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MAINTENANCE, UTILIZATION, AND DEPRECIATION ALONG THE BUSINESS CYCLE

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ABSTRACT

Maintenance, Utilization, and Depreciation along the Business Cycle*

In this Paper we look at the behaviour of maintenance, utilization and physical depreciation over the business cycle. We do so within the context of a real business-cycle model where the decisions of firms about physical capital utilization, maintenance and improvement or scrapping are endogenous. We distinguish between labour input devoted to output production and labour input devoted to maintaining and improving or scrapping existing capital. Firms must first decide the total number of work hours and then how to allocate workers between output production and capital maintenance. The model encompasses the baseline real business-cycle model, where the depreciation rate is fixed, or versions of that model where the depreciation rate is an exogenous stochastic process. It also encompasses versions of the real business-cycle model where capital utilization is an explicit endogenous variable or enters implicitly a variable work effort. Our model is capable of providing a unified explanation of several stylized facts of business cycle behaviour, including (a) a low correlation between labour productivity and output, (b) a low correlation between wages and productivity and (c) a relatively strong correlation between real wages and hours worked. Making the business cycle propagation richer reduces the variance of the Solow residual needed to match output volatility.

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NON-TECHNICAL SUMMARY

Nearly all growth and business-cycle models make the assumption of fixed geometric (physical) capital depreciation. The loss of the ability of capital to yield productive services is thus a constant proportion to the beginning-of-period stock of capital. Although this law of motion does possess microeconomic foundations, Feldstein and Rotschild (1974) have found it to be an oversimplification that yields an 'implausible and unsatisfactory' representation of depreciation. Further, the endogeneity of utilization, maintenance, improvement and scrapping decisions imply that depreciation varies along the business cycle.

There have been several attempts to endogenize utilization, maintenance improvement and scrapping. Most of them rely on the so-called Hicks (1946)–Malinvaud (1953)–Diewert (1976) technology, where inputs are used to produce outputs and end-of-period inputs. These studies, both theoretical and empirical, provided ample evidence that δ is not fixed but varies over time and along the business cycle. However, these attempts were limited to a partial equilibrium framework, where output was exogenously determined. With the exception of Greenwood, Hercowitz and Huffman (1988), general equilibrium formulations of endogenous utilization are fairly recent. These studies emphasize the important implications of endogenous utilization on the propagation mechanism of the underlying economies. However, ignoring maintenance, improvements and scrapping, they do not account for a complete description of the propagation mechanism at work with endogenous depreciation (notable exceptions are Licandro and Puch (1997) and McGrattan and Schitz (1999)). The purpose of this Paper is thus to account for endogenous utilization, maintenance, and scrapping decisions of firms within a general equilibrium framework. This is done by integrating the two strands of literature mentioned above.

The Paper also aims to answer one major criticism addressed at business-cycle models: they need highly volatile technological shocks to mimic output volatility. This problem has remained the Achilles heel of the RBC literature and has generated a number of studies aiming at reducing of the variance of technology shocks. Most notable among these is the work of Burnside, Eichenbaum and Rebelo [1993, 1995], where labour hoarding is used as a way to endogenize the utilization rate of both capital and labour inputs and thus provide an amplification mechanism that allows to reduce the variance of the innovations to technology by nearly 50%, relative to the baseline RBC model. The second purpose of this Paper is to provide an alternative explanation for reducing the importance of the technology shocks in RBC models – endogenous utilization, maintenance, improvements and scrapping.

Our explanation has the advantage of not relying on a highly controversial assumption, such as household preferences depending on work effort rather than time devoted to work.

We develop a stochastic general equilibrium model, in which we consider two types of labour inputs and two types of technology shocks. The first type of labour input can only be used in the production of output. The second type of labour input can be used either to maintain and improve existing capital or to scrap it. This introduces a trade-off between maintenance / scrapping / improvement activities and producing output, which changes with the face of the business cycle. Business cycles are driven by two technological shocks. The first shock is the traditional Solow residual. The second shock affects depreciation. ‘Low’ values of the Solow residual and ‘high’ values of the ‘depreciation’ shock make maintenance and improvement activities relatively more productive. The effect of a productivity shock on depreciation can thus be decomposed in two: a substitution and an income effect. The substitution effect is positive as a high Solow residual causes output to be more efficient than output maintenance. Utilization increases and maintenance decreases driving depreciation up. The income effect is negative as a high Solow residual causes output to be more efficient, releasing labour to do maintenance. Thus, maintenance increases, driving depreciation down.

Four versions of the model depending on the information structure of the agents are considered. We are particularly interested in a version of the model where the shocks are revealed after total labour input has been decided but before it has been allocated between production and maintenance, thus providing a way to account for labour hoarding. The model is calibrated using US quarterly data. All versions of the model are able to match output volatility with lower variance Solow residuals than the baseline RBC model. Finally a version of the model with both technological – the Solow residual – and depreciation shock can account for the Dunlop–Tarshis stylized fact.

1. Introduction

Nearly all growth and business cycle models are characterized by the hypothesis of fixed geometric (physical) capital depreciation. That is, they assume that the law of motion of capital is given by an expression of the form:

$$K_{t+1} = I_t + (1-\delta)K_t$$

where K_{t+1} is the capital stock at the beginning of period t+1, $\delta \in [0,1]$ is the constant fraction of the existing capital stock, depreciating in each and every period, and I_t is gross investment in period t. That is, the loss of the ability of capital to yield productive services is a constant proportion to the beginning–of–period stock of capital. Although this law of motion does possess microeconomic foundations, it is an extreme oversimplification.[1] In the introduction of their seminal paper Feldstein and Rotschild (1974) motivated their work by declaring: ‘‘ *We hope not only to show that a model with a constant replacement rate is implausible and unsatisfactory but also to provide a basis for better empirical work in the future. The magnitude of replacement investment (the annual rate of replacement investment generally exceeds expansion investment) makes this issue a matter of substantial importance.* ’’ They proceeded to show that for a variety of technical (depreciation pattern) and economic reasons, the replacement ratio, or in our terminology the depreciation rate (δ), cannot be a constant. The (economic) endogeneity of decisions pertaining to utilization, maintenance, improvement and scrapping implies a systematic variation of the depreciation rate for both growth and business cycle environments. In a way similar but not identical to Feldstein and Rotschild (1974), we use the word depreciation to reflect the loss of the ability of existing capital to yield productive services. Depreciation happens due to aging, accelerates with utilization, and decelerates with maintenance. Moreover, we take the word ‘‘improvement’’ (‘‘scrapping’’) to reflect those activities that result in the amount of capital services that can be extracted from the existing capital been higher (lower) than the amount of those services that could have been extracted if capital was not used in the production process.[2]

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[1] The microeconomic foundations of this assumption are founded on the renewal theory of operations research See, Jorgenson et al. (1967). However, Feldstein and Rotschild (1974) show that Jorgenson's (1965]) conjecture — ‘‘ *It is a fundamental result of renewal theory that the distribution of replacement ... approaches a constant fraction of the capital stock for (almost) any distribution of replacements over time and for any initial distribution of capital stock. This result holds for a constant stock and for a growing stock as well.* ’’ — generalizing the applicability of fixed proportional depreciation ‘‘*to be invalid except in the extreme and uninteresting case of an economy with constant exponential growth of capital.*’’

[2] In particular, we use the word ‘‘maintenance’’ to characterize a situation, where there is no improvement, but the capital services that can be extracted from the existing capital, after the latter has been used in the production process, are higher than the amount of those services that would had been available if no such activities were undertaken.

There have been several attempts to endogenize utilization, maintenance improvement and scrapping. Epstein and Denny (1980) and Choi and Kollintzas (1985) relied on the Hicks (1946) – Malinvaud (1953) – Diewert (1976) technology, where inputs are used to produce outputs and end–of–period inputs, to endogenize all of these processes. These studies provided ample evidence that δ is not fixed. And, in fact that it varies over time and along the business cycle. However, their attempts were limited to a partial equilibrium framework, where output was exogenously determined. With the exception of Greenwood, Hercowitz and huffman (1988), general equilibrium formulations of endogenous utilization are fairly recent. (See, for example, Beaudry and Devereux (1996) and DeJong et al. (1996)). These studies emphasize the important implications of endogenous utilization on the propagation mechanism of the underlying economies. However, they ignore maintenance, improvements and scrapping. McGrattan and Schmitz (1999) introduce maintenance expenditures within the context of a real business cycle model but they abstract from capital utilization decisions. Licandro and Puch (1997) account for both endogenous utilization and maintenance. They model maintenance as an alternative that uses capital which would have been used in production otherwise. They argue that maintenance activity must be countercyclical, because it is cheaper for a firm to maintain machines when they are stopped than when they are in used. The purpose of the present paper is to account for endogenous utilization, maintenance, and scrapping decisions of firms within a general equilibrium framework. This is done by integrating the two strands of literature mentioned above.

King and Rebelo (1997) evaluating real business cycle (RBC) models state that: ‘‘*the Solow residual is a problematic measure of technology shocks — that has remained the Achilles' heal of the RBC literature*.’’ This has generated a number of studies aiming at the reduction of the variance of technology shocks. Most notable among these is the work of Burnside, Eichenbaum, and Rebelo [1993, 1995], where they use variable work effort, effectively to endogenize the utilization rate of both capital and labor inputs. In so doing they have managed to reduce the variance of the innovations to technology by nearly 50%, relative to the baseline RBC model.[3] The second purpose of this paper is to provide an alternative explanation for reducing the importance of the technology shocks in RBC models — endogenous utilization, maintenance, improvements and scrapping. Our explanation has the advantage of not relying on a highly controversial assumption, such as household preferences depending on work effort rather than time devoted to work.[4]

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[3] See, e.g., Prescott (1986)

[4] Actually, Burnside et al. (1993) recognize the potential of endogenous capital utilization rates in this respect. Similarly, Beaudry and Devereux (1996) recognize the importance of variable capital utilization rates in affecting the Solow residual.

In Section 2, we develop the model. We consider two types of labor inputs and two types of technology shocks. The first type of labor input is the traditional one — it can only be used in the production of (new) output. The second type of labor input can be used either at maintaining and improving existing capital or in scrapping it. This, of course, induces a labor input allocation decision, based on a tradeoff between such activities and producing output. This tradeoff has been recognized at least since Keynes.[5] Clearly, it changes with the face of the business cycle and, hence, it affects and is affected by it. We hope that in this manner we can account for another difficulty of RBC models — the Dunlop–Tarshis stylized fact, as we disassociate productivity from labor input.

The two technology shocks are introduced to put some additional structure into the tradeoff described above. The first shock is the traditional Solow residual. But the second shock affects depreciation. ‘‘Low’’ values of the Solow residual and ‘‘high’’ values of the ‘‘depreciation’’ shock make maintenance and improvement activities relatively more productive. We consider four versions of the model depending on the information structure of the agents. We are particularly interested in a version of the model where the shocks are ‘‘known’’ after total labor input has been decided but before it has been allocated between production and maintenance. This is an alternative way (to Burnside et al. (1993)) to account for labor hoarding. In fact, as it turns out the model nests the baseline RBC model (BRBC) as well as the Greenwood et al. (1998) model (GHH).

In Section 3, we calibrate our model, using the standard data set for the US economy. In Section 4 we discuss the simulation results. First we provide further empirical justification for the Feldstein and Rotschild (1974) objections about the constancy of δ. All versions of the model are able to match output volatility with lower variance Solow residuals than the BRBC. The version of the model that performs better in terms of the Dunlop–Tarshis stylized fact is the one with both technological — the Solow residual — and depreciation shock. In particular, the model is capable of generating (a) a low correlation between labor productivity and output, (b) a low correlation between wages and productivity and (c) a relatively strong correlation between real wages and hours worked. A last section concludes.

2. The model

We consider an economy that consists of a large number of dynastic households and a large number of firms. Firms are producing a homogeneous final product that can be either consumed or

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[5] ‘‘*We have defined the user cost as the reduction in the value of the equipment due to using it as compared with not using it, after allowing for the cost of maintenance and improvements which it would be worth while to undertake and for purchases from other enrepreneurs.*’’ – p. 70 of the General Theory.

invested by means of capital and labor services. Firms own their capital stock and hire labor supplied by the households. Households own the firms. In each and every period three perfectly competitive markets open — the markets for consumption goods, labor services, and financial capital in the form of firms' shares. The basic difference between this and the BRBC model, however is in the form of physical capital depreciation. That is, depreciation is endogenized, in the sense that it becomes the product of the utilization, maintenance, and scrapping decisions of firms.

2.1 The representative household

Household preferences are characterized by the lifetime utility function:

$$\sum_{t=0}^{\infty} \beta^t u(c_t, \ell_t) \tag{1}$$

where $0<\beta<1$ is a constant discount factor, c_t is consumption in period t, ℓ_t is the fraction of total available time devoted to leisure in period t, and $u(c,\ell): \Re_+ \times [0,1] \rightarrow \Re$ is a temporal utility function with standard properties. $E_t(.)$ denotes the mathematical conditional expectations operator where expectations are conditioned on the information available at the beginning of period t, Ω_t. We will use the following temporal utility function in the sequel:

$$u(c_t, \ell_t) = \log(c_t) + \gamma \ell_t$$

The utility function is linear with respect to leisure. Thus, our model can be viewed as an extension of Hansen's (1985) model, where labor is indivisible, in the sense that all employed workers work for a fixed amount of time.

In each and every period t, the representative household faces a budget constraint of the form:[6]

$$c_t + (1+g_n)(1+g_z) p_t s_{t+1} \leq (p_t + d_t) s_t + w_t h_t \tag{2}$$

where p_t is the price of a share at the beginning of period t, s_t is the number of shares held by the representative household at the beginning of period t, w_t is the wage rate in period t, h_t is the fraction of total time devoted to work in period t,and d_t are the dividends per share paid out to the firm's shareholders at the end of period t. g_n and g_z are the exogenous gross growth rates of population and a parameter that measures the rate of growth labor augmenting technological progress.

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[6] Implicit in (2) is the fact that we have expressed all quantity variables and the wage rate in terms of efficiency units of labor. β should be thought of as an adjusted discount factor for technological progress. Further, we assume that there exists a system of unemployment insurance, and that each household chooses to be fully insured such that there is no *ex-post* heterogeneity on the labor market. Thus, the budget constraint we write down assumes that the insurance problem has been solved previously.

Finally, in each and every period t, the representative household is faced with the following feasibility constraints:

$$c_t, s_{t+1}, \ell_t, h_t \geq 0 \tag{3}$$

$$h_t + \ell_t \leq 1 \tag{4}$$

The second inequality in (3) does not allow for the short–selling of stocks and the associated Ponzi–game. (4) states that the household allocates her total time endowment — normalized to 1 — between productive activities and leisure.

2.2 The representative firm

The representative firm produces a homogeneous final good by means of capital and labor services, such that:

$$c_t + i_t \leq y_t \tag{5}$$

$$y_t = A_t k_t^{\alpha} \hat{h}_t^{1-\alpha} \tag{6}$$

where 0<α<1. $\hat{h}_t$ is the share of hours hired by the firm devoted to productive activities, k_t denotes beginning of period t capital stock. The parameter A_t represents a stochastic shock to technology or Solow residual, which evolves according to:

$$\ln(A_t) = (1-\rho_a)\ln(\overline{A}) + \rho_a \ln(A_{t-1}) + \varepsilon_{at}$$

The unconditional mean of $\ln(A_t)$ is $\ln(\overline{A})$, $|\rho_a|<1$, and ε_{at} is the innovation to $\ln(A_t)$ with a standard deviation of σ_a.

Physical capital accumulation is given by

$$(1+g_n)(1+g_z)k_{t+1} = i_t + \tilde{k}_t \tag{7}$$

where i_t denotes investment in period t, and $\tilde{k}_t$ is the amount of physical capital services available at the end of period t. This law of motion of physical capital differs from the traditional capital accumulation equation

$$(1+g_n)(1+g_z)k_{t+1} = i_t + (1-\delta)k_t \text{ with } 0 < \delta < 1$$

As already said, the latter is based on the hypothesis that capital depreciates geometrically at a constant exogenous rate δ. On the contrary, equation (7) does not place any restriction on capital depreciation. It allows for capital depreciation to depend on the capital utilization, maintenance, improvement and scrapping decisions of the firm.

We assume that the depreciation technology is given by

$$\tilde{k}_t = B_t g(k_t, \hat{h}_t, \tilde{h}_t) \qquad (8)$$

where $g(k_t, \hat{h}_t, \tilde{h}_t): \Re \times [0,1] \times [0,1] \rightarrow \Re_+$ is a homogeneous of degree one, differentiable, concave physical depreciation function which is strictly increasing with k_t and $\tilde{h}_t$ and decreasing with $\hat{h}_t$. $\tilde{h}_t$ is the share of labor services devoted to maintenance activities. Thus, the greater is the level of beginning–of–period capital stock, the greater is the level of end–of–period capital stock. The more hours the firm allocates in production activities, so that physical capital is used more intensively, the smaller is the level of end of period capital. This effect transiting through hours used in production can thus be read as a depreciation–in–use effect. Finally, the more the firm decides to maintain, *i.e.*, the higher $\tilde{h}_t$ is, the less physical capital depreciates. Thus, g(.) expresses the fact that firm decides the total amount of hours it will hire in period t, and how it will split these hours between productive and maintenance activities. As we will show in Section 4, the effect has an ‘‘opportunity cost’’ approach interpretation (see, e.g., Aghion and Saint-Paul (1998)).

Further g(.) satisfies the following Inada conditions

$$\lim_{\tilde{h}\rightarrow 0} \frac{\partial g(k,\hat{h},\tilde{h})}{\partial \tilde{h}} = +\infty \qquad \lim_{\tilde{h}\rightarrow \hat{h}+\tilde{h}} \frac{\partial g(k,\hat{h},\tilde{h})}{\partial \tilde{h}} = 0$$

$$\lim_{\hat{h}\rightarrow 0} \frac{\partial g(k,\hat{h},\tilde{h})}{\partial \hat{h}} = 0 \qquad \lim_{\hat{h}\rightarrow \hat{h}+\tilde{h}} \frac{\partial g(k,\hat{h},\tilde{h})}{\partial \hat{h}} = -\infty$$

Figure 1 illustrates the properties of the depreciation/maintenance technology.

— Please Insert Figure 1 —

The parameter B_t represents a stochastic shock to the depreciation technology, which evolves according to

$$\ln(B_t) = (1-\rho_b)\ln(\overline{B}) + \rho_b \ln(B_{t-1}) + \varepsilon_{bt}$$

The unconditional mean of $\ln(B_t)$ is $\ln(\overline{B})$, $|\rho_b|<1$, and ε_{bt} is the innovation to $\ln(B_t)$ with a standard deviation of σ_b. An increase in B in period t corresponds to the fact that more physical capital is passed to period t+1. This implies that the maintenance technology is more efficient. This can thus be interpreted as a positive shock on the maintenance activity.

An example of such a depreciation function that we will use later is:

$$\tilde{k}_t = B_t \frac{k_t}{\hat{h}_t + \tilde{h}_t}(\theta \hat{h}_t + \tilde{h}_t^{\theta}(\tilde{h}_t + \hat{h}_t)^{1-\theta}) \qquad (9)$$

where $0<\theta<1$. Notice then that the depreciation rate is given by

$$\delta_t = 1 - B_t \frac{\theta \hat{h}_t + \tilde{h}_t^{\theta} (\tilde{h}_t + \hat{h}_t)^{1-\theta}}{\hat{h}_t + \tilde{h}_t}$$

such that

$$\frac{\partial \delta_t}{\partial \hat{h}_t} = \frac{B_t}{(\hat{h}_t + \tilde{h}_t)^2} \theta \tilde{h}_t \left[\left(\frac{\hat{h}_t + \tilde{h}_t}{\tilde{h}_t} \right)^{1-\theta} - 1 \right] > 0$$

$$\frac{\partial \delta_t}{\partial \tilde{h}_t} = \frac{B_t}{(\hat{h}_t + \tilde{h}_t)^2} \theta \hat{h}_t \left[1 - \left(\frac{\hat{h}_t + \tilde{h}_t}{\tilde{h}_t} \right)^{1-\theta} \right] < 0$$

so that higher labor input devoted to output production raises the depreciation rate. On the other hand, whenever the firms decides to allocate a higher amount of work hours to maintenance activities, the depreciation rate decreases.

The representative firm chooses its level of investment, decides how much hours to hire in period t and allocates them between maintenance ($\tilde{h}_t$) and productive activities ($\hat{h}_t$), so as to maximize its expected present value. Financial market equilibrium implies that the latter can be written as follows:

$$E_0 \sum_{t=0}^{\infty} q(0,t)(y_t - w_t h_t - i_t) \tag{10}$$

where

$$q(0,t) = \prod_{\tau=0}^{t} \frac{p_\tau}{p_{\tau+1} + d_{\tau+1}}$$

This maximization is subject to the capital accumulation equation and the feasibility constraints

$$k_t, \hat{h}_t, \tilde{h}_t \geq 0$$

$$\hat{h}_t + \tilde{h}_t \leq h_t$$

2.3 Nesting standard models

Our model nests other models in the literature. First of all, it is easy to recover the baseline RBC model (BRBC) by setting:

$$\theta = 0$$

$$B = 1 - \delta$$

$$\sigma_b = 0$$

It is worth noting that in this case the production function can be rewritten as

$$y_t = A_t k_t^{\alpha} h_t^{1-\alpha}$$

Second, whenever the variance of B_t is not constrained to 0, the model also nests the stochastic depreciation case studied by Ambler and Paquet (1994).

Third, it is possible to nest a model à la Greenwood et al. (1988) (GHH hereafter). It is worth noting that they actually consider that depreciation is only due to the use of capital in the production process. The higher the rate of capital utilization, the higher is physical capital depreciation. Let

$$y_t = A_t (u_t k_t)^{\alpha} h_t^{1-\alpha}$$

and

$$\tilde{k}_t = D_t k_t \left(1 - \frac{u_t^{\varphi}}{\varphi} \right) \text{with } \varphi > 1$$

where

$$u_t = \left(\frac{\hat{h}_t}{h_t} \right)^{\frac{1-\alpha}{\alpha}}$$

We recover GHH if we set[7]

$$D_t = B_t \frac{\theta u_t^{\alpha/(1-\alpha)} + (1 - u_t^{\alpha/(1-\alpha)})^{\theta}}{1 - u_t^{\varphi} / \varphi}$$

and then set B_t such that $E(D_t)=1$ and $V(\ln(D_t))=0$.

Finally a version of McGrattan and Schmitz (1999) where only maintenance activities affect the depreciation rate can be obtained by letting

$$\tilde{k}_t = D_t k_t \left(1 - \psi(\tilde{h}_t) \right)$$

where $\psi(0) = 1, \psi(h_t) = 0$, $\psi'(.) < 0$ and $\psi''(.) > 0$

$$D_t = B_t \frac{\theta \hat{h}_t + \tilde{h}_t^{\theta} (\hat{h}_t + \tilde{h}_t)^{1-\theta}}{1 - \psi(\tilde{h}_t)}$$

and then set B_t such that $E(D_t)=1$ and $V(\ln(D_t))=0$.

2.4 Equilibrium

We consider two types of equilibria corresponding to two information structures. In the first one, the representative firm observes Ω_t — to be explicitly stated later on — and decides investment, hours and the splitting between productive and maintenance activities. In the second one, that will be

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[7] Instead of the Solow residual that we consider above, GHH considers a shock on investment.

referred to labor hoarding, the firm first decides the amount of hours before shocks are revealed (that is conditional on $\Omega_t^* \subseteq \Omega_t$).

A competitive equilibrium allocation for the economy with complete information is a sequence of functions of the form:

$$\left\{\left[c_t(\Omega_t), s_{t+1}(\Omega_t), \ell_t(\Omega_t)\right];\left[y_t(\Omega_t), k_{t+1}(\Omega_t), h_t(\Omega_t), \hat{h}_t(\Omega_t), \tilde{h}_t(\Omega_t)\right];\left[p_t(\Omega_t), d_{t+1}(\Omega_t), w_t(\Omega_t)\right]\right\}_{t=0}^{+\infty}$$

such that:

(i) Given $\left\{p_t(\Omega_t), d_t(\Omega_t), w_t(\Omega_t)\right\}_{t=0}^{+\infty}$, $\left\{c_t(\Omega_t), s_{t+1}(\Omega_t), \ell_t(\Omega_t)\right\}_{t=0}^{+\infty}$ is a solution to the representative household's problem ;

(ii)Given $\left\{p_t(\Omega_t), d_t(\Omega_t), w_t(\Omega_t)\right\}_{t=0}^{+\infty}$, $\left\{y_t(\Omega_t), k_{t+1}(\Omega_t), h_t(\Omega_t), \hat{h}_t(\Omega_t), \tilde{h}_t(\Omega_t)\right\}_{t=0}^{+\infty}$ is a solution to the representative firm's problem ;

(iii) Given $\left\{\left[c_t(\Omega_t), s_{t+1}(\Omega_t), \ell_t(\Omega_t)\right];\left[y_t(\Omega_t), k_{t+1}(\Omega_t), h_t(\Omega_t), \hat{h}_t(\Omega_t), \tilde{h}_t(\Omega_t)\right]\right\}_{t=0}^{+\infty}$, $\left\{p_t(\Omega_t), d_t(\Omega_t), w_t(\Omega_t)\right\}_{t=0}^{+\infty}$ clear all markets in the sense that :

$$\begin{aligned} y_t(\Omega_t) &= c_t(\Omega_t) + i_t(\Omega_t) \\ 1 &= h_t(\Omega_t) + \ell_t(\Omega_t) \\ h_t(\Omega_t) &= \hat{h}_t(\Omega_t) + \tilde{h}_t(\Omega_t) \end{aligned}$$

Likewise, we can define a competitive equilibrium allocation with incomplete information as a sequence of functions of the form:

$$\left\{\left[c_t(\Omega_t), s_{t+1}(\Omega_t), \ell_t(\Omega_t^*)\right];\left[y_t(\Omega_t), k_{t+1}(\Omega_t), h_t(\Omega_t^*), \hat{h}_t(\Omega_t), \tilde{h}_t(\Omega_t)\right];\left[p_t(\Omega_t), d_{t+1}(\Omega_t), w_t(\Omega_t^*)\right]\right\}_{t=0}^{+\infty}$$

where $\Omega_t^* \subseteq \Omega_t$, and where analogous conditions holds with appropriate the corresponding structure. Thus, we consider the following versions of the model:

- Version V1: This corresponds to the case where the cycle is only driven by Solow residual, and where there is complete information $(\Omega_t^* = \Omega_t = (k_t, A_t))$.
- Version V2: The cycle is only driven by Solow residuals, and hours are decided before these shocks are known to the firm $(\Omega_t = (k_t, A_t))$ and $(\Omega_t^* = (k_t, A_{t-1}))$. Then, as the technology shocks are revealed, the firm decides to allocate hours to productive and maintenance activities. As already mentioned, this can be viewed as a labor hoarding mechanism à la Burnside et al. (1993).

- Version V3: The cycle is now driven by both Solow residuals and depreciation shocks, and information is complete $(\Omega_t^* = \Omega_t = (k_t, A_t, B_t))$.
- Version V4: The cycle is driven by both sources of shocks, but firms decide hours when only Solow residuals are known $(\Omega_t = (k_t, A_t, B_t))$ $(\Omega_t^* = (k_t, A_{t-1}, B_{t-1}))$. Then, as the shocks are revealed, hours are splitted between productive and maintenance activities. This case will be referred as ‘‘labor hoarding’’.

2.5 The production/maintenance arbitrage

The Euler conditions of this model are:

$$u_{c_t} = \beta E_t u_{c_{t+1}} (\tilde{k}_{k_{t+1}} + F_{k_{t+1}})$$

$$F_{\hat{h}_t} + \tilde{k}_{\hat{h}_t} = \tilde{k}_{\tilde{h}_t}$$

The first describes the equality of the cost of the last unit of output invested in any period t, u_{c_t}, to the expected discounted benefit associated with the consumption of the output that this unit will generate next period, $\beta E_t u_{c_{t+1}} (\tilde{k}_{k_{t+1}} + F_{k_{t+1}})$. The $F_{k_{t+1}}$ is the marginal product of capital. $\tilde{k}_{k_{t+1}}$ is the surviving fraction of that investment. In the BRBC, $\tilde{k}_{k_{t+1}}$ reduces to $1-\delta$.

The second condition states that labor should be allocated between production and maintenance in such a way as to equate the marginal product of the two processes. $F_{\hat{h}_t}$ is the marginal product of labor, $\tilde{k}_{\hat{h}_t}$ is the depreciation–in–use and $\tilde{k}_{\tilde{h}_t}$ is the marginal product of maintenance activity. It can be easily shown that by virtue of the concavity and the Inada type conditions, there is a unique level of $\tilde{h}_t$ and $\hat{h}_t$ that satisfies the above conditions. (See appendix A)

3. Calibration

The model is calibrated according to the methodology described by Cooley and Prescott (1995). We are interesting in matching the BRBC model's steady state in order to have a common benchmark to evaluate our models. The parameters are reported in table 1. g_z and g_n are measured from data as the rate of growth of real per capita output and the rate of population growth, respectively equal to 0.012 and 0.0156 on an annual basis. In versions V1 to V4 and in the BRBC model, payments to factor services exhaust output, such that α corresponds to capital's share in output, which is equal, according to Cooley and Prescott (1995), to 0.4 in the US economy.

— Please Insert Table 1 —

We impose that $\tilde{k} / k = 1 - \delta$, where δ is the average mean of the depreciation rate in the US economy. Using the physical capital law of motion, we compute δ such that its value matches the steady–state investment/capital ratio in the US economy (i/k=0.076). This leads to an annual depreciation rate of 0.048 (δ=0.012 on a quarterly basis). Given values for g_n, g_z, α and δ, β is computed such that we match the capital/output ratio, which is 3.32 on annual basis. This yields a value of β =0.9326 on an annual basis, such that β=0.9827 on a quarterly basis.

The two parameters defining the depreciation technology, θ and $\overline{B}$ are set such that:[8]

$$\frac{\overline{B}}{h}\left(\theta\hat{h}+\tilde{h}^{\theta}h^{1-\theta}\right)=1-\delta$$

$$w=\overline{B}\frac{k}{h}\left(\frac{\tilde{h}}{h}\right)^{\theta-1}\left(\theta+(1-\theta)\frac{\tilde{h}}{h}\right)-(1-\delta)\frac{k}{h}$$

The first condition corresponds to the fact that $\tilde{k} / k$ is equal to one minus the depreciation rate in steady state. The second condition is the firm labor demand. We have to impose the share of hours the firm devotes to maintenance/improvement activities. As noticed by McGrattan and Schmitz (1999), there does not exist data on maintenance for the US economy. Nevertheless, they report data, which indicate that the share of total maintenance and repair in GDP is 5.7% in Canada. We use this value, such that this implies that the firm devotes 9.5% of its total hours to maintenance activities. Solving the previous system, we get θ=0.98 and $\overline{B}$ =1.0002.

The total fraction of time devoted to market activities is determined on the basis of studies by Becker and Ghez (1975) and Juster and Stafford (1991), which have found that households devote one third of their total time endowment to market activities. Here, we follow Cooley and Prescott (1995) and set this value to 0.31. This allows us to calibrate γ, the marginal utility of labor, given, in steady state, by

$$\gamma=\frac{1-\alpha}{h}\frac{y}{c}$$

Finally, we have to put structure on the shocks. Both shocks is supposed to follow AR(1) processes. Concerning the technology shocks, we assume that $\overline{A}=1$. The persistence parameter is set to 0.95, accordingly to previous studies. The standard deviation of innovations is set such that each

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[8] Obviously this does not apply to the standard RBC model.

model matches exactly the standard deviation of the cyclical component of output.[9] The calibration of the the shocks to maintenance activities (versions V3 and V4) was undertaken using the following procedure. As no data are available for either maintenance or depreciation along the Business cycle, we used the Canadian data used by McGrattan and Schmitz (1999). They find, using annual data, that the standard deviation of maintenance and repair expenditures is 1.47 times that of GDP. Therefore, we set the volatility of the shock to maintenance activity such that the model matches this number. The value of the implied standard deviation will be reported in table 2.

In the Greenwood et al. (1988) type of model, we impose that $E(D_t)=1$. Then we sue the definition of depreciation, such that φ is set to match the level of the depreciation rate. This yields the values reported in table 1.

The models are then log–linearized around their deterministic steady state, that turns out to be unique in each case. Then, each linear dynamic rational expectations system is solved using a method discussed in Farmer (1993). We then assess the ability of the model to mimic business cycle features of the US economy, and try to evaluate the gain from endogenizing the depreciation along the business cycle.

4. Simulation

In this section we address the question of the ability of the model to mimic a sample of selected moments that characterize the US business cycle. All reported statistics (See table 2) are taken from Cooley and Prescott (1995) and are computed on US quarterly data from 1954:1-1991:2. The series are first detrended using the Hodrick–Prescott filter with a λ set at a value of 1600. Since our model does not deal with durables, consumption is consumption of nondurables and services, which explains the low volatility in actual data (0.86). Hours worked are total hours of work, taken from Establishment Survey.

In our simulations, the depreciation rate was computed using the law of motion of physical capital:

$$\delta_t = 1 - \left(\frac{K_{t+1}}{K_t} - \frac{I_t}{K_t} \right)$$

It appears that δ is more volatile than output and is procyclical. The more capital is used the more it depreciates. This yields another interpretation in terms of « opportunity cost ». Recessions, because they lower the opportunity cost of postponing productive activities, are a good time to allocate ressources to maintenance activities. This is illustrated in figure 2 and 3 that report the

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[9] This cyclical component is obtained applying a Hodrick and Prescott (1980) filter on the data, with λ =1600.

impulse response functions of various aggregates to a positive technological shock. As can be seen from figure 2, in face of a positive shock on technology, labor shifts away from maintenance activities as the opportunity cost of renuncing to output production increases. On the contrary, in bad times, firms invest in maintenance.[10] Physical capital is maintained and it is used less intensively, lowering the depreciation rate. The model can then account for a ‘‘virtue of bad times’’ type behavior (See, e.g., Aghion and Saint-Paul (1998)). We also report statistics for the Solow residual as it is conventionally measured. Indeed, according to our model, the conventionally measured Solow residual, s_t, is related to the true technology shocks, A_t, and the ratio between hours in productive activities and the total amount of hours hired by the firm, $\hat{h}_t / h_t$, via the relationship:

$$s_t = A_t \left(\frac{\hat{h}_t}{h_t} \right)^{1-\alpha}$$

It follows that any aggregate that is correlated with $\hat{h}_t / h_t$ will also be correlated with the Solow residual, even though it is not correlated with A_t.

As usual, it appears that our model is consistent with the general pattern of business cycle features. Consumption is less volatile than output and investment displays more volatility. Hours are almost as volatile as output but more volatile than aggregate productivity. All aggregates are procyclical.

First of all, it is worth emphasizing that the internal properties of the model differ in terms of magnification of shocks. Indeed, it appears that the exogenous volatility needed to mimic the standard deviation of output is lower as soon as we endogenize the depreciation rate. Compared to the standard RBC model, V1–V4 need a lower standard deviation of innovations to the Solow residual. What seems to really matter is the hypothesis of the depreciation technology. It is thus the ability of firms to split hours between two activities, production and maintenance, that introduces a channel through which shocks are magnified. But, the GHH version is able to generate higher volatility in investment than versions V1–V4. Indeed, as depreciation is due to a more intensive use of physical capital in this model, booms are associated with higher investment in order to compensate the loss induced by higher depreciation. Therefore, this increases investment volatility. In versions V1 and V2, where only Solow residual is introduced, this effect is compensated by the maintenance activity that prevents firms from investing too much in booms. The volatility of investment is thus reduced compared to the previous case, but it remains higher than in the standard RBC model. When shocks to depreciation are

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[10] This supports results found by Licandro and Puch (1997).

introduced (versions V3–V4), the volatility of investment increases since maintenance becomes an uncertain activity.

— Please Insert Table 2 —

As can be seen from Table 2, the models perform well in terms of hours volatility. This is essentially due to the indivisibility in labor hypothesis, which has been showed to be efficient in increasing volatility of hours by Hansen (1985). But, we note that version V2 and V4 are performing better than the GHH version. Because firms have to decide how many hours to hire before the technology shocks are known, their labor demand is uncertain and they increase their response to shocks. If a firm experiences a positive shock, the inherent persistence of technology shocks, makes it more profitable to increase hours in order to benefit from another positive shock in the future. Relative to V2, V4 performs a bit better along this line. Indeed, as shown in figure 5, the depreciation rate falls sharply following a depreciation shock, so that more capital is passed to the following period. Thus, the expected real wage increases and the intertemporal substitution effect driving hours dynamics is reinforced.

Another feature that emerges from Table 2 is that the ‘‘naïve’’ Solow residual is more volatile than the technology shock. Indeed, as aforementionned, the conventionally measured Solow residual does not take into account the split of hours between production and maintenance. It is thus endogenous, such that

$$\ln(s_t) = \ln(A_t) + (1-\alpha)\left(\ln(\hat{h}_t) - \ln(h_t)\right)$$

Following a shock to the depreciation/maintenance technology, the firm reallocates labor input between the two activities, thus yielding a change in the Solow residual. Therefore, less volatile technology shocks are required in versions V1 to V4 compared to the BRBC version.

The models generally fail to account for the high serial correlation in output dynamics, even with relatively high persistence in technology shocks. This property is shared by a lot of models in the RBC literature (See e.g. Cogley and Nason (1995)). However, as soon as the labor hoarding phenomenon is introduced, the models (versions V2 and V4) match output persistence, as shown by Burnside et al. (1993). This can be explained by the fact that labor does not react instantaneously to a technology shocks, so that the instantaneous response of output is due to the rise in total factor productivity. Then, hours increase, and sustain the rise in output, thus leading to increase the first order autocorrelation.

Concerning correlations of aggregates with output, it appears that consumption, investment and hours are procyclical. But the level of the correlations are too high, especially for consumption as long as we consider the standard RBC model, the GHH model, and versions V1–V2. But as soon as shocks to maintenance are introduced, the correlation between consumption and output diminishes sharply. Indeed, this shock affects the marginal return of savings, without affecting directly household's wealth. This creates a dissociation between output and consumption that lowers their correlation. It is finally worth noting that versions V2 and V4 of the model allow to dissociate apparent productivity and the real wage, as although too high the correlation between the real wage and productivity lies around 0.75 whenever labor hoarding is taken into account.

Analyzing more specifically depreciation, it appears that the volatility of depreciation obtained from GHH is higher than that exhibited by versions V1–V2. Indeed, as we have already pointed out, depreciation is due to a more intensive use of physical capital in the model. Thus, after a positive technology shock, hours will increase and depreciation will follow. Volatility of depreciation is thus high. In versions V1–V2, the maintenance activity counteracts the depreciation–in–use effect, so that after a positive technology shock capital will depreciate more but will be maintained — since even if the firm devotes a lower share of its total hours to those activities it still maintains and repairs. The depreciation rate will thus react less than in the previous case, and the volatility will be lower. In version V3 and V4, the depreciation rate axhibits higher volatility as the maintenance activity becomes incertain. In face of a positive shock to the maintenance technology, the depreciation rate drops (see figure 5). Indeed, on impact it is more profitable for the firm to devote a higher share of its labor input to maintenance activities. Therefore, as can be seen from figure 4, $\tilde{h}_t$ increases, although the firm does not shift its total labor demand. Thus, more capital is passed to the next period, corresponding to a decrease of the depreciation rate. But what can also be noted from figure 5 is that the depreciation rate is highly senstive to maintenance shocks, even though the volatility of B_t is low, the depreciation rate fluctuates much compared to V1 and V2, but also to the GHH model.

δ is procyclical as long as we consider the GHH and V1–V4 versions. As we explained earlier, in these versions of the model, the co–movement of output and δ is uncertain. This is because the effect of the Solow residual on δ can be decomposed in two: a substitution and an income effect. Let us consider a technological shock, as reported in figure 2 and 3. The substitution effect is positive as a high Solow residual causes output to be more efficient than maintenance and repair activities. Thus, utilization increases and maintenance decreases. This effect may be interpreted within the scope of the so–called ‘‘opportunity cost’’ approach to fluctuations. Indeed, in face of a positive shock to technology the opportunity cost of maintaining and repairing rises, as it corresponds to a shift of hours away from productive activities and thus to nenonce to profits. Therefore, maintainance appears to be beneficial within recessions. This implies that δ goes up in face of a technological shock. The income effect is negative as a high Solow residual causes output to be more efficient, releasing labor to do maintenance. Thus, maintenance increases, driving δ down. As it turns out in these versions, the substitution effect dominates the income effect (See figure 3).[11] In versions relying on Solow residual only, the correlation between δ and output is extremely high. But, as soon as a maintenance shock is introduced in the model, the model leads to much lower correlations. Indeed, as a maintenance shock occurs in the economy, the marginal return from increasing hours allocated to maintenance activity increases, so that it counters the effect of a positive technology shocks (see figures 4 and 5). Otherwise stated, technology and maintenance shocks exert opposite effect on depreciation. Thus, would only depreciation shocks considered, δ would become countercyclical.

— Please Insert Figure 2–5 —

Finally, it also appear that endogenizing depreciation allows to explain the Dunlop-Tarshis stylized fact. It is particularly true in versions V2 and V4. Version V4, that incorporates a labor hoarding phenomenon and where both Solow residual and depreciation shocks are introduced, allows to mimic particularly well the correlation between hours and productivity and that between hours and the real wage. In period t, the firm decides to hire a given amount of hours without knowing the realization of the shocks. Then the shocks are revealed, and it allocates hours between productive and maintenance activities. Therefore, even if total hours increase, this does not necessarily corresponds to an increase in marginal productivity of labor. Part of this adjustment can be due to an increase in marginal return of maintenance activity. Thus, that creates a dissociation between aggregate productivity, as conventionally measured, and the marginal productivity of labor input (see for instance the correlation between productivity and the real wage in table 2) that lowers the correlation between hours and productivity. The introduction of a maintenance shock magnifies this effect. When a maintenance shock occurs, the marginal return of hours in maintenance activity raises, such that it leads the firm to allocate more resources in that activity. So, ceteris paribus, output is lower, since hours in output are lower, while total amount of hours increases so that aggregate productivity diminishes. This thus acts negatively on the correlation between hours and productivity.

5. Concluding Remarks

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[11] A similar effect was found in the partial equilibrium models of Epstein and Denny (1980) and Choi and Kollintzas (1985).

Almost all growth and business cycle models incorporate the assumption that capital depreciation is a fixed fraction of the existing capital stock. Feldstein and Rotschild (1974) have made it clear that this assumption has both weak theoretical foundations and empirical underpinnings. In this paper we developed an RBC model that endogenizes the depreciation process. We did this by considering explicitly the capital utilization, maintenance, improvement and scrapping activities of firms. Thus, in our model it is possible to examine the effect of various changes in the environment on the depreciation process. The main idea is that firms hire labor that they can either use for the usual production purposes or to maintain capital. Labor that goes into production implies capital utilization and depreciation-in-use. Labor that goes into maintenance implies less depreciation. There are two interesting tradeoffs in this model that they go back a long way - at least to Keynes. First, capital can increase either by buying more new capital or maintaining more the existing one. Second, labor can be allocated in producing current output or maintaining capital that will produce more output in the future. This makes the standard RBC propagation mechanism much more sophisticated. In fact, depending on the nature of the technology shocks - Solow residuals and ‘‘depreciation shocks’’ – and the timing of information vis a vis these shocks we constructed six different versions of the model. One of these versions is the baseline RBC model (Prescott (1986)). Another version shares the Greenwood et al. (1988) feature of depreciation being a convex function of utilization, whereby maintenance is ignored. And, two of these versions share the Burnside et al. (1993) feature of labor hoarding behavior, whereby the total labor input is decided before at least one of the technology shocks are known.

Our theoretical work suggests that maintenance could be an important determinant of output, employment, investment and capital depreciation.The richness of the business cycle propagation mechanisms of the model is manifested in the reduction of the variance of the Solow residual necessary to much output variation in the data. This is quite important for as King and Rebelo (1997) point out the relatively large size of the Solow residual remains is the Achilles' heal of RBC models. Finally, the labor hoarding versions of the model can account for the Dunlop-Tarshis stylized fact, since in these versions productivity and labor input are disassociated. In particular, the model is capable of generating (a) a low correlation between labor productivity and output, (b) a low correlation between wages and productivity and (c) a relatively strong correlation between real wages and hours worked.

— APPENDIX —

A. Uniqueness of $\tilde{h}$ and $\hat{h}$

Taking into account the fact that $h_t = \hat{h}_t + \tilde{h}_t$, the function g is a concave function of $\hat{h}_t$. The problem is thus, knowing the level of total hours, determining the level of $\hat{h}_t$. The first order condition associated to this problem , taking into account that $h_t = \hat{h}_t + \tilde{h}_t$, is given by:

$$F_{\hat{h}_t} + g_{\hat{h}_t} = 0$$

which rewrites as

$$F_{\hat{h}_t} = -g_{\hat{h}_t} \text{ or } \phi(\hat{h}) = \psi(\hat{h})$$

where $\phi(\hat{h}) = F_{\hat{h}_t}$ and $\psi(\hat{h}) = -g_{\hat{h}_t}$. By concavity of F and g, we know that $\phi(\hat{h})$ is decreasing whereas $\psi(\hat{h})$ is increasing. Further, from the inada conditions, we know that $\lim_{\hat{h}\to 0} F_{\hat{h}} = +\infty$ whereas $\lim_{\hat{h}\to 0} g_{\hat{h}} = 0$ so that $\hat{h}_t$ is unique.

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Table 1: Calibration

Population rate of growth (quarterly)	g_n	0.0030
Rate of growth of technology (quarterly)	g_z	0.0039
Capital elasticity of output	α	0.4000
Depreciation parameter	θ	0.9844
Discount rate factor (quarterly)	β	0.9827
Marginal disutility of labor	γ	2.6898
Persistence of technology shock	ρ_a	0.9500
Mean of technology shock	$\overline{A}$	1.0000
Persistence of Depreciation/ maintenance shock	ρ_b	0.9500
Mean of Depreciation/ maintenance shock	$\overline{B}$	1.0002
Elasticity of depreciation rate(a)	φ	3.1192
Mean of depreciation shock(a)	$E(D)$	1.0000
Variance of depreciation shock(a)	$Var(D)$	0.0000

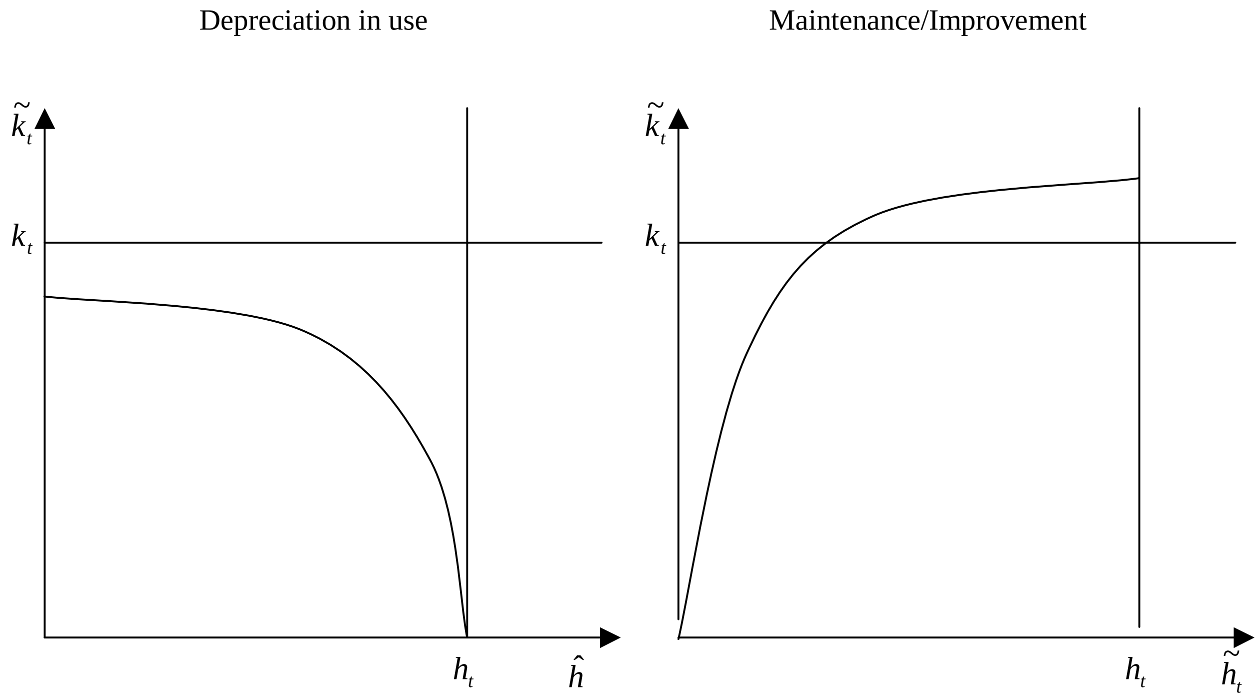
(a) Specific to the GHH model

Table 2: Selected second order moments

	Data	BRBC	GHH	V1	V2	V3	V4
σ_a	–	(0.710)(a)	(0.545)	(0.538)	(0.600)	(0.532)	(0.593)
σ_b	–	–	–	–	–	(0.029)(a)	(0.032)
Standard deviation							
y	1.72	1.72	1.72	1.72	1.72	1.72	1.72
c	0.86	0.42	0.43	0.36	0.37	0.40	0.42
i	5.34	5.68	7.14	5.81	5.80	5.92	5.90
h	1.69	1.37	1.36	1.41	1.58	1.46	1.52
$\hat{h}$	–	–	–	1.75	1.80	1.79	1.83
$\tilde{h}$	–	–	–	1.84	1.98	1.83	1.96
y/h	0.73	0.42	0.43	0.36	0.61	0.40	0.62
w	0.76	0.42	0.43	0.63	0.37	0.40	0.42
δ	–	–	1.76	1.24	1.25	3.02	3.38
s (b)	–	0.90	0.91	0.88	0.95	0.87	0.94
A (c)	–	0.90	0.69	0.68	0.76	0.67	0.75
First order autocorrelation							
y	0.85	0.69	0.69	0.68	0.83	0.68	0.82
δ	–	–	0.68	0.68	0.83	0.70	0.69
Correlation with output							
c	0.77	0.87	0.88	0.88	0.87	0.72	0.71
i	0.91	0.99	0.99	0.99	0.99	0.99	0.99
h	0.91	0.99	0.99	0.99	0.93	0.98	0.93
$\hat{h}$	–	–	–	0.99	0.96	0.98	0.95
$\tilde{h}$	–	–	–	-0.97	-0.91	-0.95	-0.89
y/h	0.37	0.87	0.88	0.88	0.55	0.72	0.48
w	0.68	0.87	0.88	0.88	0.87	0.72	0.71
δ	–	–	0.97	0.98	0.98	0.25	0.26
s	–	0.99	0.99	0.99	0.94	0.99	0.93
Correlation with productivity							
h	-0.03	0.78	0.80	0.82	0.22	0. 58	0.14
w	0.22	1.00	1.00	1.00	0.75	1.00	0.74
Correlation with wages							
h	0.64	0.78	0.80	0.82	0.70	0.58	0.51

(a) in percent
(b) denotes the « naïve » Solow residual
(c) denotes the technological shock
(d) Taken from the establishment survey

Figure 1: Depreciation/maintenance technology



Depreciation in use

Maintenance/Improvement

Figure 2: IRF to a technological shock (I)

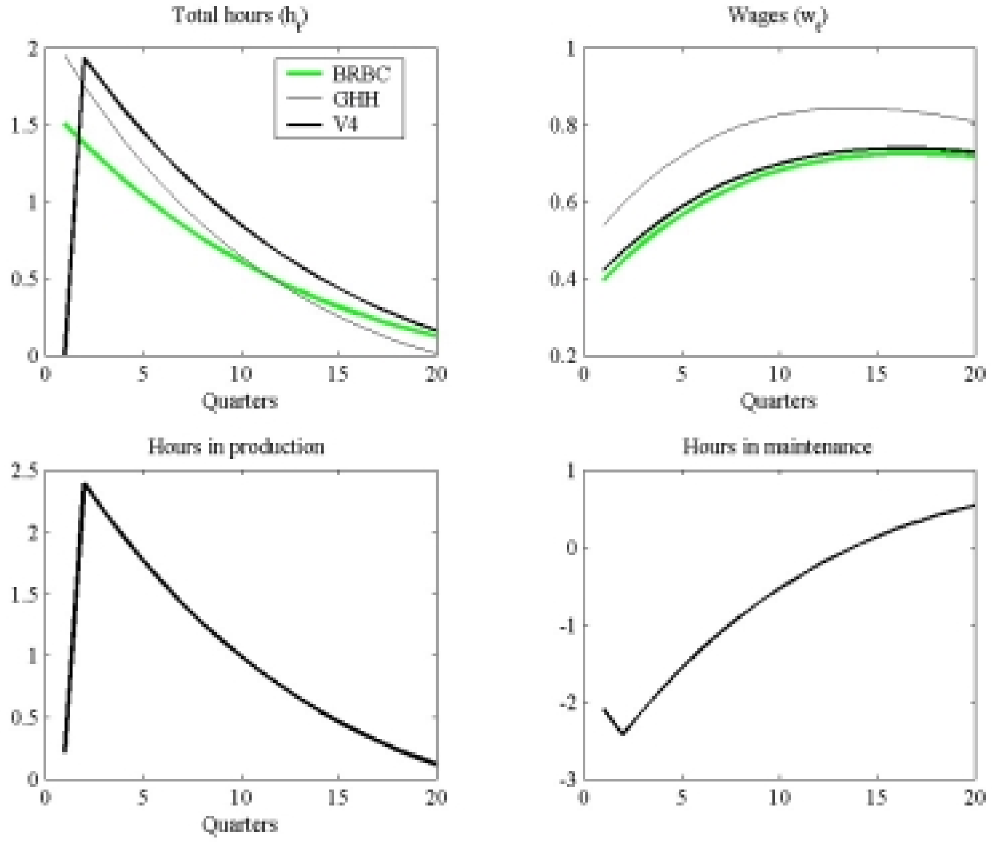


Figure 3: IRF to a technological shock (II)

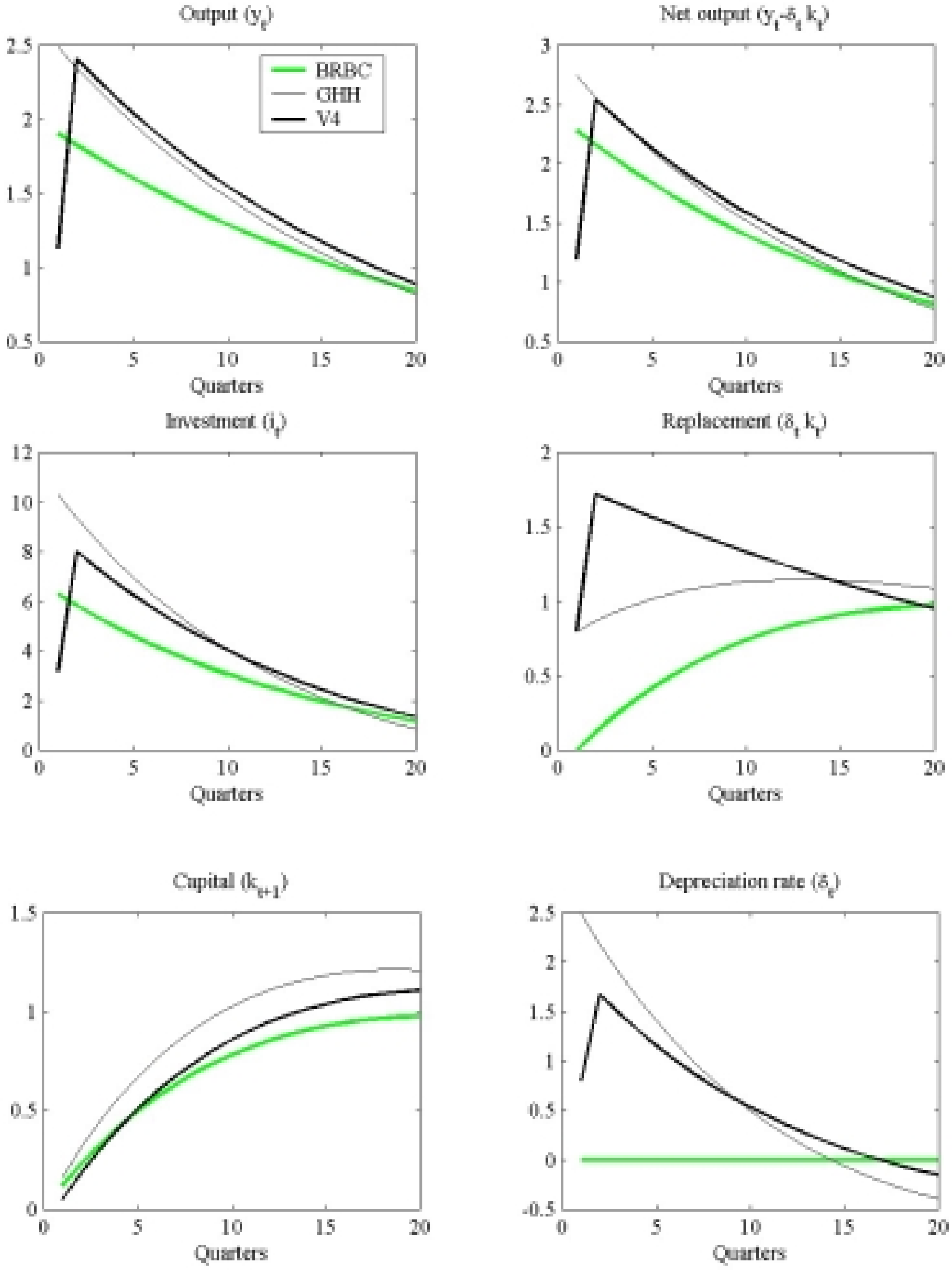


Figure 4: IRF to a maintenance/depreciation shock (I)

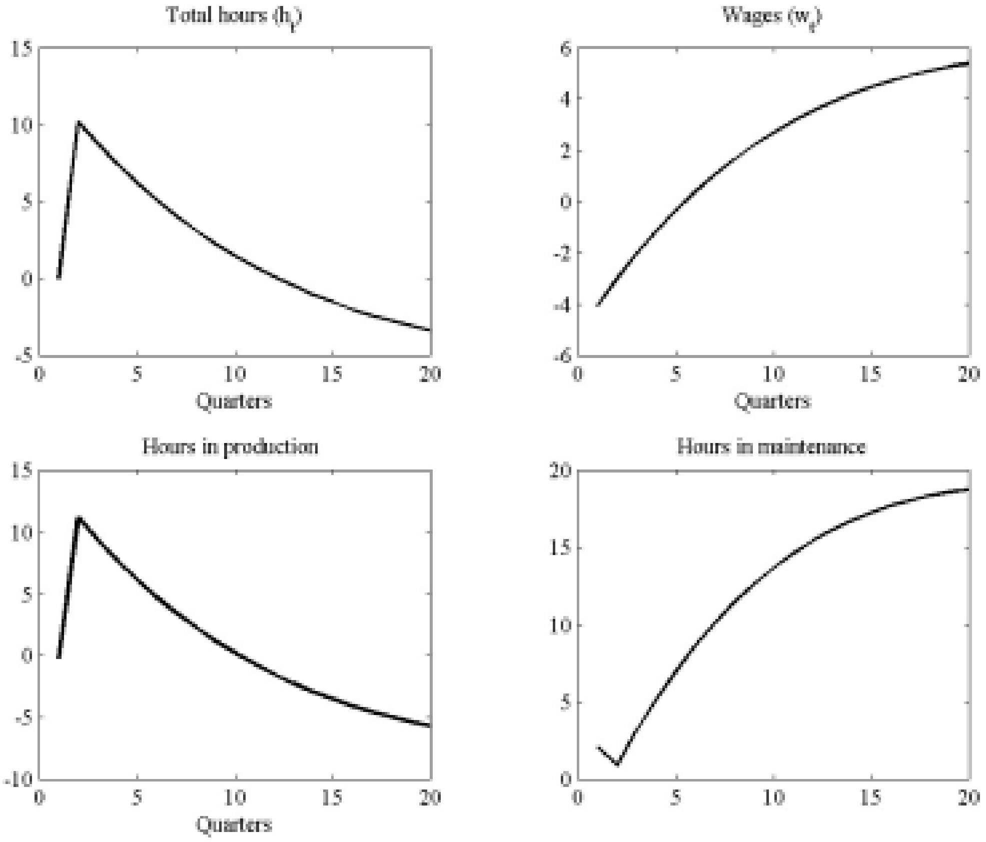
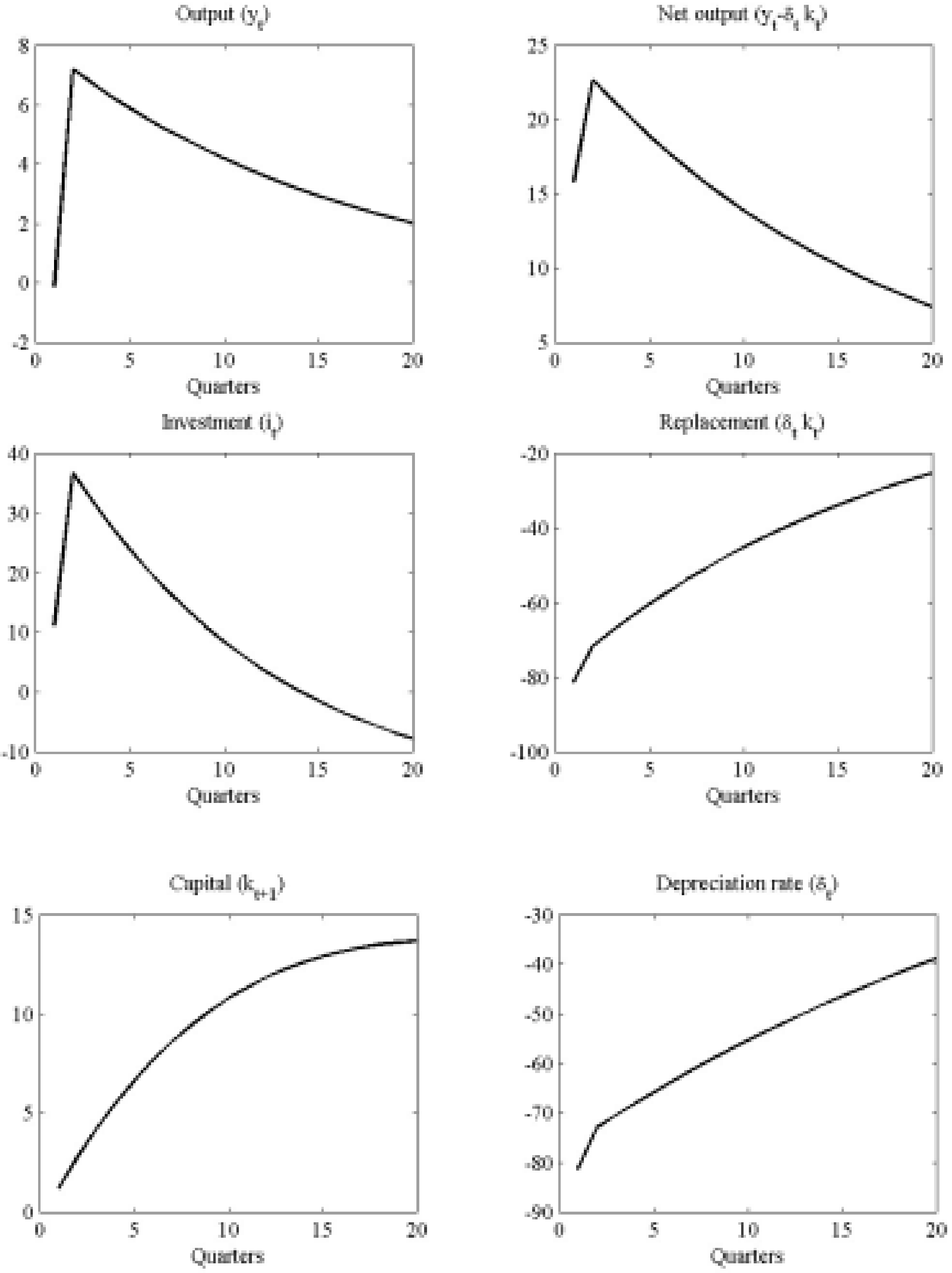


Figure 5: IRF to a maintenance/depreciation shock (II)



Output (y_t)

Net output ($y_t - \delta_t k_t$)

Investment (i_t)

Replacement ($\delta_t k_t$)

Capital (k_{t+1})

Depreciation rate (δ_t)