Capital maintenance and depreciation over the business cycle

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\textbf{Abstract}

This paper develops and estimates a stochastic general equilibrium model with capital maintenance, which affects endogenously the depreciation rate of capital. The estimate of maintenance series is found to track survey-based measures for Canada quite closely and to generate the procyclical pattern of maintenance observed in the data. We use our model estimates to infer the time profile of equipment capital depreciation in Canadian and US manufacturing. The depreciation rate is estimated to be volatile and highly procyclical in both countries.

1. Introduction

Casual empiricism suggests that expenditures on capital maintenance constitute an integral part of the capital accumulation process. Broadly, outlays on capital maintenance cover the \textit{“deliberate utilization of all resources that preserve the operative state of capital goods”} (Bitros, 1976). As pointed out by Feldstein and Foot (1971), surveys on planned investment in the US for the period 1949–1968 suggest that roughly one-half of ‘gross’ investment aimed at maintaining the operative state of capital goods (replacement and modernization) as opposed to ‘new’ investment (expansion). Capital maintenance is, thus, directly related to capital depreciation and many authors have studied the optimal maintenance level at the firm level with the depreciation rate modeled as an endogenous function of maintenance outlays.\textsuperscript{1}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{JEL classification:} & E22 \\
\hline
\textbf{Keywords:} & Real business cycle \\
\hline
& Endogenous capital depreciation \\
\hline
& Maintenance \\
\hline
\end{tabular}
\end{table}

\textsuperscript{1} See, among others, Schmalensee (1974), Nickell (1978), Schworm (1979) and Parks (1979) for early contributions in this literature. Also, some empirical studies at the sectoral level have confirmed that capital deterioration is affected by maintenance expenditures; see Nelson and Caputo (1997) and the references cited therein for a brief survey of the empirical findings.

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http://dx.doi.org/10.1016/j.jedc.2013.12.008
McGrattan and Schmitz (1999) were the first to provide a detailed picture on the size of aggregate capital maintenance using evidence from the Canadian survey on Capital and Repair Expenditures, which is the only source of aggregate long-run data on capital expenditures in newly purchased assets (‘new’ investment) and maintenance available at the national level. According to this survey, total (private and public) maintenance and repair expenditures in Canada amounted on an average to around 6.3% of GDP for the period 1956–1993. This number is roughly equal to one-third of spending on ‘new’ investments and, when compared to other ‘engines of growth’, is somewhat lower than education spending (6.8% of GDP), but far above the average spending on R&D (1.4% of GDP) over the same period, suggesting that maintenance expenditures are ‘too big to ignore’.

This paper develops and estimates a Dynamic Stochastic General Equilibrium (DSGE) model, in which capital maintenance together with capital utilization affect endogenously the capital depreciation rate. Our model is found to perform well in replicating key features of the data and allows us to derive the time profile of endogenous capital depreciation in a general equilibrium setup. Several studies have attempted to estimate the depreciation rate, mainly in US manufacturing, using various single or multi-equation econometric approaches (see Epstein and Denny, 1980; Hulten and Wykoff, 1981a,b; Nadiri and Prucha, 1996a,b; Jorgenson, 1996; Oliner, 1996; Huang and Dievert, 2011). Most of these papers find that the depreciation rate is fairly stable and that a constant depreciation rate may be a valid approximation for calibration exercises. On the other hand, Tevlin and Whelan (2003) point out that the rapid depreciation of computing equipment that took place in the 1990s led to a rise of the estimated depreciation rate for aggregate equipment capital. This assessment is confirmed by Doms et al. (2004) and Geske et al. (2007). Our results complement the findings in those studies: the implied depreciation rate for equipment capital in Canadian and US manufacturing displayed substantial volatility and a highly procyclical pattern over the last 50 years.

What generates the difference in our estimate relative to the previous ones is the behavior of capital maintenance. While investment spending can be typically obtained from fixed non-residential private investment on property, plant and equipment in national accounts, and capital outlays from panel data for two-digit or plant-level manufacturing firms (in the US Compustat Industrial database), capital maintenance is mainly undertaken by employees. Hence there are no recorded market transactions. Moreover, maintenance and repair services purchased by firms in the market are typically treated as transactions involving intermediate goods. Thus, although maintenance activities are included in measured real output, their magnitude cannot be recovered by standard sources, like national accounting systems. Given the scarcity of available estimates for maintenance, we use the ‘Capital and Repair Expenditures,’ survey, which covers the period 1956–2005, to obtain proxies for maintenance and ‘new’ investment of equipment capital in the Canadian manufacturing sector. According to this data, total expenditures in ‘new’ investment and maintenance was on an average 16.7% of manufacturing output, with the average share of maintenance over total investment amounting to 36.1% and accounting for 6% of output and 4.9% of the capital stock. Turning to the cyclical properties of the data, we observe that maintenance expenditures are procyclical. Fig. 1a and b plots spending on capital maintenance and the associated maintenance to capital ratio (henceforth, MK ratio), and manufacturing output. Both measures of maintenance are strongly procyclical in agreement with the evidence reported by McGrattan and Schmitz (1999).²

We set up an otherwise standard Real Business Cycle (RBC) model in which capital outlays comprise, apart from ‘new’ investment that adds directly to the capital stock, maintenance expenditures that affect the capital decay rate. We also employ a general specification for the depreciation function that embeds the effect of capital utilization on depreciation, as in Burnside and Eichenbaum (1996), and its interactions with capital maintenance. The structural parameters of the model are estimated with Bayesian techniques using aggregate Canadian manufacturing data for output, capacity utilization, total investment, consumption and hours worked as observables for the period 1956–2005. The model generates estimates for capital maintenance expenditures that mimic reasonably well the cyclical behavior of actual survey-based series for Canada. Given the success of the model for Canada we also obtain consistent estimates for capital maintenance in the US over the period 1958–2009, a period for which there has been no systematic data collection on this type of outlays.³ We then use these estimates to obtain the time profile of the depreciation rate of equipment capital in Canadian and US manufacturing over the business cycle.

To the best of our knowledge very few DSGE macroeconomic models have attempted to endogenize maintenance outlays. Early contributions to this literature can be found in Licandro and Puch (2000) and Collard and Kollintzas (2000). In both studies maintenance moves countercyclically, which contradicts the stylized facts presented in Fig. 1a and b. Collard and Kollintzas (2000) consider two types of labor that can be used in production and maintenance, respectively. Since higher productivity causes labor in production activities to be more efficient, maintenance activities may fall after a total

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² Descriptive statistics point towards a contemporaneous correlation between maintenance and MK ratio with output of 0.63 and 0.60, respectively. This correlation seems to be higher in the first part of the sample: for the period 1956–1983 the corresponding correlation coefficients amount to 0.85 and 0.86.

³ We note that the US Census Bureau has added in the Annual Survey of Manufacturers entries on Repair and Maintenance services of buildings and/or machinery for the years 2007, 2008, and 2009. The definition includes payments on purchased services for all maintenance and repair work on buildings and equipment. Payments made to other establishments of the same company and for repair and maintenance of any leased property also are included. Excluded are extensive repairs or reconstruction that was capitalized, which is considered capital expenditures, costs incurred directly by the establishment in using its own work force to perform repairs and maintenance work, and repairs and maintenance provided by the building or machinery owner as part of the rental contract. ‘New’ investments and maintenance account on an average for 8.7% of total (equipment and structures) US manufacturing output, with maintenance amounting to 20.9% of total investment.
factor productivity (henceforth TFP) shock, but, at the same time, higher output efficiency releases labor towards maintenance activities. In equilibrium the first effect dominates and maintenance is countercyclical driving depreciation rates up during booms. In our specification the impact of technology shocks on maintenance depends solely on its interaction with capital utilization. Licandro and Puch (2000) argue that maintenance should be countercyclical because it is cheaper for firms to repair and maintain machines in recessions. They formalize this argument by assuming that the cross derivative of the depreciation function with respect to maintenance and utilization is positive. Our estimates instead suggest that the sign of this derivative is negative.

Some papers have investigated issues that affect the trade offs discussed in this paper. For example, Whelan (2002) and Tevlin and Whelan (2003) study how investment and depreciation respond to technology shocks, a feature that is crucial to determine the magnitude of the depreciation rate, particularly in high-technology sectors like computing. Boucekkine and Ruiz-Tamarit (2003) and Saglam and Veliov (2008) have studied how depreciation reacts to different types of technology shocks. Boucekkine et al. (2009) distinguish between endogenous age-related depreciation, which depends on optimal capital utilization when new capital goods arrive, and endogenous capital scrapping. They find that the scrapping rate drops when neutral technical progress accelerates while age-related depreciation remains unaffected, whereas both age-related depreciation and scrapping rates increase with investment-specific technical progress. In our model, a TFP shock raises capital utilization, maintenance and depreciation, while an investment-specific shock reduces the price of investment, leading to higher capital utilization and depreciation. When maintenance is considered, the fall in the price of investment increases the relative price of maintenance and agents find it optimal to decrease maintenance expenditures, which further raises the depreciation rate. Boucekkine et al. (2010) examine the short-run responses of investment and maintenance and

![Graph](image-url)
find that they move in the same direction following technology shocks, thus, suggesting that they act complementary to each other.

The rest of the paper is organized as follows. Section 2 presents the model. Section 3 discusses the results from the Bayesian estimation and presents the model dynamics. Section 4 presents the estimates for the time profile of capital depreciation in Canada and the US. Finally, Section 5 concludes.

2. The model

2.1. Households

The economy is inhabited by infinitely lived agents who derive utility from consumption, $C_t$, and disutility from hours worked, $h_t$, at each period $t$. The present-value utility of the household is given by

$$
E \sum_{t=0}^{\infty} \beta^t h_t^\alpha \left( \frac{C_t^{1-\alpha}}{1-\alpha} - \lambda_\theta h_t^\gamma \right) \left( 1 + \theta_\delta - \lambda_\partial + \theta_\delta h_t^\gamma \right)
$$

(1)

where $\sigma > 0$ is the risk aversion coefficient, $\theta_\alpha > 0$ determines the supply elasticity of hours, and $\lambda_\alpha > 0$ is a preference parameter. Parameter $\beta$ is a subjective discount factor with $0 < \beta < 1$ and $E$ is the expectation operator. $\theta_\alpha$ and $\theta_\delta$ represent a preference shock and a labor supply shock, respectively; both shocks are assumed to follow an AR(1) process with i.i.d. Normal error term: log $\theta_\alpha$ and log $\theta_\delta$ are Normal i.i.d. shocks. We introduce both a labor supply and a preference shock in our model because the literature has shown that both are important to reproduce the dynamics of business cycle fluctuations (see e.g. Smets and Wouters, 2007).

The representative household owns the capital stock and receives income from renting the effective capital stock (capital services), $U_t K_t$, to the firm at a rate $r_t$, where $U_t$ is the utilization rate of the capital stock $K_t$ and from working at a wage rate $w_t$. The household allocates her income stream between consumption $C_t$, ‘new’ investment $I_t$, and capital maintenance $M_t$:

$$
C_t + I_t + M_t \leq w_t h_t + r_t U_t K_t
$$

(2)

The rate at which capital depreciates depends positively on its utilization and negatively on maintenance expenditures. ‘New’ investment, $I_t$, is related to the capital stock accumulation by

$$
Z_t h_t = K_{t+1} - \left( 1 - \delta \left( U_t \frac{M_t}{K_t} \right) \right) K_t + V \left( \frac{K_{t+1}}{K_t} \right) K_t
$$

(3)

where $\delta(\cdot)$ is the depreciation function and $V(\cdot)$ is a function of gross investment regulating capital adjustment costs. The variable $Z_t$ denotes an investment-specific technology shock that represents technological advances either in the investment good (like technological advances) or in the process for producing it, thus affecting the real price of investment. Greenwood et al. (1997, 2000) have shown that technology shocks involving investment-specific rather than neutral technological change can be a major source of the business cycle. Fisher (2006) shows that the combined impact of neutral and investment-specific shocks is important in explaining fluctuations of output and labor in the US with investment-specific shocks mattering more than TFP shocks. As a result, including investment-specific shocks in the model is crucial for studying the dynamics of maintenance. We let log $Z_t / Z_{t-1} = \rho_t log(Z_{t-1} / Z_t) + \epsilon_t$, where $\epsilon_t$ is an i.i.d. Normal error.

We specify the capital adjustment costs function to be of the form

$$
V \left( \frac{K_{t+1}}{K_t} \right) = \frac{b}{2} \left( \frac{K_{t+1}}{K_t} - 1 \right)^2
$$

(4)

where $b > 0$ is a parameter measuring the degree of capital adjustment costs.

2.2. The depreciation function

As in McGrattan and Schmitz (1999), we assume that depreciation is a decreasing function of maintenance expenditure, so that as maintenance services per unit of the capital stock increase, the rate at which capital depreciates decreases. Following Greenwood et al. (1988) and Burnside and Eichenbaum (1996) we also allow depreciation to be an increasing function of capital utilization. Hence, the depreciation function is parameterized as

$$
\delta \left( U_t \frac{M_t}{K_t} \right) = \phi \psi U_t^p + (1 - \psi) e^{-\gamma M_t / K_t} v^p
$$

(5)

where $\phi, \gamma \geq 0$. Given the trade-off between the production benefits and the depreciation costs of capital utilization, the agent will, in general, not find it optimal to fully utilize the capital stock. Under our assumptions there is also a trade-off in allocating resources between ‘new’ investment $I_t$ and capital maintenance $M_t$, which will be determined by their respective returns.

The parameters $\phi$ and $\gamma$ in Eq. (5) determine the effect of utilization and maintenance on the rate of depreciation of capital, respectively. When $\phi > 0$, $\partial \delta / \partial U > 0$, whereas when $\phi = 0$, capital utilization does not affect the rate at which capital depreciates. Similarly, if $\gamma > 0$, $\partial \delta / \partial M < 0$ and $\partial^2 \delta / \partial M^2 > 0$, while $\gamma = 0$ implies that maintenance expenditures do not affect the capital depreciation rate. Moreover, when the capital stock is not utilized and maintenance expenditures are very high, there is no...
depreciation, i.e. \( \delta(0, \infty) = 0 \). Notice that specification (5) nests the one used by McGrattan and Schmitz (1999) for \( \psi = 0 \) and the one in Burnside and Eichenbaum (1996) for \( \psi = 1 \). When maintenance is assumed to be constant in the benchmark model, the depreciation function takes the form \( \delta(U_t) = \delta U_t^{\psi} \), in line with Greenwood et al. (1988) and Burnside and Eichenbaum (1996).

As described in Boucekkine and Ruiz-Tamarit (2003) and Boucekkine et al. (2010), the sign of the cross derivative \( \partial^2 \delta / \partial M \partial U \) is crucial to determine the degree of complementarity or substitutability between investment and maintenance. The sign of this derivative is determined by \( \theta \); when \( \theta > 1 (\theta < 1) \) the cross derivative is negative (positive). In the steady state the value of \( \theta \) depends on the values of parameters \( \gamma, \phi \) and \( \alpha \). In our exercise we let \( \theta \) to take values larger or smaller than one.

### 2.3. Production side and market clearing

Firms use capital services and labor hours to produce a final good, \( Y_t \), that can be used for consumption, investment and maintenance activities. The representative firm then chooses its factor inputs, hours worked, \( h_t \), and capital services, \( U_tK_t \), to produce a given level of \( Y_t \) in order to minimize the production costs:

\[
w_t h_t + r_t U_t K_t
\]

subject to the technological constraint

\[
Y_t = (U_t K_t)^{1-\alpha}(X_t h_t)\alpha
\]

where \( X_t \) represents a neutral labor-augmenting technology TFP shock: \( \log(X_t) = \rho_{\eta} \log(X_{t-1}) + \epsilon_{\eta t} \), where \( \epsilon_{\eta t} \) is an i.i.d. Normal error.

In equilibrium the goods market clears and we have

\[
Y_t = C_t + I_t + M_t + G_t
\]

where \( G_t \) is a public spending shock: \( \log(G_t) = \rho_{\psi} \log(G_{t-1}) + \epsilon_{\psi t} \), where \( \epsilon_{\psi t} \) is an i.i.d. Normal error.

### 2.4. Model solution

The representative agent chooses sequences of \( C_t, h_t, U_t, I_t, \) and \( M_t \), to maximize (1) subject to (2) and (3). The first-order conditions are given by

\[
\eta_{t+1} = aC_t^{-\alpha} Y_t \quad \frac{h_t}{U_t}
\]

\[
(1-\alpha) Y_t \frac{U_t}{Z_t} = \xi \theta \rho_{\eta} (\psi U_t^\phi + (1-\psi)e^{-\gamma M_t/K_t^\phi} K_t U_t^{\phi-1})
\]

\[
\xi \theta \rho (1-\psi) U_t^\phi + (1-\psi)e^{-\gamma M_t/K_t^\phi} e^{-\gamma M_t/K_t} = Z_t
\]

\[
\beta E_t \left\{ \eta_{t+1}^{\mu} C_{t+1}^{-\alpha} \left[ r_{t+1} U_{t+1} + \frac{M_{t+1}}{K_{t+1}} - \frac{M_{t+1}}{Z_{t+1}} + \frac{b}{2} \left( \frac{K_{t+2}}{K_{t+1}} - 1 \right)^2 \right] \right\}
\]

\[
= \eta_t^{\mu} C_t^{-\alpha} \left( 1 + b \left( \frac{K_{t+2}}{K_t} - 1 \right) \right)
\]

Eq. (9) gives the first-order condition for hours worked and Eq. (10) sets the marginal return of a rise in the capital utilization rate equal to its opportunity cost measured by the increased capital depreciation rate. Eq. (11) is the optimality condition with respect to maintenance and sets the marginal benefit of maintenance equal to its cost. Finally, Eq. (12) modifies the usual optimality condition that equates the marginal productivity with the user cost of capital, since a marginal increase in the capital stock implies a rise in its required maintenance cost. Firms set the marginal products of effective capital and hours worked equal to the return of capital and the wage rate, respectively.

### 3. Estimation and dynamics

#### 3.1. Data and priors

In order to investigate the dynamics of the model, we log-linearize the equilibrium conditions around the steady state.\(^4\) The log-linearized model is estimated with Bayesian techniques. We estimate the mode of the posterior distribution by maximizing the log posterior function, which combines the log of prior with the log likelihood of the data, using the

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\(^4\) The steady-state conditions, the log-linear equations, and a full description of the data sources are presented in the online Appendix.
The steady-state depreciation rate, which equals the steady-state investment to capital ratio, is derived as
A series on capital utilization in U.S. manufacturing is compiled using data from the Board of Governors of the Federal
series are extended to 2009 using the corresponding entries as reported in the U.S. Census Annual Survey of Manufacturers.
account for endogenous utilization and find an average depreciation rate of 12.6% for the period 1947
(1996) and Fraumeni (1997) report average depreciation rates of 15% for durable equipment in US manufacturing; Kollintzas
depreciation rate of 13.3% for equipment; Nadiri and Prucha (1996a) an average of 5.9% between 1960 and 1988; Jorgenson
elasticity of labor supply,
distributions. We allow the intertemporal elasticity of substitution,
compatible with estimates obtained in the literature and describe most parameters with truncated Normal or Gamma
collected in Table 2. The priors are independent of the data used. We set most priors so that parameters vary in a range
determined as with Canadian data.

Data on US manufacturing output, employment, hours worked, capital expenditures, and capital are obtained from the NBER-CES Manufacturing Industry Database, provided by Becker and Gray (2009), which covers the period 1958–2005. The series are extended to 2009 using the corresponding entries as reported in the U.S. Census Annual Survey of Manufacturers. A series on capital utilization in U.S. manufacturing is compiled using data from the Board of Governors of the Federal Reserve System. The steady-state depreciation rate, which equals the steady-state investment to capital ratio, is derived as the average of the series for manufacturing machinery and equipment over the sample and set to 0.117. This figure is in line with existing estimates of depreciation rates in US manufacturing. For example, Hulten and Wykoff (1981b) estimate a depreciation rate of 13.3% for equipment; Nadiri and Prucha (1996a) an average of 5.9% between 1960 and 1988; Jorgenson (1996) and Fraumeni (1997) report average depreciation rates of 15% for durable equipment in US manufacturing; Kollintzas and Choi (1985) and Bischoff and Kokkelenerg (1987) report values of 12.5% of 10.6%, respectively; Epstein and Denny (1980) account for endogenous utilization and find an average depreciation rate of 12.6% for the period 1947–1971. The steady-state MK ratio is obtained by multiplying this value by the average maintenance to investment ratio for the available US data for total manufacturing, thus, obtaining 0.0309 for the machinery and equipment sector. The rest of the parameters are determined as with Canadian data.

All other structural and auxiliary parameters are estimated. Prior shapes, prior means and standard deviations are collected in Table 2. The priors are independent of the data used. We set most priors so that parameters vary in a range compatible with estimates obtained in the literature and describe most parameters with truncated Normal or Gamma distributions. We allow the intertemporal elasticity of substitution, σ, to vary in the (0.01,6) interval. The inverse of the Frisch elasticity of labor supply, θ_n, varies in the (0.01,10) interval. The existence of endogenous maintenance might affect the law of motion for capital since it provides an additional investment smoothing mechanism relative to the standard model where depreciation is fixed. For that reason we pose a prior that reflects this idea assuming a priori that capital adjustment costs should be close to zero and let θ vary in the (0,10) interval. The interval for the share of labor, α, in the production function is centered about the standard estimated value for this parameter and is represented by a Normal distribution. The parameters of the depreciation function γ and φ, which determine the elasticity of depreciation to changes in maintenance expenditures and the capital utilization respectively, are described by Gamma distributions. Given the absence of calibrated values for parameter γ we assume a relatively diffused prior and we set the prior mean of φ to 0.9 with a standard deviation of 0.2. Finally, the persistence parameters of the AR(1) processes are Beta distributed and the standard errors of the innovations are assumed to follow an inverse-gamma distribution.

3.2. Posterior estimates

The left panel of Table 3 shows the results of the model for Canada. The first panel displays results for the standard RBC model and the second panel results for the model with endogenous maintenance. We report the posterior mean and 90% credible intervals.5 Regarding the shocks considered, all exhibit low persistence with the labor supply shock displaying the highest persistence and the preference and government spending shocks being the least persistent. Standard deviations of the shocks are estimated to be low in accordance to our priors.

All posterior estimates assume economically plausible values. The posterior mean for θ_n equals 2.05, which implies a Frisch elasticity of 0.49. This number is in the interval (0.01,0.85) of the values estimated in microeconometric studies for Canada. The posterior value for the labor share is somewhat higher than the initial value of 0.7, but remains within reasonable bounds. The relative risk aversion parameter, σ, is usually estimated in the [0.5,6] range, with lower values typically estimated from microeconometric data. The credible intervals for σ are within this range. In calibration exercises of DSGE models the parameter determining capital adjustment costs, b, varies from values around 3 (Woodford, 2003) to 19 (Casares and McCallum, 2006). Our estimates for b vary between (7,10) with Canadian data and (5.3, 9) with US data.

5 Prior and posterior distributions are available upon request.
6 See Evers et al. (2008) for a summary of such estimates.
Maintenance expenditures are high the depreciation rate of the capital stock equals estimated mean values of differences in the estimated persistence of the different shocks. Technology shocks seem to be more volatile in the US. The variances of the preference and the labor supply shocks assume significantly lower values, while there are no significant changes in utilization and maintenance is also smaller. A higher labor supply elasticity implies that the economy can adjust to shocks relying more on the labor margin and less on adjustments in utilization, which come at a cost of higher adjustment costs.

Table 1
Calibrated parameters and steady-state values.

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Steady-state value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$ Discount factor</td>
<td>0.98</td>
</tr>
<tr>
<td>$I/K$ Investment to capital ratio</td>
<td>0.0882 (Canada), 0.1170 (US)</td>
</tr>
<tr>
<td>$M/K$ Maintenance to capital ratio</td>
<td>0.0494 (Canada), 0.0309 (US)</td>
</tr>
<tr>
<td>$\delta$ Depreciation</td>
<td>$I/K$</td>
</tr>
<tr>
<td>$M/I$ Maintenance to investment ratio</td>
<td>$M/I$</td>
</tr>
<tr>
<td>$\gamma$ Elasticity of $\dot{\psi}$ to changes in maintenance</td>
<td>$1/\beta - 1 + I/K + M/K$</td>
</tr>
<tr>
<td>$\phi$ Elasticity of $\dot{\psi}$ to changes in utilization</td>
<td>$I^*/(1-\alpha)$</td>
</tr>
<tr>
<td>$\lambda$ Output to capital ratio</td>
<td>$Y/I$</td>
</tr>
<tr>
<td>$\rho$ Persistence to output ratio</td>
<td>$G/Y*Y/K$</td>
</tr>
<tr>
<td>$\theta$ Labor share</td>
<td>Normal 0.7 0.05 0.01 1</td>
</tr>
<tr>
<td>$\rho_\psi$ Persistence productivity shock</td>
<td>Beta 0.5 0.2 0.01 0.99</td>
</tr>
<tr>
<td>$\rho_z$ Persistence investment-specific shock</td>
<td>Beta 0.5 0.2 0.01 0.99</td>
</tr>
<tr>
<td>$\rho_e$ Persistence preference shock</td>
<td>Beta 0.5 0.2 0.01 0.99</td>
</tr>
<tr>
<td>$\rho_s$ Persistence labor supply shock</td>
<td>Beta 0.5 0.2 0.01 0.99</td>
</tr>
<tr>
<td>$\rho_f$ Persistence of fiscal shock</td>
<td>Beta 0.5 0.2 0.01 0.99</td>
</tr>
<tr>
<td>$\sigma_\psi$ Volatility productivity shock</td>
<td>Normal 0.1 Inf 0.01 3</td>
</tr>
<tr>
<td>$\sigma_z$ Volatility investment-specific shock</td>
<td>Normal 0.1 Inf 0.01 3</td>
</tr>
<tr>
<td>$\sigma_e$ Volatility preference shock</td>
<td>Normal 0.1 Inf 0.01 3</td>
</tr>
<tr>
<td>$\sigma_s$ Volatility labor supply shock</td>
<td>Normal 0.1 Inf 0.01 3</td>
</tr>
<tr>
<td>$\sigma_f$ Volatility fiscal shock</td>
<td>Normal 0.1 Inf 0.01 3</td>
</tr>
</tbody>
</table>

Table 2
Prior distribution of structural parameters and shock processes.

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Prior shape</th>
<th>Prior mean</th>
<th>Prior std deviation</th>
<th>Lower bound</th>
<th>Upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ Elasticity of $\dot{\psi}$ to changes in maintenance</td>
<td>Normal 10 10 0</td>
<td>0 0.01 1 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\phi$ Elasticity of $\dot{\psi}$ to changes in utilization</td>
<td>Gamma 0.9 0.2</td>
<td>0 0.01 1 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b$ Adjustment costs</td>
<td>Normal 0 4 0 10</td>
<td>0 0.01 1 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma$ Relative risk aversion</td>
<td>Normal 2 3 0.01 6</td>
<td>2 0.01 1 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\theta_n$ Inverse Frisch elasticity</td>
<td>Normal 1.25 2 0.01 10</td>
<td>2 0.01 1 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha$ Labor share</td>
<td>Normal 0.7 0.05 0.01 1</td>
<td>0.7 0.05 0.01 1</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$\rho_\psi$ Persistence productivity shock</td>
<td>Beta 0.5 0.2 0.01 0.99</td>
<td>0.5 0.2 0.01 0.99</td>
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</tr>
<tr>
<td>$\rho_z$ Persistence investment-specific shock</td>
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<td>0.5 0.2 0.01 0.99</td>
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<tr>
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<td>0.5 0.2 0.01 0.99</td>
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<tr>
<td>$\rho_s$ Persistence labor supply shock</td>
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<td>0.5 0.2 0.01 0.99</td>
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<tr>
<td>$\rho_f$ Persistence of fiscal shock</td>
<td>Beta 0.5 0.2 0.01 0.99</td>
<td>0.5 0.2 0.01 0.99</td>
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<tr>
<td>$\sigma_\psi$ Volatility productivity shock</td>
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<td>0.1 Inf 0.01 3</td>
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<td>$\sigma_z$ Volatility investment-specific shock</td>
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<td>$\sigma_e$ Volatility preference shock</td>
<td>Normal 0.1 Inf 0.01 3</td>
<td>0.1 Inf 0.01 3</td>
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<tr>
<td>$\sigma_s$ Volatility labor supply shock</td>
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<tr>
<td>$\sigma_f$ Volatility fiscal shock</td>
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<td>0.1 Inf 0.01 3</td>
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Turning to the parameters of the depreciation function, the posterior value of parameter $\phi$ is slightly higher than values assumed for this parameter in the literature and the posterior estimate for parameter $\gamma$ is positive, confirming that as maintenance expenditures increase the depreciation rate decreases. Using the posterior mean values of $\gamma$, $\phi$, and $\alpha$, we find that the implied value for parameter $\theta_n$ is 2.25, whereas the implied mean values for $\psi$ and $\xi$ are, respectively, 0.52 and 0.19. These estimates imply that when capital is fully utilized and there are no expenditures in maintenance, the capital stock depreciates at the rate $\psi = 3.7%$ per year. Instead, when the capital stock is fully utilized and maintenance expenditures are high the depreciation rate of the capital stock equals $\xi = 4.4%$ per year.

The right panel of Table 3 presents the corresponding estimates for the US. In contrast with the results for Canadian data, the variances of the preference and the labor supply shocks assume significantly lower values, while there are no significant differences in the estimated persistence of the different shocks. Technology shocks seem to be more volatile in the US. The estimated mean values of $\sigma$ and $\theta_n$ in the US are substantially lower than their estimated values for Canada. The estimates of risk aversion for the US are within reasonable ranges, although the mean estimate for $\theta_n$ implies a labor supply elasticity of 2.9. Adjustment costs are also estimated to be smaller in the US and the mean estimate for the elasticity of depreciation to changes in utilization and maintenance is also smaller. A higher labor supply elasticity implies that the economy can adjust to shocks relying more on the labor margin and less on adjustments in utilization, which come at a cost of higher...
The first row of Fig. 2 plots the estimated IRFs of the variables of interest to a one-standard-deviation shock to TFP. The productivity shock raises the marginal product of the production factors and, as a result, capital utilization, investment and capital increase in response to the shock, generating a surge in output and consumption. Given the increase in utilization, the depreciation rate increases. Maintenance also increases to balance the detrimental effects of the surge in capital utilization on depreciation.

The investment-specific shock affects the production of investment goods. The second row of Fig. 2 presents IRFs of the two models in response to shocks in the price of investment. The fall in the price of investment does surge investment in the impact period, increasing capital and, due to complementarities in production, hours and capital utilization. In the model with maintenance, the fall in the price of investment also increases the relative price of maintenance. Agents find it optimal depreciation. As a result, the high labor supply elasticity, due to complementarities in the production function, boosts utilization movements. Given the low estimates of $\phi$ in the US, depreciation is not affected substantially by utilization. At the same time, $\gamma$ is relatively smaller and maintenance needs to increase relatively more to mitigate the effects of utilization on depreciation. The movements in utilization imply that capital will move less in equilibrium in response to shocks reducing the need of high capital adjustment costs in the capital law of motion. Finally, given the US estimates for $\gamma$ and $\phi$, the implied values for the parameters of the depreciation function are $\theta = 2.73$, $\psi = 0.58$ and $\xi = 0.16$. Such values imply that the "natural" depreciation rate of US manufacturing capital equals $\xi(1-\psi)^\theta = 1.5\%$, which is lower than the corresponding Canadian rate.

The estimates of the maintenance model are comparable with estimates of a standard RBC model without capital maintenance keeping the same set of observables, calibrated parameters and priors. When we contrast the log data densities in the two models for Canada and the US, the differences do not appear to be substantial for Canada, but they are significant for the US. The model with endogenous maintenance for Canada attains a log data density of 462.7, whereas the densities in the two models for Canada and the US, the differences do not appear to be substantial for Canada, but they are significant for the US. The model with endogenous maintenance for Canada attains a log data density of 462.7, whereas the densities in the two models for Canada and the US, the differences do not appear to be substantial for Canada, but they are significant for the US. The model with endogenous maintenance for Canada attains a log data density of 462.7, whereas the densities in the two models for Canada and the US, the differences do not appear to be substantial for Canada, but they are significant for the US.

### Table 3

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<th>Country</th>
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<th>Maintenance model</th>
<th>Standard model</th>
<th>Maintenance model</th>
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<td>90% credible set</td>
<td>Post. mean</td>
<td>90% credible set</td>
<td>Post. mean</td>
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<td>$\gamma$</td>
<td>19.19</td>
<td>8.37; 29.79</td>
<td>1.71</td>
<td>1.40; 2.02</td>
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<td>$\phi$</td>
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<td>1.64; 2.75</td>
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<td>0.76; 1.40</td>
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<td>$b$</td>
<td>9.02</td>
<td>7.83; 10.00</td>
<td>8.67</td>
<td>7.16; 10.00</td>
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<td>2.70</td>
<td>1.59; 3.80</td>
<td>3.20</td>
<td>1.82; 4.54</td>
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<td>0.71; 3.40</td>
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<td>$\alpha$</td>
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<td>0.75</td>
<td>0.68; 0.82</td>
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<td>0.34; 0.74</td>
<td>0.53</td>
<td>0.33; 0.73</td>
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<td>$\rho_z$</td>
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<td>0.46</td>
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<td>0.72</td>
<td>0.58; 0.85</td>
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<td>0.029</td>
<td>0.024; 0.034</td>
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<td>$\sigma_z$</td>
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<td>0.062</td>
<td>0.047; 0.077</td>
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<td>$\sigma_h$</td>
<td>0.104</td>
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<td>0.113; 0.180</td>
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<td>$\sigma_b$</td>
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<td>0.096</td>
<td>0.049; 0.144</td>
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<td>$\sigma_x$</td>
<td>0.215</td>
<td>0.178; 0.249</td>
<td>0.214</td>
<td>0.178; 0.248</td>
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</table>
to decrease maintenance expenditures on impact, which further increases the depreciation rate. Notice that the response of maintenance to investment-specific shocks is crucial to identify this type of shocks in the short run. After an investment-specific shock maintenance expenditures are reduced on impact while output increases, while for the rest of the disturbances considered the two variables always comove.

The third row of Fig. 2 plots the IRFs to a negative labor supply shock. The shock reduces hours on impact and, due to factor complementarity in the production function, it also reduces capital utilization and investment. The fall in capital utilization reduces maintenance expenditures and the induced movements in utilization and maintenance reduce the depreciation rate in equilibrium.

The next row of Fig. 2 shows that a positive preference shock crowds out investment and, as a result, reduces hours, capital, and capital utilization. Consequently output also falls in equilibrium. The fall in utilization decreases capital depreciation and the need for capital maintenance and maintenance falls also in equilibrium.

Finally, the last row of Fig. 2 presents the IRFs to a government spending shock. The increase in government spending crowds out investment, but, due to the negative wealth effect, labor supply and capital utilization increase in equilibrium. The rise in capital utilization raises the depreciation of capital and maintenance expenditures increase as well. In the model with endogenous maintenance utilization increases much more leading to a significant increase in the volatility of depreciation relative to the standard RBC model.

4. The time profile of capital depreciation

Given the estimates we obtained in the previous section, we next analyze the inferred time profile of variable capital depreciation in Canadian and US manufacturing resulting from our model. Although several studies have attempted to estimate the depreciation rate (especially in US manufacturing) using various single or multi-equation econometric approaches (see Epstein and Denny, 1980; Hulten and Wykoff, 1981a,b; Nadiri and Prucha, 1996a,b; Jorgenson, 1996; Huang and Diewert, 2011), there is no study that has provided estimates for depreciation series that are generated within a general equilibrium framework. An exception that uses time-varying depreciation within a general equilibrium setup is Chen et al. (2006), who calibrate the Japanese economy in order to investigate the driving forces of the saving rate. The time profile of their reported (exogenous) depreciation rates indicates that they were exceptionally high in the 1950s and 1960s, but declined substantially over the following decades. Recently, Liu et al. (2011) and Furlanetto and Seneca (forthcoming) show that a reduced form depreciation shock is extremely important in fitting the business cycle.

4.1. Canada

Prior to our calculations, it is useful to assess the fit of our model by comparing model estimates for capital maintenance and the actual series from the Canadian Survey. Since actual series for maintenance are not used in the estimation of our
model, this exercise can serve as an additional test of our specification. The Bayesian estimation uses the Kalman filter to derive the log-likelihood, conditional on the set of observables. The same recursive algorithm enables us to sequentially update a linear projection for the system and as a by-product to generate smoothed estimates for the endogenous variables. Fig. 3 displays the estimated trend deviations of the series for maintenance to capital ratio vs the actual trend deviations of the series from the Canadian Survey on Capital and Repair Expenditures. The model fits fairly well the pattern for the MK ratio for most of the period covered with most of the peaks captured well by the estimated series, which are less volatile in general. The contemporaneous correlation between the actual and the estimated series amounts to 0.50. In line with their data counterpart, the estimated series are highly procyclical with the contemporaneous correlation of actual output and estimated maintenance equal to 0.66. Moreover, the cross-correlations remain high for lags (−1) to (−3) and for lead (+1) of output, similarly to the actual series.7 To further assess the fit of our model we also calculate the ratio of maintenance to ‘new’ investment series for Canada, which are two key variables in our setup. The estimated series are depicted in Fig. 4. Again, our estimates track well the actual series: the correlation between actual and simulated series is 0.72.8

In Fig. 5 we depict the estimated depreciation rate of equipment capital in the Canadian manufacturing sector over the period 1956–2005 (centered at 8.82%) along with actual output trend deviations. Table 4 contains the detailed figures for the depreciation rates of machinery-equipment capital in Canadian manufacturing. The depreciation rate of equipment capital is found to have a standard deviation of 1.2% and ranges between 5.4% and 11.3% over the period with a strongly procyclical profile: the correlation coefficient with output trend deviations amounts to 0.56. The correlation is higher (0.71) in the 1956–1983 period of the sample, when output and the MK ratio exhibit a high correlation, and drops substantially (0.36) in the 1984–2005 period. This picture indicates that the long-run depreciation rate of equipment capital in Canadian manufacturing has exhibited substantial swings reflecting periods of fast and slow growth in the manufacturing sector and the associated pattern of capital maintenance.9

4.2. US

Given the success of the model in replicating the main features of the actual series of capital maintenance in Canadian manufacturing, we use our approach to estimate series for capital maintenance in the US manufacturing sector, where there has been no systematic collection of data on capital maintenance until 2007. Our estimates, thus, provide an assessment of the behavior of capital maintenance in the US over the last 50 years using the average value of years 2007–2009 as a proxy of the steady-state maintenance to ‘new’ investment ratio. Fig. 6 plots the estimated series for maintenance to capital ratio and output (in trend deviations) and Table 5 contains the estimated series of maintenance expenditures for machinery-equipment capital in US manufacturing for the period 1958–2009 expressed in current thousands USDs. As in the case of Canada, maintenance is found to be highly procyclical with a correlation coefficient of 0.85 with significant positive correlations also for the first lag and the first lead of output. The main peaks and troughs of the business cycle are well

7 Detailed cross-correlograms are available upon request.
8 An implication derived from Figs. 3 and 4 is that the endogenously determined capital stock in our model is too volatile and does not replicate the second moment of the official capital stock series. This is due to the fact that endogenous maintenance dampens the responses of investment and does not operate directly through the accumulation of capital. Instead, our model performs much better in estimating the second moment of investment series.
9 We note that a straightforward extension would be to generate alternative capital stock series that can be contrasted with official capital stock estimates. However, the comparison would be internally inconsistent as the official capital stock series are created under a different set of assumptions than those maintained here.
captured by movements in maintenance. A similar picture emerges for the maintenance to ‘new’ investment ratio (Fig. 7), which is also procyclical with a correlation coefficient of 0.51.

Similar to Canada, we use our estimated series for capital maintenance in the US to obtain estimated series for the depreciation rate in machinery-equipment capital over the period 1958–2009. Fig. 8 plots the estimated depreciation rate and the output trend deviations for US manufacturing capital and Table 5 contains the detailed figures for the depreciation rates of machinery-equipment capital in US manufacturing. As in Canada, the depreciation rate in US manufacturing has been quite volatile and procyclical. In particular, the estimates indicate that the estimated range of the depreciation rate of equipment capital in US manufacturing varies between 9.3% and 13.7% over the period 1958–2009. In accordance with the Canadian estimates, the correlation with output trend is positive and equals 0.56.

These results shed some further light in the variability of capital depreciation, as few studies have focused on its behavior over time. Epstein and Denny (1980) report that the average depreciation rate in total US manufacturing over the period 1947–1971 ranged between 10.8% and 14.5%. Kollintzas and Choi (1985) report a similar range of 10.7–14.1% over the same time period, whereas Bischoff and Kokkelenberg report a range of 9.6–11.8% over a period extended to 1978. Tevlin and Whelan (2003) report that the depreciation rate of non-computing equipment capital in the private business sector rose from 11% in 1965 to 14% in 1997, a rise that is largely attributed to the pattern of capital depreciation in the computing sector, which rose from 8% in 1965 to 16% in 1997. Notably, Nadiri and Prucha (1996a) report that the constant depreciation rate assumption cannot be rejected for the US electrical machinery industry. Our evidence, based on machinery-equipment capital, generates a somewhat wider spread for capital depreciation, which is not unreasonable given the 50-year time span of our study. Importantly, our implied depreciation rate follows a highly procyclical pattern, a feature that has only been indirectly captured by Epstein and Denny (1980) for some cycles.
5. Conclusions

This paper formulated and estimated a DSGE business-cycle model in which the depreciation rate is endogenously determined by expenditures on capital maintenance. An important feature of our approach, apart from its general-equilibrium character, is that we were able to derive the cyclical movements of capital depreciation, in the absence of time-series data on capital maintenance that are largely unavailable. Our evidence on the time profile of the capital depreciation rate, which has been found to be procyclical and quite volatile, is contrasted to the standard assumption of constant capital depreciation, adopted routinely in most studies of macroeconomic fluctuations, and can provide significant insights into their sources and propagation mechanisms.

Our evidence may provide important potential insights for the tax treatment of capital assets and their depreciation. Given the procyclicality of depreciation, the state of the economy should be taken into account in the formation of the tax code and the calculation of variables affecting the values of assets, like interest rates. Nevertheless we emphasize that our implied estimates are in no way intended to provide definitive estimates of depreciation or their cyclical pattern. There is a
Table 5

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<th>Year</th>
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<th>Year</th>
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<td>0.1061</td>
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Fig. 7. Estimated maintenance to 'new' investment ratio and output (trend deviations) in US manufacturing.

Fig. 8. Output (trend deviations) and depreciation rate: US manufacturing capital (equipment and structures).
great deal of room for further research, particularly in the areas of using more disaggregated data for the assessment of depreciation rates related to sectoral capital stocks within the context of a general equilibrium approach. Our findings should, thus, be viewed as an example of what can be achieved with a DSGE approach that accounts for capital maintenance. In this vein, the model can also be used to estimate unmeasured capital expenditures, like spending on capital maintenance, in other countries, as they form an important part of economic activity in order to estimate cross-country depreciation rates stemming from a general-equilibrium setup.

Acknowledgements

We benefited from comments by participants to the XXXVI Simposio Of the Spanish Economic Association (University of Malaga), the 4th Italian Doctoral Workshop in Economics and Policy Analysis (Collegio Carlo Alberto), the Workshop on Advances in Business Cycles and Business Growth Analysis (Rimini Centre for Economic Analysis) and to seminars at University of Pavia. Alice Albonico thanks G. Ascari and L. Rossi for insightful comments. Financial support from AUEB Basic Research Funding Program (Contract Number: EP-1710–28) is acknowledged by Sarantis Kalyvitis. The financial support from the Spanish Ministry of Science and Innovation through grant ECO2012-32392 and the Generalitat of Catalonia through grant SGR2009-00350 is acknowledged by Evi Pappa.

References