panels A and C of Table 1 indicates that the model with capital-adjustment costs is capable of replicating the majority of the stylized facts that characterize Canadian business cycles. First, it generates procyclical behavior in consumption, investment, employment and savings, and produces stochastic processes for the ratio of the balance of trade to output and foreign interest payments that are almost serially uncorrelated. Second, it replicates the same ranking of percentage variability in which the actual aggregates are ordered. In fact, with the exception of $r^A$, it mimics the actual percentage standard deviations very closely. Third, the model replicates some of the first-order autocorrelation coefficients calculated with the actual data.

Table 1 also illustrates that the adjustment-cost model is capable of replicating the correlation between savings and investment. In fact, the comovement between savings and investment is already higher than what is actually observed in the Canadian data (0.50 v. 0.43). This result shows that the model can replicate the observed correlation between savings and investment and at the same time explain actual business cycles, all without affecting the assumption of perfect international mobility of financial capital. Thus, the findings of the theoretical analysis, based on numerical
simulations of overlapping-generations models, by Obstfeld (1985) and Finn (1988) are successfully extended to a calibration exercise in the context of an infinite-horizon economy, and the argument of Feldstein and Horioka (1980) appears to be invalidated.

The introduction of explicit adjustment costs improves the match between the actual sample moments and the artificial economy's moments. The model with adjustment costs generates statistical moments of volatility, persistence, savings correlation and GDP correlation of private investment that are closer approximations of the actual moments than those obtained with the neoclassical model\(^\text{17}\). Furthermore, the moments of the trade-balance-output ratio and the domestic capital stock are also closer to the observed moments, although the variability, persistence and comovement of foreign assets (and foreign interest payments since \(r^*\) is non-random here) are all exaggerated.

It is worth noting that the costly-adjustment model can mimic the variability of both investment and the trade-balance-output ratio very closely. This observation reaffirms the suggestion that the introduction of adjustment costs may play an important role in open-economy real business cycles. Furthermore, following Greenwood (1983), the productivity disturbances can be reinterpreted as real-exchange-rate disturbances, and hence these results also indicate that relatively small and transitory terms-of-trade shocks are capable of causing the observed fluctuations in the balance of trade and foreign assets.

Panel C of Table 2 lists the moments calculated for the artificial economy with capital-adjustment costs calibrated under the assumption that \(\gamma = 1.001\). In this case, the model requires a 1.29% shock with 0.41 persistence
and an adjustment-cost coefficient $\Phi = 0.023$. As in the case of the neoclassical model, it is observed that changes in the degree of risk aversion only affect the stochastic process of foreign asset holdings. The model generates a better approximation of the actual moments in the same way as before, with the variability of foreign interest payments falling to 9.5%, their first-order autocorrelation increasing to 0.93 and their comovement with GDP changing to -0.085.

An important disadvantage of cost-of-adjustment models in general is that they tend to produce testable vector autoregressions where the effects of highly persistent shocks cannot be distinguished from the effects of significant adjustment costs$^{18}$. In this paper, a similar problem may arise because the variability of investment in the neoclassical model can be reduced by increasing the first-order serial autocorrelation of the disturbances (i.e. their one-step transition probability $\pi$), instead of introducing the adjustment costs. By increasing the probability of not moving to the opposite state of productivity, the probability of having to accumulate or deplete the capital stock very rapidly is reduced, and hence the variability of investment is also reduced. However, by following this route, the persistence of the shocks is driven to such a high degree that the variability and persistence of all the other aggregates is also increased, and hence the model cannot replicate actual business cycles. For instance, if in the case that $\gamma = 2 \rho_e$ is set to 0.99, the variability of investment is reduced to 5.4%, but the variability of GDP becomes 5.0% and it behaves almost as a random walk. Thus, in the context of the present model, it is possible to establish the importance of adjustment costs relative to highly persistence shocks by noting that the latter cannot be employed to mimic real-world
3.3 Comparison with Closed-Economy Models and Sensitivity Analysis.

In comparison with the existing work on closed-economy real business cycle models, the two small open-economy prototypes were calibrated using productivity disturbances that exhibit less exogenous volatility and persistence. With respect to the persistence of the disturbances, in the works of Hansen (1985), Prescott (1986) and King, Flosser and Rebelo (1988) the shocks follow a stochastic process close to a random walk, Hansen (1985) estimates their quarterly correlation at 0.95 (0.81 annually). The model with endogenous utilization and investment shocks of Greenwood, Hercowitz and Huffman (1988) requires technological disturbances with 0.51 annual persistence. In contrast, when \( \gamma = 2.0 \), the open-economy prototypes require shocks with 0.35 and 0.42 first-order serial autocorrelation for the cases of the neoclassical model and the cost-of-adjustment model respectively.

Considering now the volatility of the disturbances, the ratios of the required volatility of the shocks relative to the observed variability of output are 1.3 and 1.7 in Hansen (1985) and 1.47 in Greenwood, Hercowitz and Huffman (1988). In the open-economy models these ratios are 0.42 for the neoclassical prototype and 0.71 for the model with adjustment costs, when the risk aversion parameter is assigned a value of 2.0. Thus, although open-economy real business cycle models appear to require smaller and less persistent shocks compared with closed-economy prototypes, the open-economy model with adjustment costs does require relatively larger and more serially correlated disturbances than the neoclassical model.

The introduction of the cost of adjustment in the small open-economy
framework has very different consequences than what has been observed in closed-economy real business cycle models. Kydland and Prescott (1982) evaluated the importance of their time-to-build formulation by introducing capital-adjustment costs and studying how this affected the behavior of their closed-economy model. They observed that, setting $\Phi=1$, the statistical moments resulting from the artificial economy were largely inconsistent with U.S. quarterly detrended data. In particular, compared with the model that considers the time-to-build technology instead of adjustment costs, the standard deviation of consumption almost doubled and that of investment expenditures fell by a factor of two. In contrast, in the model studied here adjustment costs are much smaller, since $\Phi$ is 0.028 when $\gamma=2$ and 0.023 when $\gamma=1.001$, and they have the effect of reducing the percentage variability of investment without significantly affecting the behavior of consumption.

It is also worth noting that, relative to the observed sample moments and the results obtained with closed-economy prototypes, both open-economy models exaggerate the comovement between consumption (or savings) and GDP. The introduction of adjustment costs cannot alleviate this problem because such costs do not alter the fact that the intertemporal relative price of consumption is fixed in the world's capital market, and hence the consumption-substitution effects that operate in the closed-economy models are no longer at work.

The comparison of the results listed in Table 2 with the closed-economy models mentioned before shows that the conclusions obtained are robust to changes in the risk aversion parameter. Small open-economy models require relatively smaller and less persistent shocks than closed-economy models in order to replicate the observed volatility and persistence of domestic output,
although the open-economy model with costly adjustment needs disturbances that are relatively larger and more serially correlated than the free-adjustment open economy. Furthermore, the correlation between consumption or savings and output remains very high and seems insensitive to changes in $\gamma$. This is due to the mentioned fact that the intertemporal relative price of consumption is not affected by domestic productivity disturbances.

The comparison of panels B and C of tables 1 and 2 has shown that changes in the degree of risk aversion affect only the stochastic process of foreign-asset holdings, independently of whether the domestic capital stock is costly to adjust or not. The study of the overall effects that the reduction in $\gamma$ from 2.0 to 1.001 causes, indicates that using some intermediate value of this parameter is likely to make the costly-adjustment model replicate the observed sample moments better than any of the two sets of results presented. Specifically, by choosing the appropriate size for the risk aversion parameter, it may be possible to match the observed moments of foreign interest payments $r^A$ without significantly affecting the close match of the other moments. The required value for the coefficient $\gamma$ would still fall inside the rank of the estimates that are commonly regarded as credible.

4. - Conclusions.

This paper explored the relevance of capital-adjustment costs in the theory of investment of a small open economy and investigated the ability of a real business cycle model to replicate the stylized facts of Canadian business cycles. The model is capable of replicating the majority of the statistical moments obtained from the actual data, including the correlation between savings and investment, using very small capital-adjustment costs and minimal
variability and persistence in the technological disturbances. Specifically, the artificial economy generates similar procyclical and countercyclical patterns as those observed in the macro-aggregates, it replicates the observed ranking and values of the percentage standard deviations, and approximates the ranking and values of some of the first-order autocorrelation coefficients.

In contrast with the costly-adjustment model, the free-adjustment neoclassical model of investment exaggerates the flexibility of the existing savings mechanism, and results in an equilibrium stochastic process where the investment series is extremely volatile. This model exaggerates the percentage variability of investment and underestimates its first-order serial autocorrelation and its correlation with output and savings.

In comparison with some of the closed-economy real business cycle prototypes, the small open-economy model with adjustment costs is capable of replicating the observed variability and persistence of domestic output using smaller and less persistent productivity disturbances. However, this model seems to require relatively larger and more serially correlated shocks than the free-adjustment neoclassical prototype.

Finally, the sensitivity analysis of the model's performance to changes in the degree of risk aversion suggests that setting this parameter to a value inside the rank of credible estimates may result in a very close fit to the actual moments. Such a configuration of the model can be used to evaluate positive and normative effects of a variety of economic policies. This is a task left for further research.
FOOTNOTES


2. Consider, for example, a simplified version of the model of Long and Plosser (1983) where closed-form solutions can be obtained. The closed-form solution for the equilibrium interest rate is

\[ r_t = \frac{\epsilon_{t+1}}{\epsilon_t} \alpha^\alpha (L/\beta Y_t)^{1-\alpha} - 1, \]

where \( Y_t \) is output defined by a Cobb-Douglas technology, \( \alpha \) is the capital's share on output, \( \beta \) is the constant subjective discount factor and \( L \) is a constant supply of labor. If the disturbances were deterministic and stationary, evolving according to a serially autocorrelated process \( \epsilon_{t+1} = \rho \epsilon_t \) with \( 0 < \rho < 1 \), the above expression could be rewritten as

\[ r_t = (\rho \epsilon_t) \alpha^\alpha (L/\beta Y_t)^{1-\alpha} - 1. \]

Hence, under these conditions, productivity improvements always induce an increase in the equilibrium real interest rate and motivate agents to substitute current consumption for future consumption.

3. In a stochastic model the equality of returns does not hold exactly period by period. Instead, it holds in form of an expected value where the different realizations of the rates of return are weighted by the corresponding lifetime marginal utility of consumption.

4. Alternatively, as in Backus, Kehoe and Kydland (1989), the time-to-build technology of Kydland and Prescott (1982) could be used to moderate the variability of investment in the open-economy model. The adjustment-cost formulation has the advantage of allowing procyclical fluctuations in the relative price of investment goods, but it forces lagged values of this relative price to be irrelevant for current investment decisions and assumes that investment projects are completed in one period. The time-to-build technology can incorporate different gestation periods, but it assumes that the relative price of investment goods is fixed and independent of the amount of capital being accumulated.

5. A stable steady-state equilibrium for the holdings of foreign assets can also be obtained by assuming that individuals face a positive probability of dying each period. This methodology is explored in detail in Frenkel and Razin (1987).

6. Theorems (3)-(5) of Epstein (1983) show that these conditions, added to a neoclassical production technology satisfying the Inada conditions or a linear technology, are sufficient to guarantee the existence of a stationary joint limiting distribution of the capital stock and the productivity disturbances in the stochastic steady-state of a closed
economy. Given that the instantaneous-utility and time-preference functions (2) and (3) have been defined in terms of the composite C-G(L), it is straightforward to show that Theorem (5) still holds. These and other technical issues have been studied in Mendoza (1988).

7. Notice that (8) allows the relative price of investment and consumption goods to vary. The expression can be rewritten as

\[ C_t + \frac{1}{2} [I_t - \delta K_t] + TB_t \leq \exp(c_t) K_t^{\alpha} L_t^{1-\alpha}. \]

Where the marginal rate of technical substitution between \( C_t \) and \( I_t \) is given by \( q = 1 + \theta (I_t - \delta K_t) \). In equilibrium, \( q \) is the relative price of investment goods in terms of consumption goods.

8. For simplicity, (8) ignores the possibility of international trade in contingent claims and to this extent limits the option of international risk sharing. Note, however, that individuals can still insure themselves against the risk of domestic productivity changes by trading risk-less foreign assets. Furthermore, recent work by Cole and Obstfeld (1988) suggests that, under certain configurations of preferences and technology, the incompleteness of world financial markets does not affect competitive allocations.

9. The formal analysis of the dynamic optimization problem implied by the model illustrates that the evolution of the capital stock around the steady-state can be characterized as in any adjustment-cost model. The steady-state deviations of the capital stock evolve as a stable, first-order difference equation.

10. This simplifying assumption is not innocuous. Interest-rate shocks induce additional consumption-substitution and consumption-smoothing effects, the direction of the latter depending on whether the economy starts out as a net borrower or lender in the world's capital market. Numerical experiments with moderate \( r^* \) shocks did not show major changes in the set of results to be discussed in the paper, illustrating that, in the present model, the randomness of the interest rate is probably not as important as the fact that \( r^* \) does not depend on the amount of accumulated. In fact, as shown in Mendoza (1988), interest-rate fluctuations are likely to cause minor changes as long as the shocks are small and transitory, the interest rate is small and foreign interest payments are a small component of GDP.

11. As Chamberlain and Wilson (1984) have shown, solvency restrictions in stochastic models may take complicated forms. Here, however, the boundary restrictions on the rate of time preference for the case of a linear technology, established in Theorem 4 of Epstein (1983), were sufficient to ensure long-run solvency. The solvency requirement was numerically verified by noting that the limiting probability of setting foreign-asset holdings below -1.142 or above -0.23 is infinitesimal. Thus, the solvency condition that \( \lim_{t \to \infty} A_t/(1+r^*) t = 0 \) holds for every \( A_t \) that has non-zero probability of being reached in the long run, starting from any triple \( (K_0, A_0, e_0) \) in the state space. Additional
numerical experiments were performed to confirm that the limiting
distribution of the state variables is unique, stationary and stable.

12. The parameter \( \alpha \) is determined with the long-run average of the ratio of
labor income to net national income at factor prices. The depreciation
rate \( \delta \) has the value commonly used in the real business cycle literature
and with it the model generates the same investment-to-output ratio
observed in the data. The value of \( \omega \) is in the range of the estimates of
the intertemporal elasticity of substitution in labor supply \((1/(\omega-1))\)
obtained by MacCurdy (1981) and Heckman and MacCurdy (1980,1982), it
enables the model to mimic closely the percentage variability of hours
worked. The world's interest rate \( r^* \) is set to the value suggested by
Kydland and Prescott (1982) and Prescott (1986) for the real interest
rate in the U.S. economy. The parameter \( \gamma \) adopts two different values
consistent with the findings of Hansen and Singleton (1983) and Friend
and Blume (1975). The value of \( \beta \) is determined using the long-run
average of the GNP/GDP ratio and the other parameter values so as to
ensure that in the deterministic steady-state the rate of time preference
equals \( r^* \).

13. An alternative approach to this calibration strategy is to restrict the
parameters of variability and persistence of the disturbances according
to the results obtained by calculating Solow residuals with actual data.
However, the existent data on the Canadian capital stock is not very
useful for this purposes, as indicated by the poor results obtained
estimating a Cobb-Douglas production function with it and by the
countercyclical behavior it exhibits. In any event, a sensitivity
analysis of the effects caused by increasing the first-order serial
autocorrelation of the shocks is undertaken later in the paper.

14. The actual data from the Canadian economy corresponds to annual time
series from 1946 to 1985. The data were divided by the 15+ population,
logged and detrended with a linear quadratic time trend.

15. The low correlation between savings and investment in the neoclassical
model is not related to the degree of international capital mobility,
instead it follows from the size and autocorrelation of the shocks used
to calibrate the model.

16. As explained in note 7 above, the introduction of adjustment costs allows
the relative price of investment and consumption goods \( q \) to vary. When
the risk aversion parameter is set to 2, the expected value of \( q \) is
almost 1 with 1.0% standard deviation, the correlation between \( q \) and GDP
is about 0.4 and its first-order autocorrelation is -0.001. Thus, as
Kydland and Prescott (1982) point out, adjustment-costs formulations
generate a fluctuating and procyclical \( q \), but deliver the counter-factual
prediction that lagged \( q \)'s should not matter.

17. Both artificial economies generate stochastic processes for the supply of
labor that exhibit the same first-order serial autocorrelation and output
correlation as GDP, this is an implication of the specific functional
forms of preferences and technology that have been adopted.
18. The interested reader is directed to the works of Sargent (1978) and Eichenbaum (1984) for a clear illustration of this problem.

19. The results of Greenwood, Hercowitz and Huffman (1988) are easier to compare because the same detrending procedure and solution technique are used here.
REFERENCES


