Essays in Macroeconomics

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Abstract

There is growing acknowledgement that changes in expectations are an important cause of the business cycle. Business cycles are characterized by positive co-movements between consumption, investment, output and hours, yet changes in expectations can not generate such positive co-movements in the most standard neo-classical business cycle models. If one is willing to entertain a richer production technology, it is possible to obtain the kind of fluctuations typical of business cycles that are caused by expectation revisions. This thesis analyzes systematically such a production technology, characterized by a nonlinear transformation curve between consumption and investment at the aggregate level, and evaluate some of its macroeconomic implications.

This thesis comprises three essays. The first essay empirically investigates if the proposed change in the production technology improves the capacity of neo-classical business cycle models to account for the behavior of the aggregate labor market. It finds that the proposed change is a partial improvement over standard models. The second essay shows that while a nonlinear transformation curve helps in obtaining an economic expansion following good news about future productivity gains, it can do so only if the intertemporal elasticity of substitution in consumption is high. To obtain an expansion in the more general case, one has to allow for a sufficiently high degree of complementarity between capital and labor in production. The third essays estimates a version of the model to analyze its business cycle properties. In the model, the nonlinear transformation curve arises because some resources need to be spent to distribute goods to their final use. There, it is found that the estimated model reproduces well the dynamics of output and investment but produces too much consumption volatility. Moreover, it suggests that news about future productivity changes are a more important source of economic fluctuation than actual changes in productivity. Finally, the estimated model produces distribution costs that are quite in line with the data.

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Dedication

To my wife Julie and my son Olivier. This is for you.

1. Introduction

Over time, empirical evidence has shown that traditional explanations of the business cycle in terms of supply and demand shocks proved incomplete. Following the boom-bust in investment experienced in the United States and many other countries during the 1994-2003 period - the so-called "new economy" era - many analysts now consider that changes in expectations about the future are an important source of economic fluctuations. Despite this, typical models of the business cycle fail to generate an expansion in consumption, investment, output and hours following such changes. This thesis analyzes a class of models capable of generating such positive co-movements and study some of its macroeconomic implications. The main characteristic exploited is the presence of a nonlinear transformation curve between consumption and investment.

The first essay looks at the capacity of the proposed class of models to account for the behavior of the aggregate labor market at business cycle frequencies. Equilibrium models of the business cycle rely on the equality between the consumption/leisure trade-off and the marginal product of labor to determine labor input. It is now well documented that this approach proves inadequate because observable measures of the marginal rate of substitution between consumption and leisure and the marginal product of labor, constructed using standard assumptions about utility and the production function, fail to be equal. In a model with a nonlinear transformation curve, the equilibrium labor market relation is augmented with a term related to the relative price of consumption. Empirical investigation suggests that this term partly improves the capacity of equilibrium business cycle models to account for the behavior of the labor market.

The second essay studies the capacity of models with a nonlinear transformation curve to generate positive co-movements in consumption, investment, output and hours following positive news about the future. In the model, intermediate good firms are multi-product firms supplying a differentiated good to both the final consumption and investment sectors. Each intermediate good firm has a production function with multi-sectoral adjustment costs. If the curvature of the transformation curve is sufficiently high, the model generates cost complementarities, giving an incentive to produce consumption and investment jointly and making possible the required positive co-movements. It is found that if the intertemporal substitution in consumption is high enough, cost complementarities alone generate an economic expansion following positive news shocks. When the intertemporal substitution is low, cost complementarities will generate an expansion only if there is enough complementarity in production between capital and labor.

The third essay empirically estimates a model in which the nonlinear transformation curve is generated by the presence of a distribution system so as to evaluate its business cycle implications. Estimation favors a parameterization such that positive news about the future generates an economic expansion. It is found that the estimated model captures very well the dynamics of investment, output and the relative price of investment and produces distribution costs in line with the data. The estimated model also suggests that news about future changes in productivity are a more important source of business cycle fluctuations than contemporaneous changes in productivity. On the other hand, it generates too much consumption volatility and do not improve over standard business cycle models when one looks at the predicted second moments of the labor market. Paradoxically, consumption volatility is too high precisely because the curvature of the transformation curve is estimated to be fairly high. Finally, the empirical findings suggest that it would be a worthwhile investment to look at specification of preferences where the wealth effect of productivity gains on labor is small.

2. Multisectoral Adjustment Costs and the Cyclical Behavior of the Aggregate Labor Market

2.1 Introduction

Understanding the behavior of the labor market is one of the most difficult and long-lasting challenge faced by economists. Among the many questions of interest, one is concerned with fluctuations in the amount of time spent in market activities at business cycle frequencies. In equilibrium models of the business cycle, one typically relies on the equality between the consumption/leisure trade-off and the marginal product of labor to determine labor input. It is now well documented that this approach proves inadequate because observable measures of the marginal rate of substitution between consumption and leisure and the marginal product of labor, constructed using standard assumptions about utility and the production function, fail to be equal. Typically, their difference, which has come to be known as the Hall residual, will display large and persistent cyclical patterns. This behavior indicates that standard RBC models systematically fail to properly capture the dynamics of the labor market, suggesting that some important economic mechanisms are missing. Over recent years, researchers investigated whether or not this model misspecification is economically important and tried to identify potential factors underlying it.

The original contribution analyzing the cyclical fluctuations in the difference between the marginal product of labor and the observable component of the labor supply curve is that of Hall [1997]. The contribution aims at explaining fluctuations in aggregate hours using a variety of shocks. Distinguishing between the atemporal and intertemporal effect of these shocks, Hall concludes that intertemporal mechanisms are unlikely to play an important role in aggregate hours fluctuations. Rather, he attributes much of the fluctuations in aggregate hours to the atemporal effect of an aggregate preference shift, which is essentially the Hall residual[1]. Based on this finding, the author advocates the importance of developing models with a richer intratemporal analysis to understand the labor market. This is the route followed in this paper.

In a related contribution aiming at identifying possible vectors of economic fluctuations, Chari et al. [2006] build a prototype economy comprising time-varying wedges that distort the equilibrium decisions of agents operating in competitive markets. They use this artificial economy to evaluate the contribution of each wedge to economic fluctuations during the Great Depression and the 1982 recession. Of particular interest is what they coined the *labor wedge*, which corresponds to the Hall residual. They show that this wedge was a major contributor to economic fluctuations during the Great Depression and to a lesser extend during the 1982 recession. Based on this finding, they conclude that promising models of economic fluctuations should pay particular attention to mechanisms generating a labor wedge. Although they themselves remain agnostic about the underlying source of this wedge, they show that it can potentially be accounted for by a model with sticky wages and monetary policy shocks or a model with unions and antitrust policy shocks.

From a somewhat different perspective, Galí et al. [2005] use the Hall residual, which they relabel the *inefficiency gap*, to evaluate the welfare cost of business cycles. Their methodology assumes at the outset that the economy is poised with market frictions and in particular, wage and price rigidities. These rigidities translate into equivalent wage and price markups which are the underlying sources of the Hall residual. To support their argument, they present empirical evidence that fluctuations in the inefficiency gap can not be attributed to an exogenous preference shock, as proposed by Hall. Indeed, if Hall's interpretation of the residual is true, it should be invariant to other type of disturbances. Using a 4 variables VAR as in Christiano et al. [1999] and augmented with the inefficiency gap and a measure of price markup, they show that both the gap and the price markup respond endogenously to a monetary policy shock. They also demonstrate that (detrended) real

[1] Or, in Hall's nomenclature, the MRS shift. Chang and Kim [2004] and Nakajima [2005] provide a theoretical justification for this interpretation.

output, the nominal interest rate and the yield spread all Granger-causes the Hall residual at conventional level. This is evidence against the preference shock hypothesis but fully consistent with their proposed explanation of the gap: countercyclical markup variations.

Adopting an intertemporal point of view, Johri and Letendre [2006] as well as Bouakez and Kano [2006] interpret the Hall residual as an indication that some dynamic elements are missing in the labor market equilibrium equation. Consequently, constructing models with such dynamic elements should help improve their performance. Using GMM estimation, Johri and Letendre show that introducing phenomena such as learning-by-doing, habit formation or labor adjustment costs in a standard RBC model either reduce significantly or remove the persistence in the residuals but, in most cases, at the cost of dramatically increasing their size.

From a different perspective, the finding of Galí *et al.* points to the importance of properly identifying the source of the Hall residual. If it represents random preference shifts or underlying dynamic misspecification in either the kernel of the utility or the production function, then employment fluctuations are optimal and nothing should be done about it. On the other hand, if this residual measures wage and price markups, then the economy is away from its social optimum and movements in the residual involve inefficient fluctuations in the allocation of resources. In this case, some stabilization policy could be desirable.

The present paper proposes yet another exploration into the underlying source of the Hall residual. In particular, I empirically investigate whether a misspecification in the production structure could account for (part of) the residual. The paper presents a business cycle model augmented with multisectoral adjustment costs. The model still relies on the equality between the consumption/leisure trade-off and the marginal product of labor to determine employment. Unlike usual business cycle models, however, the transformation curve between the consumption goods and the investment goods is nonlinear. This generates variation in the relative price of consumption, which then becomes a relevant factor in the determination of the labor market equilibrium. As such, it is of interest to investigate whether (part of) the Hall residual simply captures variation in the relative price of consumption. This, in turn, would suggest that usual models are too restrictive in their formulation of the production set[2]. Estimation using aggregate

[2] A model with multisectoral adjustment costs potentially possesses a theoretical, if not practical, advantage over popular alternatives as a benchmark model for economic fore-

US data indicates that the model with multisectoral adjustment costs can account for part but not all of the Hall residual. Estimates obtained for the level of adjustments costs suggests plausible values in the range of 1.8 to 1.9.

The remainder of the paper is organized as follow. Section 2.2 develops the theoretical model and the role played by the multisectoral adjustment costs hypothesis is clearly identified. Sections 2.3 and 2.4 present the results of the empirical exercise. Concluding remarks are drawn in section 2.5.

2.2 The model

The basic model introduced in this section is a standard RBC model with no market frictions and constant returns to scale technology. There is an infinitely lived representative consumer that maximizes its expected discounted utility

$$\max_{\{C_t,H_t,I_t,K_{t+1}\}_{t=0}^{\infty}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\ln C_t - \frac{\vartheta_0}{\eta+1} H_t^{\eta+1} \right) \tag{2.1}$$

where β is the discount factor and η is the inverse of the Frisch wage elasticity of labor supply. Output is produced with capital and labor. The main technological feature introduced in the model is the presence of multisectoral adjustment costs. Adjustment costs imply that one can not convert consumption goods into investment goods on a one-to-one basis, so that the transformation curve between consumption and investment is nonlinear. In this model, the aggregate resource constraint writes as

$$(aC_t^\sigma + bI_t^\sigma)^{\frac{1}{\sigma}} = A_t K_t^\theta L_t^{1-\theta} \tag{2.2}$$

with $\sigma \geq 1$, $a > 0, b > 0$ and $0 < \theta < 1$. Such technology is not new to the literature, as it has been used by Sims [1989], Vallés [1997], Kim [2003] and

casts and policy analysis. As shown by Beaudry and Portier [2007] this model can generate positive co-movements between consumption, investment, employment and output following changes in expectations about the future, contrary to many popular business cycle models,. A necessary condition for this is that the aggregate production function displays cost complementarities in the production of the consumption and investment goods. With a Cobb-Douglas production function, cost complementarities obtains if $\sigma \geq 1/(1-\alpha)$. In this paper, estimation of the labor market relationship produces an estimate of the level of adjustment costs, so that it is possible to evaluate the extend to which the required condition is met.

Huffman and Wynne [1999] to cite some examples. The elasticity of substitution between consumption and investment is given by $1/(1-\sigma)$. The nonlinear transformation curve captures the idea that changing the allocation of the composite output between investment and consumption is not easily done and entails some costs. In particular, the prices of consumption and investment in terms of composite output are given by

$$p_t^C = a\left(\frac{C_t}{Y_t}\right)^{\sigma-1} \tag{2.3}$$

and

$$p_t^I = b\left(\frac{I_t}{Y_t}\right)^{\sigma-1} \tag{2.4}$$

When $\sigma = 1$, the transformation curve is linear, both these prices are constant at 1 and one obtains the canonical RBC model as a special case. As σ gets bigger, the cost of obtaining one more unit of investment in terms of foregone consumption increases. Note that given the definition of the relative price of consumption and investment, the resource constraint (2.2) can be written as

$$p_t^C C_t + p_t^I I_t = Y_t \tag{2.5}$$

where p^C, p^I represent the price of consumption and investment expressed in terms of composite output (the numeraire). Finally, capital accumulates according to

$$K_{t+1} = (1-\delta)K_t + I_t \tag{2.6}$$

Given preferences and the technology, the problem of the social planner is

$$\max_{\{C_t,H_t,I_t,K_{t+1}\}_{t=0}^{\infty}} \quad \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t (\ln C_t - \frac{\vartheta_0}{\eta+1} H_t^{\eta+1})$$

subject to

$$(aC_t^\sigma + bI_t^\sigma)^{\frac{1}{\sigma}} = A_t K_t^\theta H_t^{(1-\theta)}$$
$$K_{t+1} = (1-\delta)K_t + I_t$$

Using the definition for the relative price of consumption (2.3), the equilibrium condition for the labor market writes as

$$\vartheta_0 H_t^{\eta+1} = (1-\theta)\frac{Y_t}{p_t^C C_t} \tag{2.7}$$

Now, as in Hall, define

$$x_t = c_t - y_t + (\eta+1)h_t + \ln\left(\frac{\vartheta_0}{(1-\theta)}\right) \tag{2.8}$$

where small letters denote the log of their capital counterparts. In Hall's model, x_t should theoretically be equal to one every period. As the data suggests otherwise, he concludes that the missing element in the model is a pro-cyclical preference shift. With multisectoral adjustment costs, however, one finds that

$$x_t = -\ln p_t^C \tag{2.9}$$

Therefore, (part of) what was attributed to either a preference shift or variable markups could in fact be accounted for by the variation in the relative price of consumption induced by the multisectoral adjustment costs hypothesis. The intuition underlying this result is simple. Assume an agent chooses to increase her labor supply and uses the resulting income to increase her consumption in that period. Purchasing this extra consumption costs $p_t^C C_t$, where p_t^C is the price of consumption in terms of composite output. In standard RBC models, $p_t^C = 1$ at all time. With multisectoral adjustment costs, the relative price of consumption changes as production varies, which explains its presence in equation (2.9). Put differently, what the agent cares about is her wage in terms of consumption goods. The next section investigates the plausibility of the multisectoral adjustment costs hypothesis.

2.3 A first appraisal: linear approximation

2.3.1 Basic model

The first step in evaluating the plausibility of the multisectoral adjustment costs hypothesis is to look at the joint behavior of x_t and the relative price of consumption. Appendix A gives a detailed description of the data used in the empirical investigation.

To construct x_t, I follow Hall and set $\eta = 1.7$, a value consistent with other studies in the business cycle literature. In contrast, Galí et al. [2005] use $\eta = 5.0$ on the basis that most micro-data suggests a Frisch wage elasticity of labor supply concentrated in the range of 0.05 to 0.3. As shown by Chang and Kim [2005], however, the labor supply elasticity at the aggregate level can be significantly higher than that observed at the individual level. The Hall residual is illustrated (up to a constant) in figure 2.1.

As is apparent from the graph, the residual is characterized by significant low frequency movements. For example, the 1980's saw a significant increase in the Hall residual, mostly driven by a similar increase in hours per workers.

In the spirit of Hall, one can think structurally about these movements as representing shifts in preferences over consumption relative to leisure. These shifts potentially reflect institutional and demographic changes affecting the labor market such as an increase in the participation of women in the labor market or important changes in the structure of the tax system. Since the model presented is not appropriate to account for these low frequency movements, they are extracted from the various time series by the use of the HP filter with the usual smoothing parameter[3]. An alternative to using the HP filter would be to estimate using the level of the variables and include a high order polynomial in time to represent the trend. Using a polynomial of order 6 (or higher) in time for the trend produces results quite similar to the one obtained using the HP filter[4].

Before turning to estimation, the aggregate resource constraint (2.2) is used to write equation (2.9) as

$$x_t = -\frac{1}{\sigma}\ln a - \frac{(\sigma - 1)}{\sigma}\ln\left(1 - b\left(\frac{I_t}{Y_t}\right)^{\sigma}\right) \tag{2.10}$$

so that if the multisectoral adjustment costs hypothesis is reasonable, one should find that x_t and I_t/Y_t co-move positively. To illustrate this point, figure 2.2 displays the relation between (HP filtered) x_t and the (HP filtered) log investment ratio. The sample period extends from the first quarter of 1959 to the last quarter of 2004.

The graphical evidence seems to lend support to the working hypothesis. The correlation between the Hall residual and the investment ratio appears positive and relatively strong. Moreover, they seem to display a similar degree of persistence. As mentioned previously, this high degree of persistence in x_t was seen by Johri and Letendre [2006] as an indication of dynamic misspecification in the theoretical model. Over the whole sample, the contemporaneous correlation coefficient between these 2 variables is 0.607. The first-order autocorrelation coefficient of the Hall residual, $\rho_1(x)$, is equal to 0.834, while it is 0.813 for the investment ratio. If one focuses only on the post-1975 period, the relation between the Hall residual and the investment ratio appears even tighter. For the 1975Q1 to 2004Q4 period, the correlation coefficient increases to 0.756. Their first-order autocorrelation coefficient is 0.893 and 0.860, respectively.

[3] Specifically, for quarterly data, the smoothing parameter λ is set to 1600.

[4] This alternative strategy is used in section 2.4 where nonlinear estimation prevents the use of the HP filter.

To obtain a more rigorous measure of the degree of association between x_t and the investment ratio, one can estimate the linear projection of x_t on a constant and the investment ratio

$$x_t = \gamma_0 + \gamma_1 \ln \frac{I_t}{Y_t} + e_t \tag{2.11}$$

This could be interpreted as a linear approximation to the structural labor market equilibrium

$$x_t = -\frac{1}{\sigma} \ln a - \frac{(\sigma - 1)}{\sigma} \ln \left(1 - b \left(\frac{I_t}{Y_t} \right)^{\sigma} \right) \tag{2.12}$$

The first column of table 2.1 presents the coefficient estimates of the linear projection (2.11). As expected, the coefficient is positive and proves statistically significant. Moreover, the investment ratio explains about 37% of the variance of the Hall residual. On the other hand, the persistence of x_t is only partially reduced. The first order autocorrelation coefficient of the residual from the linear projection (2.11), $\rho_{\hat{e}_t}(1)$, is reported in the first column of table 2.2. The persistence of the linear projection's residual is about 80% that of the Hall residual, which suggests that multisectoral adjustment costs are only part of a larger misspecification issue. The lagrange multiplier tests for first and fourth order serial correlation ($LM(1)$ and $LM(4)$ respectively) indicate the presence of significant serial correlation.

The main findings remain unchanged if one focuses on a shorter sample. The second column of table 2.1 presents the coefficient estimates of the linear projection (2.11) for the post-1975 period while the second column of table 2.2 reports the persistence of its residual as well as LM tests for serial correlation. As expected from figure 2.1, the linear association between x_t and the investment ratio is stronger over the shorter sample, explaining almost 60% of the Hall residual. Despite this, the linear projection's residual remain quite persistent, its autocorrelation coefficient being only 25% smaller than that of x_t over the same period. Again, this suggests the existence of a larger misspecification issue.

One could argue that the coefficient estimates presented so far are potentially biased for the parameters of the linear projection because of the way real output is constructed. As mentioned in appendix A, real output is constructed by deflating nominal output using the GDP deflator. However, this deflator is only a noisy estimate of the "true" price of composite output[5].

[5]For one thing, many of its components are not observed prices but imputed prices based on specialists' judgment.

Since real output is present on both the left and right hand side of (2.11), there is an errors-in-variables problem. To circumvent it, one can use different deflators to calculate the consumption ratio and the investment ratio. Column three of table 2.1 presents the coefficient estimates of the linear projection when the GDP deflator is used to construct the consumption ratio and the producer price index for finished goods is used to construct the investment ratio[6]. As seen from the tables, the results obtained using these modified variables are essentially unchanged[7].

An alternative approach to solving the potential errors-in-variables problem is to use the investment to consumption ratio instead of the investment to output ratio on the right hand side of (2.11). This is an alternative way to write the structural labor market equilibrium condition. Just as was done with equation (2.10), note that from the aggregate resource constraint, one can write the relative price of consumption as

$$p_t^C = a^{\frac{1}{\sigma}} \left(1 + \frac{b}{a}\left(\frac{I_t}{C_t}\right)^{\sigma}\right)^{\frac{(1-\sigma)}{\sigma}} \tag{2.13}$$

Combining (2.13) and (2.9), the Hall residual writes as

$$x_t = -\frac{1}{\sigma}\ln a - \frac{(1-\sigma)}{\sigma}\ln\left(1 + \frac{b}{a}\left(\frac{I_t}{C_t}\right)^{\sigma}\right) \tag{2.14}$$

The fourth and fifth columns of tables (2.1) and (2.2) display the coefficient estimates of the linear projection associated with (2.14) and the persistence of its residual, for the whole and the shorter sample respectively. Relative to the results obtained using the investment ratio, the coefficient estimates obtained are somewhat smaller but still quite significant. The investment-to-consumption ratio reduces the variance of the Hall residual in proportions similar to the investment ratio. Again, the remaining persistence of

[6]The PPI universe consists of the output of all industries in the goods-producing sectors and about half of the service sector's output. It is meant to measure changes in net revenues received by producers. Consequently, it includes rebate programs, low-interest financing plans and other sales promotion techniques, inasmuch as it affect the net proceeds received by the manufacturer. Finished goods are defined as commodities that are ready for sale to the final-demand user, be it an individual consumer or a business firm. In that sense, they are closer to the National Accounts concept of prices. In national income accounting terminology, the finished goods price index roughly measures changes in prices received by producers for two categories: personal consumption expenditures on goods and capital investment expenditures on equipment.

[7]Using the all commodities producer price index instead of the producer price index for finished goods to implement the estimation strategy produces very similar results.

the linear projection's residual points to the omission of other systematic factors.

As suggested by Johri and Letendre, resiliency in the persistence of the linear projection's residual to various regressors is cause for some concern. In particular, there is always the possibility that the results obtained so far about the potential role of multisectoral adjustment costs might be spurious in that the relative price of consumption simply proxies alternative omitted mechanisms which underlies the Hall residual. If this is the case, the relative price of consumption should become irrelevant once these omitted mechanisms are included in the model. As such, it is a valuable investment to consider other potential sources of the Hall residuals before attempting to estimate the nonlinear labor market equilibrium relation. This is done in subsection 2.3.2. It is worth emphasizing that the purpose of this next subsection is not to construct a model that will fully account for the persistence of the Hall residual but rather to verify to what extend the multisectoral adjustment costs hypothesis remains relevant once other mechanisms that could account for the Hall residual are considered.

2.3.2 Model extensions

Possible extensions of the basic model can be classified into two categories: static and dynamic. Static extensions look at potentially omitted mechanisms that could affect the labor market equilibrium equation contemporaneously. Johri and Letendre [2006] investigate two such extensions: measurement error in observed labor and variable labor effort. They find that these extensions do not have any significant impact on the observed size and persistence of the first order condition residuals. Given the similarity of their setup to the current one, there is no reason to believe that these specific extensions would alter the results obtained so far and consequently are not implemented. Instead, the present document considers another possible static extension: the presence of variable markups, in the spirit of Galí et al. [2005]. On the other hand, dynamic extensions introduce dynamic terms in the first order condition for hours. Possible candidates of the latter kind include learning-by-doing mechanisms and habit formation in consumption and/or leisure. Formal dynamic extensions will be dealt with indirectly through a partial adjustment model.

Model with variable markups

The basic model presented above was a frictionless economy. I now entertain the idea that there are various market frictions. This naturally leads to the introduction of variable markups in the model. Example of models that generate variable markups and their role in the business cycle are presented in Rotemberg and Woodford [1999].

Consider in particular the case where there is imperfect competition in the goods market. In this case, the labor market equilibrium condition becomes

$$x_t = c_t - y_t + (\eta + 1)h_t = \ln \frac{(1-\theta)}{1+\mu_t} - \ln p_t^C \tag{2.15}$$

where μ_t represents the markup over marginal costs. As suggested by Galí et al. [2005], variable markups could explain part of the Hall residual. Building on equation (2.10), one can obtain a measure of the linear association between the investment ratio and the Hall residual in this augmented model by estimating the following linear projection

$$x_t = \gamma_0 + \gamma_1 \ln \frac{I_t}{Y_t} + \gamma_2 \ln \frac{(1-\theta)}{1+\mu_t} + e_t \tag{2.16}$$

To estimate the latter equation, one needs a valid measure of variable markups. When the production function is of the Cobb-Douglas form[8], markups are inversely proportional to the labor share of income[9]. Accordingly, it is possible to use a measure of labor share in equation (2.16). Obtaining an appropriate measure of the labor share is not without controversy due, in particular, to the inclusion of the government sector and the treatment of proprietor's income, which comprises both capital and labor income. As pointed out by Young [2004], while this is a potential problem when it comes to determine the average labor share over long time periods, the cyclical properties of the labor shares are not sensitive to the inclusion of the government sector or proprietor's income. To illustrate this point, figure 2.3 displays the temporal evolution of three different measures of the labor share, expressed as deviation from their respective HP trend. The series labeled `measure 1` is the labor share in the nonfarm business sector. The series `measure 2` is calculated as workers' compensation in gross domestic income while the series `measure 3` is workers' compensation in gross domestic income less proprietors' income.

[8] Or, more generally, isoelastic in the labor input.

[9] See Rotemberg and Woodford [1999] for details.

The first column of table 2.3 reports the coefficient estimate of the linear projection (2.16) when using the labor share in the nonfarm business sector as a measure of variable markups and estimating over the whole sample of available data. The second column reports the results for the smaller sample considered above. Table 2.4 reports the persistence of the associated residual.

Over the whole sample, the results obtained suggest that multisectoral adjustment costs remain an important determinant of the Hall residual even when one allows for variable markups. Interestingly, the coefficient estimates of the labor share is not statistically different from one, its theoretical value. In terms of reducing the persistence of the linear projection's residual, however, the results are rather poor. The addition of variable markups only reduces the persistence by about 5% relative to the situation without variable markups. In one focuses only on the shorter sample, the contribution of variable markups disappears somewhat, with the coefficient associated with it not being statistically significant at the 5% level. In terms of explaining the variation in the Hall residual, the contribution of variable markups does not appear economically significant. In particular, it is seen that the addition of variable markups increases the proportion of the variance explained from 57% (see table 2.2) to 60% only[10]. For the sake of comparison with table 2.1, the estimation results for the case where different deflators are used to construct real output and the case where the investment to consumption ratio replaces the investment ratio are also presented. The results are not altered in any significant way. Therefore, the conclusions reached above about the role of multisectoral adjustment costs appear robust to the presence of variable markups[11].

Partial adjustment model

It could be argued that a more pragmatic point of view concerning the size and persistence of the Hall residual is to recognize that no general equilibrium model will ever be rich enough to encompass all institutional and cyclical constraints faced by any "real life" labor market. From this point of view, the Hall residual is simply an amalgam of such things as, in addition to

[10] A simple linear projection of the Hall residual on variable markups only gives a coefficient estimate of -0.166, with a p-value of 0.73 and a R^2 of 0.005. This suggests that the bulk of the explanatory power comes from the multisectoral adjustment costs variable.

[11] The results obtained using the other two labor share measures mentioned above are quite similar and do not alter the findings in any meaningful way.

multisectoral adjustment costs, habit formation, learning processes, matching frictions, information and coordination problems as well as temporary reorganization of the workweek.

One practical way to account for all these dynamic effects while at the same time testing the robustness of the multisectoral adjustment costs hypothesis is to incorporate the latter in a partial adjustment model (PAM). In a partial adjustment model, the estimation equation is augmented with lags of the dependant variable. Therefore, it is known at the outset that it will be able to account for most of the persistence in the Hall residual. The usefulness of the PAM comes from the fact that lag dependant variables can be thought of as a proxy for important but omitted mechanisms of the labor market. Note here that no structural interpretation is given to this model. It is used only as a robustness check of the findings of the previous section, the idea being that if the multisectoral adjustment costs hypothesis remains relevant even when attempting to control for these other important mechanisms then there is confidence that the aforementioned findings are in fact not spurious.

As seen in (2.10), if the basic model with multisectoral adjustment costs held true, then in equilibrium

$$x_t = -\frac{1}{\sigma} \ln a - \frac{(\sigma-1)}{\sigma} \ln \left(1 - b \left(\frac{I_t}{Y_t}\right)^{\sigma}\right)$$

To introduce the PAM model, it is useful to think about the right hand side of the last equation as the target level $\bar{x}_t$ for the Hall residual. In a stationary steady state, this level would be attained. However, because of one of the many aspects of the labor market that a tractable model neglects, x_t can not immediately adjusts to its target value $\bar{x}_t$. Rather, it evolves according to

$$x_t - x_{t-1} = \varphi(\bar{x}_t - x_{t-1}) \tag{2.17}$$

where $|\varphi| \leq 1$ measures the speed at which the labor market reaches its target equilibrium value. This parameter depends on institutional and cyclical considerations. Rearranging, one gets

$$x_t = \varphi \bar{x}_t + (1-\varphi) x_{t-1} \tag{2.18}$$

Substituting for the target level $\bar{x}_t$ gives

$$x_t = -\frac{\varphi}{\sigma} \ln a - \varphi \frac{(\sigma-1)}{\sigma} \ln \left(1 - b \left(\frac{I_t}{Y_t}\right)^{\sigma}\right) + (1-\varphi) x_{t-1} \tag{2.19}$$

for which a linear approximation is

$$x_t = \varphi\pi_0 + \varphi\pi_1 \ln \frac{I_t}{Y_t} + (1-\varphi)x_{t-1} \tag{2.20}$$

The linear projection associated with this approximation is simply

$$x_t = \gamma_0 + \gamma_1 \ln \frac{I_t}{Y_t} + \gamma_2 x_{t-1} + e_t \tag{2.21}$$

noting from (2.20) that the coefficient related to log investment ratio in the stationary steady state is given by $\gamma_1/(1-\gamma_2)$.

Table 2.5 shows the coefficient estimates of the linear projection (2.21) and table 2.6 the persistence of its associated residual. It is interesting to note that introducing lag dependent variables to control for partial adjustment does not affect the relevance of multisectoral adjustment costs. Whether one considers the long or short sample or use the ratio of investment to consumption instead of the investment to output ratio, the coefficient estimate of the linear projection remains strongly significant[12]. Moreover, the implied stationary steady state coefficient remains quite positive, with increases in the range of 20 to 30% relative to the coefficient estimates in table 2.3, depending on the case considered. Not surprisingly, table 2.6 shows that the very simple partial adjustment model appears to provide a reasonable description of the data, even though it has no structural interpretation. Introducing a single lag of the dependent variable eliminates the remaining persistence in the linear projection's residual, as confirmed by Lagrange multiplier tests for first and fourth order serial correlation. Extending the partial adjustment model to allow for a richer dynamic structure does not alter the main substantive results[13]. In particular, the stationary steady state coefficient for the investment ratio remains very similar to the one presented in table 2.5. This is seen as lending strong support to the working hypothesis of multisectoral adjustment costs.

[12] Using different deflators to calculate real output on the left and right hand side of the equation also produces very similar results

[13] With a richer dynamic structure, the linear projection takes the form of an ADL(p,$p-1$) where p is the number of lags of the dependant variable. The pattern observed for all values of $p > 1$ tried is that only the first lag of the dependent variable is statistically significant while the first lag of the investment ratio is significant, as opposed to the contemporaneous value. Moreover, the investment ratio variables are always jointly significant. Emphasis is put on the simple partial adjustment model because 1) it is somewhat easier to justify the simple PAM as a solution to an optimization problem and 2) in the class of ADL(p,$p-1$) models, lag length selection based on information criterions favors the very parsimonious ADL(1,0).

The last column of the latter table presents the results of adding the labor share to equation (2.21). Over the long sample, the addition of partial adjustment renders the labor share not significant at usual levels. Estimation results over the shorter sample are not reported but is it noteworthy that in this case, the coefficient estimate for the labor share has the wrong sign and is not significant[14]. This further reinforces the fact that variable markups might not be as relevant a factor as multisectoral adjustment costs.

2.3.3 Summary of linear projection results

It is important to remember that up to this point, no structural interpretation has been given to the coefficient estimates obtained so far. The purpose of sections 2.3.1 and 2.3.2 was to measure the extent to which fluctuations in the relative price of consumption, which reflects the impact of multisectoral adjustment costs in an otherwise standard RBC model, might account for the Hall residual. In the basic case, it appears that there is a strong (linear) relationship between these two variables. To ensure that the results obtained are not spurious, the basic model is augmented by adding first variable markups then a lag dependant variable that serves as proxy for omitted mechanisms. If anything, these extensions appears to make the relationship between the Hall residual and the relative price of consumption even stronger. The fact that multisectoral adjustment costs still appear important once a lag dependent variable is introduced is seen as a strong signal that it is a relevant mechanism to be introduced in standard RBC models. On the other hand, the behavior of the residual from the various linear projections indicate that in all likelihood, this mechanism can not account completely for the Hall residual.

In addition, it should be noted that the results obtained are not an artifact of the data set used. All the above estimations have been conducted over the same sample period but on a more "standard" data set presented in appendix B. The conclusions carry over essentially unchanged. Results from estimation with the alternative data set are available upon request. As there seem to be tentative evidence to support the hypothesis of multisectoral adjustment costs in the data, the next step is to estimate the nonlinear structural equation (2.12) and obtain an estimate of the the degree of multisectoral adjustment cost σ[15].

[14] Estimation results for this case are available on demand from the author.

[15] This, in turn, will provide a signal as to the presence of cost complementarities in

One could argue that it would be easier to exploit the definition of relative prices (2.3) or (2.4) to obtain point estimates for σ. Such an exercise has been conducted using various measures of the relative price of consumption. That is, various measures of the price of consumption based on National Account and CPI indexes and the price of output based on the GDP deflator and PPI indexes were combined to estimate such relationship. Unfortunately, the results depend very much on the particular combination employed and it proved very difficult to obtain conclusive estimates. In particular, results varied significantly depending on whether one used a National Account measure for the price of output or a PPI-based measure. This happens because the business cycle properties of these two classes of indexes are different. As it is not clear which class is more appropriate given the theoretical model, focusing on (2.12) to obtain an estimate of σ appears a more reliable strategy. In particular, the dependency of the results to the choice of a price index is not as serious. This happens because (2.12) uses variations in both nominal spending and price which reduces the sensitivity to the choice of price measures.

2.4 Nonlinear estimation

The purpose of this section is to use structural equations (2.12) and (2.14) to obtain point estimates for the structural parameters a, b, and σ. To this end, the section is organized along the following lines. Subsection 2.4.1 discusses how to account for the low frequency preference shifts in the Hall residual using a "flexible" trend. Subsection 2.4.2 then presents estimation results for both structural equations. This will naturally lead to a discussion of the plausibility of cost complementarities, which depends directly on the estimated parameter of adjustment costs. Subsection 2.4.4 looks at the sensitivity of the results to the choice of the sample period. Finally, subsection 2.4.5 investigates how an alternative approach to accounting for the trend component affects the results.

the aggregate production process and whether this model can account for business cycle fluctuations induced by changes in expectations about the future.

2.4.1 Extracting the cyclical component

As mentioned in section 2.3, the Hall residual is characterized by a slowly evolving trend which can be structurally interpreted as low frequency preference shifts that the model as developed can not account for. In section 2.3, this trend was extracted from the time series by the use of the HP filter, which is the typical approach used in macroeconomics[16]. For the purpose of estimating the nonlinear structural equations, however, this approach proves difficult. To illustrate this point, consider equation (2.12). Interest centers on regressing the cyclical component of x_t, the Hall residual, on the cyclical component of $\ln\left(1 - b\left(I_t/Y_t\right)^{\sigma}\right)$. However, to apply the HP filter on the second term requires that it be constructed *before* applying the HP filter. This necessitates prior knowledge of the parameters b and σ, which are precisely the parameters to be estimated. One possible way to circumvent this problem is to fix arbitrary values for b and σ, construct the relative price of consumption, apply the HP filter then calculate the difference between the detrended Hall residual and the detrended relative price of consumption. One then proceeds with a grid search over possible values of b an σ, choosing as parameter estimates the ones that minimize the squared difference. While this is a valid procedure, calculating standard errors for these parameter estimates is rather complicated.

An alternative approach to the grid search is to introduce a “flexible trend” in the nonlinear regression to mimic the effect of the HP filter. This flexible trend takes the form of a n-order polynomial in time. One then estimates the parameters using nonlinear least squares. This approach has the advantage of being easy to implement and naturally produces standard errors for the estimates. In what follows, this is the approach employed. Hall [2009] uses a polynomial of order three in time to capture the trend, while Hall [2008] uses a polynomial of order four. Galí et al. [2005] also use a third order polynomial to capture the trend, although the October 2003 version of their paper used a fifth order polynomial. In both cases, they do not justify the choice of the order for the polynomial in time. The grid search procedure will also be implemented to serve as a robustness check.

In the present paper, the flexible trend $\tilde{x}_t$ will take the form of a polynomial

[16]The Baxter-King band pass filter is growing more population in this regard. The cyclical component extracted using the band pass filter and the one obtained using the HP filter are usually very similar.

of order 6 in time

$$\tilde{x}_t = \sum_{i=0}^{6} \tau_i \mathrm{t}^i$$

where t is time and the τ_i's the various coefficients of the trend. The selection of the order of the polynomial used in estimation was based on an R-squared measure adjusted for the trend in the Hall residual. Specifically, choosing an arbitrary order n of the polynomial, the Hall residual x_t was first linearly projected on the polynomial of order n, which, to keep with the notation above, I call $\tilde{x}_t^n$. The cyclical component of the Hall residual, $\ddot{x}_t^n$, is the difference between x_t and the estimated trend. Then, I ran the nonlinear regression

$$\ddot{x}_t^n = \tilde{x}_t^n - \frac{(\sigma - 1)}{\sigma} \ln \left(1 - b \left(\frac{I_t}{Y_t}\right)^{\sigma}\right)$$

The R-squared measure obtained from this procedure consistently improved when moving from a linear trend $n = 1$ to a sixth-order polynomial. Past the order 6, the R-squared obtained did not improve further and the additional coefficients estimated were consistently smaller than 1e-04. Moreover, the estimated coefficients σ and b were not significantly affected. Therefore, the results presented below are those obtained using a polynomial of order 6 in time to capture the trend. Again, it is worth emphasizing that ideally, one would want to use the cyclical component obtained by using the HP filter. As such, the value of the model selection approach proposed above can also be judged by how well it can replicate the HP filtered cyclical component of the variables. Figure 2.4 illustrates the two series in the case of the Hall residual. Clearly, both series track each other quite well, although a large gap appears between 1985 and 1990. In addition, the cyclical component generated with the flexible time trend is more volatile than its HP filtered counterpart. However, the two series appear similar enough on the whole that the results should not be significantly altered by this change of procedure. To confirm this intuition, the coefficients obtained using the flexible trend are later compared to the coefficients obtained using the grid search approach described above to show that they are indeed similar.

2.4.2 Estimation of structural equations

I now turn to estimating structural relations (2.12) and (2.14). Given the definition of the flexible trend, the nonlinear estimation equations for the

Hall residual are

$$x_t = \sum_{i=0}^{6} \tau_i \mathrm{t}^i - \frac{1}{\sigma} \ln a - \frac{(\sigma - 1)}{\sigma} \ln \left(1 - b \left(\frac{I_t}{Y_t}\right)^{\sigma}\right)$$

$$x_t = \sum_{i=0}^{6} \tau_i \mathrm{t}^i - \frac{1}{\sigma} \ln a - \frac{(1 - \sigma)}{\sigma} \ln \left(1 + \frac{b}{a} \left(\frac{I_t}{C_t}\right)^{\sigma}\right)$$

Note that the need to include τ_0 in the flexible trend makes it impossible to identify the parameter a, as it is absorbed in the intercept. As such, no attempt will be made at estimating it and will be assumed to take the value of unity in what follows. This is not a strong assumption. First, this has no impact on the estimation of the parameter b in (2.12). Second, the parameters a and b serve to determine the relative price of investment in terms of consumption in steady state. Therefore, if one fixes the value of a, the coefficient b adjusts accordingly. This will not affect the estimated value of σ and is mostly an issue for estimating equation (2.14).

Given this, the estimation equations are

$$x_t = \tau_0^* + \sum_{i=1}^{6} \tau_i \mathrm{t}^i - \frac{(\sigma - 1)}{\sigma} \ln \left(1 - b \left(\frac{I_t}{Y_t}\right)^{\sigma}\right) \tag{2.22}$$

and

$$x_t = \tau_0^* + \sum_{i=1}^{6} \tau_i \mathrm{t}^i - \frac{(1 - \sigma)}{\sigma} \ln \left(1 + \frac{b}{a} \left(\frac{I_t}{C_t}\right)^{\sigma}\right) \tag{2.23}$$

where τ_0^* is the constant incorporating the parameter a. The first column of table 2.7 presents the coefficient estimates of equation (2.22)[17] while the second column presents the coefficient estimates for the partial adjustment model version of the equation. In both cases (and all estimations to come) the parameter space is restricted so that $\sigma \geq 1.0$ and $b > 0.0$. The latter restriction implies that the relative price of investment in terms of consumption must be strictly positive[18].

Coefficient estimates for σ are again strongly significant and also significantly larger than unity (their standard error is in the range of 0.05 to 0.07). This suggests that multisectoral adjustment costs is a relevant mechanism in the

[17] Estimation is done with RATS 6.20 using the BFGS Restricted algorithm.

[18] Note that even if one does not impose the strict positivity restriction, the algorithm naturally chooses a strictly positive number for b. Imposing the restriction accelerates the estimation procedure.

determination of the Hall residual. Just as with linear projections, the use of different deflators does not substantially alter the results, nor does the inclusion of the labor share to account for variable markups. The fact that the estimate remains quite significant and is even larger in the partial adjustment model produces more confidence in the results. On the other hand, the use of the investment-to-consumption ratio leads to estimates for both coefficients that are an order of magnitude larger than the ones obtained using the investment ratio. This is somewhat troubling considering that the fitted series obtained from equations (2.22) and (2.23) are quite similar.

To illustrate this last point, figure 2.5 shows the deviations of the Hall residual and the fitted series obtained from both structural equations from the flexible trend. Clearly, both equations produce very similar predicted values for the Hall residual, although those obtained from equation (2.23) seem to fit a little better. The fact that coefficient estimates for b and σ can be quite different while producing similar fitted values for the Hall residual could potentially lead to some conflicting results in model simulation exercises.

Figure 2.5 also gives a better appreciation of the contribution of the multisectoral adjustment cost hypothesis, as opposed to the high reported R^2 which are not very meaningful due to the presence of the flexible trend. In particular, the introduction of multisectoral adjustment costs improves the fit of the model relative to the simple flexible trend. The variance of the predicted values of the Hall residual from equations (2.22) and (2.23) capture respectively 35.5% and 43.7% of the variance of the Hall residual while the contemporaneous correlation coefficients between the predicted values and the Hall residuals are respectively 0.64 and 0.66. Nevertheless, as is also clear from the figure, there are still persistent gaps remaining, a likely indication of a larger misspecification issue. Note also that the contribution appears stronger for the post 1974 period. Over the shorter sample, the predicted values capture respectively 39.7% and 45.3% of the variance of the Hall residual and the contemporaneous correlation coefficients increase to 0.70 and 0.76. This suggests that the hypothesis of multisectoral adjustment costs seem to better characterize the latter period, something investigated in subsection 2.4.4.

2.4.3 Digression on cost complementarities

At this point, it is worth coming back to an aspect of the model that was only very briefly mentioned above, the capacity of the model to generate typical business cycle fluctuations following changes in expectations about the future. In the case of the model at hand, this is possible if the aggregate production function displays cost complementarities. This, in turns, happens if $\sigma > 1/(1-\alpha)$, where $(1-\alpha)$ is the labor share of income. For usual values of the labor share (say around 2/3), the condition for the presence of cost complementarities is satisfied provided that $\hat{\sigma}$ is larger than 1.50. Estimation results obtained so far suggest that cost complementarities at the aggregate level is a distinct possibility. Whether one looks at the basic model or the model augmented to allow for variable markups, coefficient estimates are significantly larger than the benchmark value of 1.5. The partial adjustment model, which in a sense controls indirectly for omitted factors, produces an even larger coefficient, further substantiating the empirical evidence on cost complementarities. This evidence is even reinforced if one prefers the specification given by equation (2.23), the results being an order of magnitude larger than for equation (2.22). Finally, this finding will gain further support in the next section, where estimation is conducted over a shorter sample period.

2.4.4 Adjustment costs and choice of the sample period

As observed in figure 2.2, the multisectoral adjustment cost hypothesis seems to better characterize the behavior of the Hall residual in the post-1975 period. To show this formally, estimation results for equations (2.22) and (2.23) are presented when the sample period is divided in two subsamples 1959:1 to 1974:4 (short sample Ia) and 1975:1 to 2004:4 (short sample IIa). To show that the conclusions are not fundamentally affected by an arbitrary division of the sample, results for an alternative division of the sample (1959:1 to 1978:4 and 1979:1 to 2004:4) are also presented[19]. Table (2.8) displays the results.

[19] The choice of 1974:4 to divide the sample is based purely on graphical observation. The choice of 1978:4 to create the second division of the sample was chosen because it corresponds roughly to the beginning of a period of economic turbulence in the United States.

The coefficient estimate for σ obtained for the whole sample is mainly driven by variations in the latter part of the sample. If one estimates only over the period extending to 1974:4 (or 1978:4), the coefficient estimate is hardly larger than 1. Over the latter part of the sample, the estimated coefficient becomes much larger, well in the range required to have cost complementarities at the aggregate level. On the other hand, the coefficient estimates obtained using the whole sample and those obtained by deleting the first 16 years of data (short sample IIa) are quite similar in magnitude, so that there is a sense in which the results do not depend on the sample period. This finding is robust to the alternative division of the sample. The same holds true when one allows for a partial adjustment mechanism or when using different deflators to correct for the error-in-variable problem. Results for these two cases are presented in table 2.9.

A word of caution is in order for the results obtained using different deflators. While the coefficient estimates obtained over the two subsamples confirm the increase in the coefficient value for σ during the second subsample, the coefficient estimate for the first subsample is much larger than in other cases. This raises some concerns and is difficult to explain by mere inspection of the data. One such concern is the sensitivity of the results to the PPI index used. Recall that the index used in table 2.9 is the PPI for finished goods. If one uses the all commodities PPI, the coefficient estimate for the first subsample falls to 1.141 while if one uses the PPI for finished consumption goods, the coefficient is 1.565[20]. In all three cases, the coefficient estimates are around 1.8 when estimating over the second subsample.

The results obtained when allowing for variable markups, displayed in the last two columns of table 2.9, show that the conclusions reached about the importance of multisectoral adjustment costs are not altered. Interestingly, it shows that while variable markups were important in the earlier part of the sample, it is not the case when one considers the more recent history. This finding may raise some questions about the explanation proposed by Galí *et al.*. Moreover, this finding is not an artifact of the labor share measure employed, as shown in table 2.10 for three alternative definitions of the labor share.

For the sake of consistency with section 2.3, the results obtained when estimating structural equation (2.23) are presented in table 2.11. Noticing again that the coefficient estimates are an order of magnitude larger and that one still observes the increase in the adjustment cost parameter when

[20] Of course, the coefficients are statistically significant.

estimation is restricted to the smaller samples.

It is a little difficult to rationalize why the adjustment costs parameter gets larger in the latter part of the sample. If one takes the multisectoral adjustment costs hypothesis literally, this means that it is now more costly to obtain the investment goods, in terms of foregone consumption, than in the past. Alternatively, it is now harder to reorient output produced from the consumption goods sector to the investment goods sector than it used to. A possible explanation of this finding could be based on the increased specialization of today's consumption and investment goods, making it harder to reorient them from one sector to the other. As this reallocation between sectors is increasingly costly, it becomes more interesting to produce both types of goods in tandem and use joint inputs as much as possible, such as a common distribution system[21]. This use of joint inputs would be the source of costs complementarities mentioned above. How convincing this story is remains an open question...

An alternative and maybe more pragmatic approach to this finding would be that fluctuations in the Hall residual are more driven by monetary shocks in the earlier part of the sample than in the latter. Consequently, a model of real adjustment such as the one presented here should not do as well when estimated over the early part of the sample[22]. This explanation obtains graphical support from figure 2.5, where it is seen that fluctuations of the predicted values around the flexible trend are rather small.

2.4.5 Grid search approach

This section proposes an alternative approach to estimating the parameters of interest. Recall that in section 2.3, the cyclical component was defined by the use of the HP filter since this definition of the cycle is generally well accepted. The grid search approach proposed in this section allows one to obtain estimates of the parameters while permitting the use of the HP filter. However, because of the difficulty in measuring uncertainty around the estimated parameters obtained by this method, it was not chosen as the primary estimation tool. Nevertheless, it is worth obtaining alternative

[21] A standard RBC model which requires the use of resources to distribute the consumption and investment goods to their final produces a model very similar to the one presented in this paper.

[22] I thank Paul Beaudry for suggesting this explanation.

estimates using this method so as to validate the results obtained in section 2.4.

The approach is implemented as follow. First, one fixes arbitrary values for the parameters b and σ (the parameter a is still set to unity). One then constructs the relative price of consumption using either

$$p_t^C = a^{\frac{1}{\sigma}} \left(1 - b\left(\frac{I_t}{Y_t}\right)^{\sigma}\right)^{\frac{(\sigma-1)}{\sigma}} \tag{2.24}$$

or

$$p_t^C = a^{\frac{1}{\sigma}} \left(1 + \frac{b}{a}\left(\frac{I_t}{C_t}\right)^{\sigma}\right)^{\frac{(1-\sigma)}{\sigma}} \tag{2.25}$$

One then applies the HP filter on both the Hall residual and the arbitrary relative price of consumption and calculate the sum of squared difference between the two series. The operation is repeated over all admissible values of b and σ and the estimates chosen are those that minimize the sum of squared difference. Coefficient estimates are presented in table 2.12 for both relative price definitions for a grid search using the whole sample only. The table also compares the coefficients thus obtained to their NLLS counterparts.

Interestingly, the use of the HP filter as opposed to the flexible trend for extracting the cyclical components has an impact mostly on the coefficient estimates for b. More specifically, the change in the definition of the cyclical component reduces substantially (by 13% and 20% respectively) the estimates for b while the coefficient of primary interest, that of adjustment costs, remain quite similar and well in the range for cost complementarities at the aggregate level. Figure 2.6 illustrates the HP filtered Hall residual as well as the HP filtered price of consumption constructed using the parameter values shown in table 2.12.

When compared to figure 2.5, one sees that the message conveyed by 2.6 is essentially the same as the one based on the flexible trend approach. Again, the hypothesis of multisectoral adjustment costs clearly helps account for part of the Hall residual and this contribution seems more important in the latter part of the sample. Over the whole sample, the variance of the predicted values for the Hall residuals using equations (2.24) and (2.25) are respectively 30.5% and 40.0% that of the HP-filtered Hall residual, while the contemporaneous correlation coefficients are 0.60 and 0.63. Over the post 1974 period, the relative variances are 35,5% and 42,6% while the correlation coefficients are 0.70 and 0.76 respectively. The similarity of the findings using alternative methods seem to provide further support for the hypothesis of multisectoral adjustment costs and the possibilities of cost complementarities at the aggregate level.

2.4.6 Summary of nonlinear estimation results

Section 2.4 make use of structural equations (2.22) and (2.23) to obtain coefficient estimates for b as well as σ, the parameter representing the degree of multisectoral adjustment costs. In both cases, estimation is conditional on the parameter a being fixed to unity. The cyclical component is obtained by incorporating a "flexible trend" defined as a polynomial of degree 6 in time. Since the cyclical component thus obtained differ from the usual cycle defined using the HP filter, the results are validated by finding over the set of possible values for the parameters those that minimize the squared difference between the HP-filtered Hall residual and the HP-filtered relative price of consumption constructed using arbitrary parameters. This method is employed only as a validating tool since it is difficult to obtain measures of uncertainty for the selected parameters.

Overall, the results obtained confirm the hypothesis of multisectoral adjustment costs at the aggregate level. The parameter σ is always strongly significant and statistically different from unity. In addition, the level of adjustment costs appear higher over the recent past. When estimating equation (2.22) over the whole sample, the estimated level of adjustment costs is around 1.80. Introducing variable markups does not affect the results while introducing a partial adjustment mechanism only makes it larger. Restricting our attention to the shorter sample (1975:1-2004:4), the parameters are generally larger than 1.80. While it is difficult at this point to understand why the results obtained using equation (2.23) are an order of magnitude larger than the ones obtained from equation (2.22), it is clear that they also support the hypothesis of multisectoral adjustment costs.

In addition to being a statistically robust mechanism, multisectoral adjustment costs also seem to be economically important, in that it is capable of explaining part of the the Hall residual. This can be seen on figures 2.5 and 2.6, which show that the addition of the relative price of consumption helps account for the cyclical behavior of the Hall residual. Nevertheless, there is still a significant portion of the residual which remain unexplained. Combined with the robustness of the results on multisectoral adjustment costs, this suggests that the latter hypothesis is only part of a larger misspecification problem.

2.5 Conclusion

Understanding the behavior of the labor market remains nowadays a difficult challenge for macroeconomists. This paper proposes an equilibrium model of the business cycle augmented with multisectoral adjustment costs as an explanation to what is known as the Hall residual. The main characteristic of the model is a nonlinear transformation curve between consumption and investment at the aggregate level. Contrary to the canonical form of the business cycle model, multisectoral adjustment costs introduces variability in the relative price of consumption which directly affects the labor supply decision of the agent. Empirical findings using aggregate US data suggests that the multisectoral adjustment costs mechanism can explain part of the Hall residual, although it can not fully account for it. Moreover, the mechanism appears stronger over the more recent past. This finding is robust to the introduction of variable markups, to a partial adjustment mechanism as well as to changes in the shape of the trend component. Given the set of coefficient estimates obtained, a value in the range of [1.80,1.90] for the level of adjustment costs would seem an appropriate choice.

From a different perspective, the aggregate resource constraint with multisectoral adjustment costs can be interpreted as a multi-product production function. When the level of multisectoral adjustment costs is higher than the inverse of the labor share, the aggregate production function displays cost complementarities in the production of the consumption and investment good. This enables the model to potentially generate business cycle type fluctuations following changes in expectations about the future. This is a strong advantage over the canonical business cycle model. Coefficient estimates obtained in the empirical section indicate that for reasonable values of the labor share, the condition for cost complementarities at the aggregate level is met. Given that most economists would agree that some economic fluctuations arising from changes in expectations is a likely feature of any economy, this result suggests that a multisectoral adjustment costs mechanism (or any equivalent) should at least be given serious consideration in any model building exercise.

Tables and figures

Tables

Table 2.1: Parameter estimates

	Long Sample 1959:1-2004:4	Short Sample 1975:1-2004:4	Long Sample diff. deflators 1959:1-2004:4	Long Sample I to C ratio 1959:1-2004:4	Short Sample I to C ratio 1975:1-2004:4
$\hat{\gamma}_1$	0.456	0.563	0.491	0.363	0.463
msl	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$\bar{R}^2$	0.365	0.568	0.388	0.369	0.592

Marginal Significance Level calculated using Robust Standard Errors

Table 2.2: Persistence of residuals

	Long sample 1959:1-2004:4	Short Sample 1975:1-2004:4	Long Sample diff. deflators 1959:1-2004:4	Long Sample I to C ratio 1959:1-2004:4	Short Sample I to C ratio 1975:1-2004:4
$\sigma^2_{\hat{x}}/\sigma^2_x$	0.368	0.572	0.391	0.373	0.595
$\rho_{\hat{e}_t}(1)$	0.661	0.662	0.638	0.647	0.626
LM(1)	139.617	90.371	124.175	129.781	75.128
mls	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
LM(4)	34.364	26.331	30.703	31.954	21.397
mls	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

Table 2.3: Parameter estimates, equation (2.16)

	Long Sample 1959:1-2004:4	Short Sample 1975:1-2004:4	Long Sample diff. deflators 1959:1-2004:4	Long Sample I to C ratio 1959:1-2004:4	Short Sample I to C ratio 1975:1-2004:4
$\hat{\gamma}_1$	0.539	0.601	0.549	0.428	0.494
msl	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$\hat{\gamma}_2$	0.908	0.525	0.761	0.905	0.538
msl	(0.000)	(0.061)	(0.005)	(0.000)	(0.041)
$\bar{R}^2$	0.468	0.593	0.463	0.472	0.619

Marginal Significance Level calculated using Robust Standard Errors

Table 2.4: Persistence of residuals, equation (2.16)

	Long sample 1959:1-2004:4	Short Sample 1975:1-2004:4	Long Sample diff. deflators 1959:1-2004:4	Long Sample I to C ratio 1959:1-2004:4	Short Sample I to C ratio 1975:1-2004:4
$\sigma^2_{\hat{x}}/\sigma^2_x$	0.474	0.600	0.469	0.478	0.625
$\rho_{\hat{e}_t}(1)$	0.625	0.641	0.617	0.615	0.607
LM(1)	115.144	80.284	112.395	109.557	67.721
msl	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
LM(4)	28.704	23.125	28.514	27.362	19.014
msl	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

Table 2.5: Parameter estimates, equation (2.21)

	Long Sample 1959:1-2004:4	Short Sample 1975:1-2004:4	Long Sample I to C ratio 1959:1-2004:4	Long Sample Labor Share 1959:1-2004:4
$\hat{\gamma}_1$ mls	0.202 (0.000)	0.248 (0.000)	0.156 (0.000)	0.234 (0.000)
$\hat{\gamma}_2$ mls	0.707 (0.000)	0.663 (0.000)	0.706 (0.000)	0.670 (0.000)
$\hat{\gamma}_3$ mls	–	–	–	0.213 (0.146)
$\bar{R}^2$	0.748	0.827	0.745	0.752
$\hat{\gamma}_1/(1-\hat{\gamma}_2)$	0.689	0.737	0.531	0.711

Marginal Significance Level calculated using Robust Standard Errors

Table 2.6: Persistence of residuals, equation (2.21)

	Long sample 1959:1-2004:4	Short Sample 1975:1-2004:4	Long Sample I to C ratio 1959:1-2004:4	Long Sample Labor Share 1959:1-2004:4
$\rho_{\hat{e}_t}(1)$	-0.060	-0.104	-0.034	-0.051
LM(1) mls	0.869 (0.352)	2.039 (0.156)	0.289 (0.591)	0.627 (0.430)
LM(4) mls	1.477 (0.211)	0.327 (0.859)	0.347 (0.846)	1.067 (0.374)

Table 2.7: Parameter estimates, equation (2.22) and (2.23)

	Long Sample 1959:1-2004:4	Long Sample Diff. Deflator 1959:1-2004:4	Long Sample PAM model 1959:1-2004:4	Long Sample I/C ratio 1959:1-2004:4	Long Sample var. Markups 1959:1-2004:4
$\hat{b}$	6.161	5.422	7.699	11.342	6.153
msl	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$\hat{\sigma}$	1.843	1.818	1.927	2.277	1.828
msl	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$\hat{\gamma}$	–	–	–	–	0.722
msl	–	–	–	–	(0.000)
$\bar{R}^2$	0.926	0.917	0.983	0.929	0.932

MLS calculated using Robust Standard Errors

Table 2.8: Parameter estimates, equation (2.22), two subsamples

	Long Sample 1959:1-2004:4	Short Sample Ia 1959:1-1974:4	Short Sample IIa 1975:1-2004:4	Short Sample Ib 1959:1-1978:4	Short Sample IIb 1979:1-2004:4
$\hat{b}$	6.161	4.914	6.446	4.945	5.582
msl	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$\hat{\sigma}$	1.843	1.026	1.872	1.045	1.805
msl	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

Marginal Significance Level calculated using Robust Standard Errors

Table 2.9: Error-in-variable, partial adjustment model and variable markups

	Part. Adj. Mech. 59:1- 74:4	Part. Adj. Mech. 75:1- 04:4	Different Deflator 59:1- 74:4	Different Deflator 75:1- 04:4	Var. Mark. nonfarm bus. 59:1- 74:4	Var. Mark. nonfarm bus. 75:1- 04:4
$\hat{b}$	4.981	7.663	3.946	5.863	5.153	6.442
msl	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$\hat{\sigma}$	1.076	1.939	1.663	1.835	1.100	1.867
msl	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.004)
$\hat{\gamma}$	–	–	–	–	1.503	0.205
msl	–	–	–	–	(0.000)	(0.253)

Marginal Significance Level calculated using Robust Standard Errors

Table 2.10: Model with variable markups, alternative definition of the labor share

	Var. Mark. nonfin sect. 59:1- 74:4	Var. Mark. nonfin sect. 75:1- 04:4	Var. Mark. meas. 1 59:1- 74:4	Var. Mark. meas. 1 75:1- 04:4	Var.Mark. meas. 2 59:1- 74:4	Var. Mark. meas. 2 75:1- 04:4
$\hat{b}$	5.190	6.509	5.126	6.435	5.085	6.308
msl	(0.000)	(0.000)	(0.000)	(0.039)	(0.000)	(0.000)
$\hat{\sigma}$	1.106	1.873	1.075	1.868	1.086	1.855
msl	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$\hat{\gamma}$	1.674	0.231	1.889	0.154	1.944	0.419
msl	(0.000)	(0.444)	(0.000)	(0.685)	(0.000)	(0.384)

Marginal Significance Level calculated using Robust Standard Errors
`measure 1` is workers' compensation in GDP
`measure 2` is workers' compensation in (GDP-proprietors' income)

Table 2.11: Parameter estimates, equation (2.23), two subsamples

	Long Sample	Short Sample IIa	Short Sample IIb
	1959:1-2004:4	1975:1-2004:4	1979:1-2004:4
$\hat{b}$	11.342	13.375	12.100
msl	(0.000)	(0.000)	(0.000)
$\hat{\sigma}$	2.277	2.481	2.468
msl	(0.000)	(0.000)	(0.000)

msl calculated using Robust Standard Errors

Table 2.12: Parameter estimates, NLLS vs grid search

	equation 2.24 NLLS	equation 2.24 Grid Search	equation 2.25 NLLS	equation 2.25 Grid Search
$\hat{b}$	6.161	5.392	11.342	8.969
$\hat{\sigma}$	1.843	1.772	2.277	2.245

sample period is 1959:1 to 2004:4

Figures

Figure 2.1: Hall residual

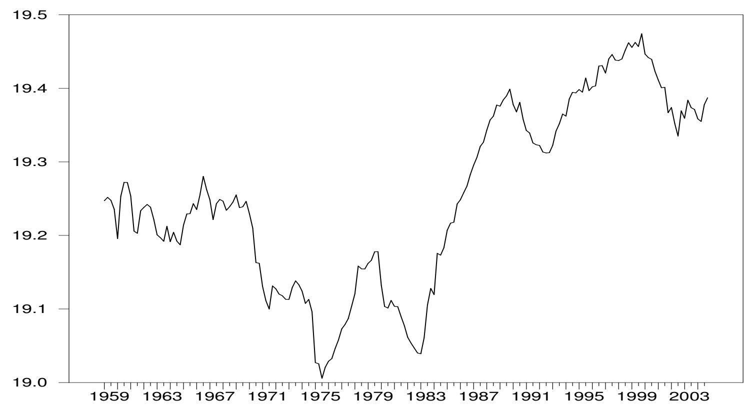


Figure 2.2: Correlation between Hall residual and investment ratio

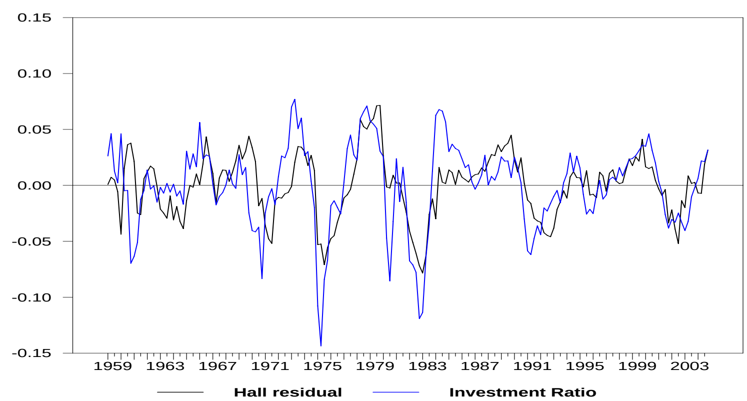


Figure 2.3: HP-filtered measures of the labor share

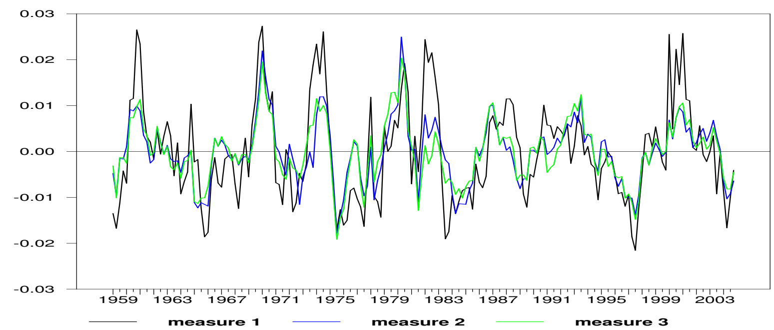


Figure 2.4: Cyclical component of the Hall residual

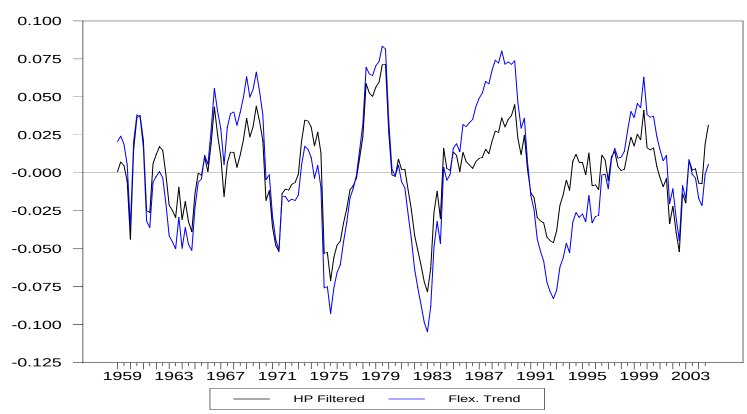


Figure 2.5: Contribution of multisectoral adjustment costs, flexible trend approach

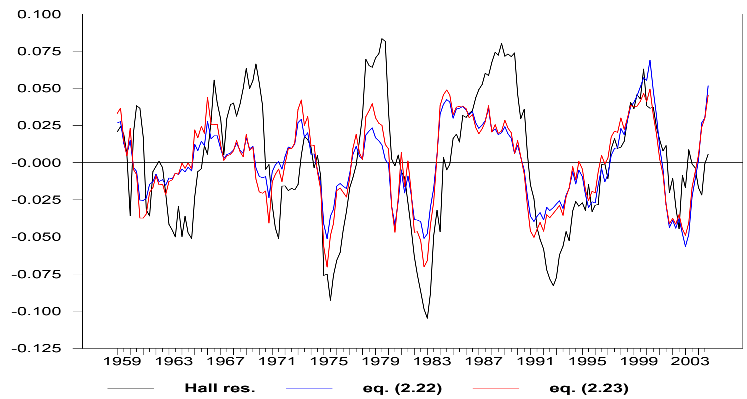
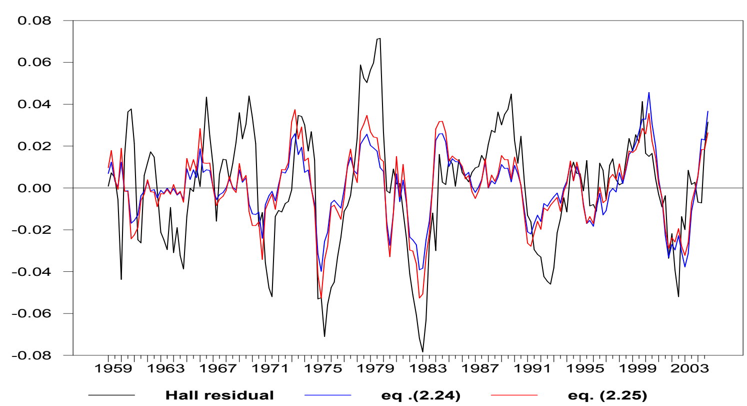


Figure 2.6: Contribution of multisectoral adjustment costs, grid search approach



3. Complementarities, Expectation Revisions and the Business Cycle

3.1 Introduction

Until recently, it was generally accepted that business cycles could be meaningfully decomposed into fluctuations arising from demand shocks - caused by policy and preference changes - as well as supply shocks caused by unexpected technological changes. The investment boom and subsequent bust experienced by the United States between 1994 and 2003 - the so-called "new economy" era - poses serious challenges to this common view. An alternative explanation that is now acknowledged by many analysts can be told along the following lines. Agents receive a signal that leads them to be optimistic about the future profitability of investment. This triggers an investment boom and an economic expansion. When profitability fails to live up to expectations, there is an investment bust and an economic slowdown. That downward revisions in expectations about future technological progress was (at least partly) responsible for the investment bust between 2000 and 2003 is given formal support in the work of Karnizova [2004]. This proposed explanation is reasonable even when agents are rational because they typically receive a significant amount of signals which, even though informative, are not perfect. Rotemberg [2003] shows that people indeed receive and process prior information about future productivity improvements driven by new technologies since they take time to diffuse in the economy.

The idea that changes in expectations can spur business cycle fluctuations, formally defined as positive co-movements in consumption, investment, output, hours and stock prices, is far from novel. The argument is found in contributions dating back to Beveridge [1909] and Pigou [1926]. Despite the attractiveness of the notion, it remains surprisingly difficult to generate such fluctuations from usual models employed in the business cycle literature. As shown in Beaudry and Portier [2007], to cite only one example, canonical one and two sectors neoclassical equilibrium growth models can not generate the kind of co-movements observed in a typical business cycle following a change in expectations about future total factor productivity. In a standard model of the business cycle, good news about future TFP will typically stimulate consumption but depress hours, investment and output: a recession arises from good news! The intuition underlying this result is easily understood in the case of the neoclassical growth model with fixed labor supply. In this case, current output depends on current TFP and the pre-determined capital stock. News about future productivity that leaves current productivity unaffected will have an immediate effect on consumption through a wealth effect while leaving current output unchanged. If, following the news, consumption increases, then investment can only fall because aggregate output remains unchanged. With endogenous labor, the same shock that lead to an increase in consumption would also depress labor supply if leisure is a normal good, making matters worse.

Of course, this shortcoming of usual business cycle models is of minor importance if changes in expectations are rarely the underlying cause of economic fluctuations. Empirical evidence suggests otherwise. Beaudry and Portier [2004] find that for the period ranging from 1948Q1 to 2000Q4, about 50% of aggregate US business cycle fluctuations are explained by a shock that does not affect productivity in the short run but affects the latter with substantial delay. They obtain similar findings for aggregate Japanese data and sectoral US data (Beaudry and Portier [2005]). In a different context, Fujiwara et al. [2008] also obtain similar results. A natural structural interpretation for this shock is that of a shock representing “news” about future technological opportunities, which naturally induces changes in expectations. In a very general sense, news shocks represent any information that helps to predict future economic fundamentals without affecting current fundamentals. This can be, for example, a technological innovation that takes time to diffuse in the economy. This finding provides empirical support for the emerging “news view” of aggregate fluctuations and suggests that any relevant model should be able to generate business-cycle type fluctuations following changes in expectations about the future while current fundamentals remain unchanged.

Along with the emerging news view of aggregate fluctuations came the recent development of theoretical (closed economy) models capable of generating such expectation driven business cycles (EDBC). These models aim at generating an *increase* in consumption, investment, output and hours following news about *future* productivity gains[23]. To obtain this EDBC, one needs (1) that news about future productivity lead to an increase in investment demand and (2) that this increase in investment demand is satisfied by an increase in hours worked and not a reduction in consumption. To obtain (1), one typically uses some form of capital adjustment costs. As emphasized by Beaudry and Portier [2004] and Den Haan and Kaltenbrunner [2007], the main challenge in building a model that can generate EDBC is to find a way to satisfy condition (2).

The solution adopted by Den Haan and Kaltenbrunner [2007] is to introduce a labor market matching framework in a standard RBC model with endogenous labor supply. A matching framework helps in obtaining the required expansion because anticipated increases in productivity benefits those already engaged in productive activities. Firms and workers not engaged in such activities will be able to benefit from the expected gain only if they can form a productive relationship. Since a matching framework requires time and resources to form such relationships, firms and workers not engaged in a working relation have an incentive to post new jobs and start looking for work immediately instead of waiting for the actual increase in productivity. The ensuing gains in employment generate increases in consumption and investment before productivity actually improves. One caveat of the model is that while it can generate positive co-movements between consumption, investment and hours following changes in expectations about future productivity, it can not do so *contemporaneously*. More specifically, given the timing of their model, employment and capital are predetermined when the news shock hit the economy. This implies that the amount of available output is constant so that consumption and investment initially have to move in opposite direction. In that sense, their model does not exactly reproduce an EDBC as defined above.

To generate EDBC, Christiano et al. [2007] instead develop a monetized version of a RBC model which includes habit persistence in consumption,

[23]One could argue that obtaining this result in an open economy setting is fairly simple and that restricting attention to closed economy setting is too restrictive. On the other hand, this would indirectly suggests that expectation driven business cycles is only an open economy phenomenon. There are reasons to believe this is not the case, as the boom-bust in investment observed in the US was also observed in most countries around the world.

adjustment costs in terms of the change in the flow of investment[24], sticky prices and wages and an inflation-targeting monetary authority. The paper demonstrates a number of interesting results. First, they show that an RBC model which jointly includes habit formation and the flow specification of adjustment costs is sufficient for generating positive co-movements in consumption, investment, output and hours[25]. In this sense, the model can produce EDBC as defined by Beaudry and Portier [2007]. These two features allow to obtain the required positive co-movements because the flow specification of adjustment costs generates an incentive to start investing immediately when agents learn about future productivity gains while habit formation in consumption helps to stimulate labor supply because it contributes to increase the marginal utility of leisure.

The necessity of developing a monetized version arises because the model produces two counterfactual results. First, the stock market falls following the good news about future productivity. Second, it can not produce a boom phase that lasts more than 4 to 6 quarters. The monetized version with nominal frictions does not suffer from these two "shortcomings". This happens because following the news shock, real wage should increase to discourage employment. Because wages are sticky, one way to obtain higher real wages would be to let inflation decrease. An inflation-targeting monetary authority will lower interest rates to prevent this drop, which contributes to amplify the boom and generate the rise in the stock market. Therefore, employment is inefficiently high and the cycle brought by the news too important. Put differently, monetary policy is welfare-reducing in this case since it generates a much bigger boom than what would have been optimal.

An alternative model that essentially exploits the same real ingredients as the model of Christiano *el at.* is that of Jaimovich and Rebelo [2006]. In particular, their model features habit persistence in consumption, adjustment costs to investment[26] or capital utilization and variable capital utilization. Their model differs from the contribution of Christiano *et al.* primarily in the specification of preferences. Specifically, they propose preferences that exhibit a weak short-run wealth effect on the labor supply. In a sense, they

[24]More precisely, the adjustment costs is a function of the change in investment I_t/I_{t-1} as opposed to I_t/K_t as usually found in the literature. They call the first specification "flow specification" while they call the second specification "level specification".

[25]More specifically, both the habit formation and the *flow* specification of adjustment costs are important. The model with habit formation and the *level* specification can not generate positive co-movements between consumption and investment

[26]In the case of investment, the flow specification of adjustment costs

are a sort of hybrid between the preferences of King et al. [1988] and those of Greenwood et al. [1988]. The weak short-run wealth effect on the labor supply is very helpful in generating EDBC since hours do not decrease when agents learn about the future gain in productivity. As such, this model can generate EDBC provided that preferences be very close to the GHH form. Then, the incentive to work more comes from variable capital utilization which increases the marginal product of labor. Given the similarities between this model and the contribution of Christiano *et al.*, it is not surprising that the response of both models to a realized news shocks are qualitatively similar. Consumption, output, investment and hours increase before the shock is realized while Tobin's marginal q falls. The main difference between the two models is the response of hours when the shock materializes. While the model of Christiano *et al.* predicts a drop in hours, the model of Rebelo and Jaimovich predicts a further increase because of the weak short-un wealth effect. Which response is appropriate remains, again, an empirical question.

Another type of modification in preferences is exploited in the work of Karnizova [2007]. Specifically, she assumes that in addition to using wealth for consumption purposes, agents derive utility from it. This assumption is coined "spirit of capitalism" and has been used to resolve puzzles related to asset pricing, saving behavior and cross-county growth differences. The main idea underlying the capacity of this model to generate EDBC is that the boom in the stock market that follows news about future productivity growth induces agents to work more. That is, because agents value their wealth, they see the time of the stock market boom as a good time to work: an increase in the value of assets stimulate labor supply. Some features of the model are worth noting. First, it can generate EDBC without relying on the flow specification of adjustment costs. In fact, while the model presented uses an intertemporal adjustment costs specification, it can generate EDBC without relying on adjustment costs altogether[27]. In addition, the model predicts that the real wage falls when the news shock hits the economy. This happens because the news generate a stock market boom that stimulates labor supply while labor demand remains unaffected. This is unlike the previous two models which predict the opposite[28]. The response of real wages to news shocks could potentially help discriminate between competing models.

[27] The necessary condition for EDBC becomes more stringent, however.

[28] The real model, in the case of Christiano *et al.*

An alternative mechanism capable of generating EDBC is to introduce cost complementarities in production. Cost complementarities means that the marginal cost of producing one type of goods - the consumption goods say - decreases as the production of the other type of goods increases. The reason cost complementarities help in obtaining EDBC is fairly intuitive: a shock which leads to an increase in investment demand makes the production of the consumption goods cheaper. The lower price of consumption stimulates its demand leading to positive co-movements between consumption and investment.

The idea that cost complementarities can generate EDBC was theoretically presented in the work of Beaudry and Portier [2007]. The present paper proposes to investigate it formally. Cost complementarities are introduced through a nonlinear transformation curve between the consumption and investment goods. The paper presents a market environment that leads to such a nonlinear transformation curve. In this environment, intermediate good firms are multi-product firms supplying a differentiated good to both the consumption and investment sectors. Each intermediate good firms has a production function with multi-sectoral adjustment costs. In such a production function, the transformation curve between the two differentiated goods follows a constant elasticity of substitution functional form. Such production function is not new to the literature, as it has been used by Sims [1989], Vallés [1997], Kim [2003], Fisher [1997] and Huffman and Wynne [1999]. Moreover, it includes the canonical RBC model as a special case.

One of the findings of the paper is that as conjectured by Beaudry and Portier [2007], adding cost complementarities helps in obtaining positive co-movements between consumption, investment, output and hours. On the other hand, it is not sufficient to simply add cost complementarities to a standard RBC model to obtain the required joint *increase* in all these quantities following news about future productivity gains. On the contrary, unless one is willing to admit a high intertemporal elasticity of substitution in consumption, all variables positively co-move in the *wrong* direction. That is, when agents learn of future productivity gains, all variables decrease! This happens because with standard preferences and a Cobb-Douglas production function, agents can fully beneficiate from the increased productivity by simply working harder and investing more when the productivity gain materializes. Adding complementarity between productive factors changes this dynamics[29]. Given that labor and capital are complement in production,

[29] As will be discussed later, recent estimates of production functions using US and

one must start accumulating capital immediately to gain full benefits from the expected productivity gain. Thus, the model is capable of generating EDBC in more general cases.

The remainder of the paper illustrates the role played by each ingredients of the model in generating EDBC. It is organized as follow. Section 3.2 presents the economic environment. Then, section 3.3 shows the dynamic adjustment of the model economy to news about future TFP growth when we add the various complementarities sequentially. The analysis will naturally lead to a discussion about real wages and the specification of preferences, in particular the role of intertemporal elasticity of substitution in consumption. These discussions are found in section 3.4 and 3.5. Finally, section 3.6 concludes.

3.2 Model description

This section presents the market environment that leads to a nonlinear transformation curve between the consumption and investment goods at the aggregate level. This nonlinear transformation curve generates cost complementarities which, in turns, allow for business cycle fluctuations generated by changes in expectations about the future. The model keeps the competitive market paradigm and is a simple extension of the basic RBC model with one stock of capital. The model is coined Multisectoral Adjustment Costs model (MAC) because the transformation curve between the consumption and investment goods is of the constant elasticity of substitution form. This captures the fact that it can be costly to reorient production from one type of goods to an other. It comprises the canonical RBC model as a special case.

3.2.1 Production sector

The economy consists of $N > 0$ competitive intermediate goods sectors (industries) and 2 competitive final goods sectors. The representative firm in each intermediate sector is a multi-product producer that sells potentially different inputs to the 2 final goods sectors, consumption C_t and investment

Canadian data suggests that complementarity between capital and labor is a distinct possibility.

I_t. Total output of the consumption good is given by an aggregator function $C_t = f_C(X_{1,t}, \ldots, X_{N,t})$ with X_j representing the input of sector j to the consumption good sector. Total output of the investment good is given by the aggregator function $I_t = f_I(Z_{1,t}, \ldots, Z_{N,t})$ with Z_j representing the quantity of input sold by sector j to the investment good sector. Both aggregator functions are increasing, concave and symmetric functions of their arguments. They are also homogenous of degree one and twice continuously differentiable.

Each intermediate good firm j produces both X_j and Z_j according to the following identical multi-product production function

$$(aX^{\sigma}_{j,t} + bZ^{\sigma}_{j,t})^{\frac{1}{\sigma}} = \left(\theta K^{\mu}_{j,t} + (1-\theta)(A_t H_{j,t})^{\mu}\right)^{\frac{1}{\mu}} \tag{3.1}$$

where $0 < \theta < 1$, $\mu \leq 1$, $\sigma \geq 1$ and $K_{j,t}$,$H_{j,t}$ represents the amount of capital and labor used by firm j at time t. A_t is labor-augmenting technology assumed common to all firms. Parameters a and b determine the price of investment in terms of consumption. Equation (3.1) describes a production function with multi-sectoral adjustment costs. The parameter σ measures the capacity of the firm to reallocate its raw output from the input for the consumption sector to the input for the investment sector. Formally, σ measures the inverse of the elasticity of substitution between X_j and Z_j. When $\sigma = 1$, the transformation is linear between the two types on input. As σ gets bigger, the cost of obtaining one more unit of X_j in terms of foregone Z_j increases. In the context of a multi-product firm, one plausible explanation of this cost is that the outcome of some of the intermediary steps leading to the production of one type of goods enters naturally as input in intermediary steps leading to production of the other type of goods. For example, metal scraps from the production of one type of goods being used as input in the production of the other type of goods. A larger value for σ means that there is more of that joint production taking place. Then, if a firm increases the production of one type of goods without increasing that of the other type of goods, it throws away valuable resources which is the source of the increase in costs.

The hypothesis of multi-sectoral adjustment costs has some noteworthy implications. First, the model will generate variability in the relative price of X_j and Z_j, a desirable property given observable data. Second, this multi-product production function displays cost complementarities if

$$\frac{(1-\mu)}{(\sigma-\mu)} < 1 - \theta \left(\frac{K}{Y}\right)^{\mu} \tag{3.2}$$

This result is shown in appendix C. Note that the condition depends on the capital to output ratio. In the simulations to come, the economy is initially at its non stochastic steady state. As such, it is the steady state level of capital to output that determines if the condition is met. On the other hand, when $\mu = 0$, so that the production function is Cobb-Douglas, the condition simplifies to

$$\sigma > \frac{1}{(1-\theta)}$$

and cost complementarities depend only on the size of the degree of multi-sectoral adjustment costs relative to the inverse of the labor share of output.

Now, given the assumptions about the aggregator functions f_C and f_I and the production function of multi-product intermediate good firms, the symmetric equilibrium aggregate resource constraint writes as

$$(aC_t^\sigma + bI_t^\sigma)^{\frac{1}{\sigma}} = (\theta K_t^\mu + (1-\theta)(A_t H_t)^\mu)^{\frac{1}{\mu}}$$

which, using composite output Y_t as the numeraire, can alternatively be written as

$$p_t^C C_t + p_t^I I_t = Y_t$$

where

$$p_t^C = a\left(\frac{C_t}{Y_t}\right)^{\sigma-1}$$

and

$$p_t^I = b\left(\frac{I_t}{Y_t}\right)^{\sigma-1}$$

are respectively the price of consumption and investment. When $\sigma = 1.0$ and $a = b = 1.0$, one obtains the canonical RBC model as a special case. Finally, capital accumulates according to

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

3.2.2 Household sector

The economy is populated by an infinitely lived representative household that maximizes its expected discounted utility

$$\max\ \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{(C_t - gC_{t-1})^{1-\gamma}}{1-\gamma} - \frac{\vartheta_0}{\eta+1} H_t^{\eta+1}\right] \tag{3.3}$$

where β is the discount factor, C_t denotes consumption and H_t denotes hours worked. The endowment of time is normalized to 1. $\mathbb{E}_0 = \mathbb{E}(.|\mathcal{F}_0)$ represents the expectation operator conditional on the information set available at time 0. η is the inverse of the Frisch wage elasticity of labor supply. γ is the inverse of the intertemporal elasticity of substitution in consumption. The parameter g captures the degree of habit persistence in consumption. When $\gamma = 1$, $g = 0$ and $\eta = 0$, we have preferences of the Hansen-Rogerson type. The reason for considering habit persistence will be discussed later but it is worth noting immediately that it is not fundamental to obtain the desired results. Finally, ϑ_0 is a positive constant.

3.2.3 Competitive equilibrium

A rational expectation equilibrium for this economy is a set of stochastic processes $\{C_{t+j}, H_{t+j}, I_{t+j}, K_{t+j+1}\}_{j=0}^{\infty}$ such that 1) the representative household maximizes lifetime utility and 2) all market clears. Given K_0 and a stochastic process for A_t, equilibrium allocations are found by solving the planner's problem

$$\max\ \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{(C_t - gC_{t-1})^{1-\gamma}}{1-\gamma} - \frac{\vartheta_0}{\eta+1} H_t^{\eta+1} \right]$$

subject to

$$(aC_t^{\sigma} + bI_t^{\sigma})^{\frac{1}{\sigma}} = (\theta K_t^{\mu} + (1-\theta)(A_t H_t)^{\mu})^{\frac{1}{\mu}} \tag{3.4}$$

$$K_{t+1} = (1-\delta)K_t + I_t \tag{3.5}$$

$$H_t \leq 1 \tag{3.6}$$

The equations characterizing the equilibrium allocation are

$$(C_t - gC_{t-1})^{-\gamma} - \beta g \mathbb{E}_t (C_{t+1} - gC_t)^{-\gamma} = \lambda_t p_t^C \tag{3.7}$$

$$\vartheta_0 H_t^{1+\eta-\mu} = (1-\theta)\lambda_t A_t^{\mu} Y_t^{(1-\mu)} \tag{3.8}$$

$$q_t = \lambda_t p_t^I \tag{3.9}$$

$$q_t = \beta \mathbb{E}_t \left[\theta \lambda_{t+1} \left(\frac{Y_{t+1}}{K_{t+1}} \right)^{1-\mu} + (1-\delta) q_{t+1} \right] \tag{3.10}$$

where

$$p_t^C = a \left(\frac{C_t}{Y_t} \right)^{\sigma-1} \tag{3.11}$$

$$p_t^I = b\left(\frac{I_t}{Y_t}\right)^{\sigma-1} \tag{3.12}$$

in addition to equations (3.4), (3.5), (3.11), (3.12) and the transversality condition

$$\lim_{t\to\infty} \beta^t \lambda_t K_{t+1} = 0$$

λ_t is the multiplier associated with the aggregate resource constraint while q_t is the multiplier associated with the capital accumulation equation. Equation (3.7) is the first order condition with respect to consumption and (3.8) equates the marginal rate of substitution between consumption and hours to the real wage expressed in terms of the consumption goods. Equation (3.10) describes the consumption-saving choice. Note that by setting $\gamma = 1$, $g = 0$, $\eta = 0$, $\mu = 0$ and $\sigma = 1$, one obtains the canonical RBC model with Hansen-Rogerson preferences as a special case.

To understand the role played by each element of the model, the next section presents the response of the model economy to news shocks and compare these responses to those obtained from the canonical RBC model. There, it will be shown that cost complementarities are fundamental in obtaining EDBC. On the other hand, to obtain the result more generally in the current setting also requires some complementarity in the production function as well as some habit persistence in consumption.

3.3 Quantitative evaluation of the model

This section examines the response of the model economy to news about the future. To this end, the model is linearized about its deterministic steady state and calibrated using standard values in the business cycle literature. Appendix D presents the linearized equations used in simulating the dynamic impulse responses. In what follows, the interest centers on the response of the model to an experiment where agents receive a signal about future improvement in TFP then find out that their expectation does not materialize. On a particular note, the section will highlight the specific contribution of habit formation in consumption in generating a potentially more reasonable response to the news shock in a very general case.

3.3.1 Parameterization

For the following experiments, the basic parametrization considered is presented in table 3.1. The chosen values are for the most part standard in the business cycle literature. The coefficient ϑ_0 is set so that the steady state level of hours worked is equal to 1/3. The parameter $\eta = 0.0$, so that preferences are linear with respect to labor at the representative agent level. In the experiments, two values of the inverse of the intertemporal elasticity of substitution in consumption γ are considered (0.25 and 1.0) since they generate different responses of the model to a news shock. This, in turns, will affect the degree of habit formation g and the degree of complementarity in production μ that are required for the models to generate EDBC. The parameter a does not affect the dynamic response of the MAC model while it is only very mildly influenced by the value of the parameter b. As such, they are set to unity.

3.3.2 Generation process for news shocks

To generate the various impulse response functions, it is necessary to postulate a process for news shocks about future technological progress. To this end, we consider the following simple generation process for technology

$$\ln A_t = \rho \ln A_{t-1} + \xi_{t-p} + e_t \tag{3.13}$$

where e_t and ξ_t are uncorrelated white noise processes. Up until period 1, the economy is in its stationary steady state. At time 1, agents receive a signal ξ that technology will be higher in period $p+1$. This is the source of expectation revisions. In period $p+1$, either their expectation is fulfilled ($e_{p+1} = 0$) or their expectation is not realized ($e_{p+1} = -\xi_1$). This is obviously a crude representation of any real life situation where agents would continually update their expectations. For illustrating the mechanisms at work, however, this simplification serves its purpose well. In all experiments that follow, $\rho = 1$, $p = 3$, $\xi_1 = 1.0\%$ and $e_4 = -1.0\%$, so that in period 1, agents learn that technology is expected to permanently increase by 1% in period 4. Then, in period 4, agents learn that their expectation is not realized.

3.3.3 Response of MAC model to news shock

This section illustrates the response of the MAC model to news shocks. The first model considered is the canonical RBC model, which is a special case of the MAC model with $g = 0$ (no habit formation), $\sigma = 1.0$ (no adjustment costs) and $\mu = 0.0$ (Cobb-Douglas production function). Two cases are considered: $\gamma = 1.0$ (low intertemporal elasticity of substitution in consumption) and $\gamma = 0.25$ (high intertemporal elasticity of substitution in consumption). This basic case serves to illustrate that the standard RBC model can not generate positive co-movements between consumption, investment, output and hours following changes in expectations about future technology. Figure 3.1 illustrates the response of the economy to news about future technology that is eventually not realized.

Consider first the case $\gamma = 1.0$. When learning about the good news, agents immediately increase consumption because of the wealth effect. As leisure is a normal good, hours fall since wages go up only in the future so that there is no substitution effect today to counteract the wealth effect on leisure. Because the capital stock is predetermined and technology has not increased yet, output falls as well. The only way to reconcile higher consumption and lower output is through a decrease in investment. The good news generate an output recession. When, in period 4, agents learn that they were overoptimistic, consumption drops while hours, output and investment all increase. Clearly, consumption, on the one side, and investment, output and hours, on the other side, move in opposite direction.

In the case of a high intertemporal elasticity of substitution in consumption $\gamma = 0.25$, the initial response of consumption and hours, output and investment are reversed. Nevertheless, the negative co-movements between consumption and hours, output and investment is still observed. Adding capital adjustment costs *à la* Tobin or generalized intertemporal adjustment costs[30] does not alter this result. See Beaudry and Portier [2007] for a theoretical proof of this result. One important thing to note at this point is that with log preferences in consumption, news about future productivity do not lead to an increase in investment demand, while it does when there is a high degree of intertemporal substitution in consumption.

To illustrate how cost complementarities in production alter the findings above, figure 3.2 shows the impact of the news shocks in the MAC model

[30] That is, $K_{t+1} = [I_t^\pi + ((1-\delta)K_t)^\pi]^{1/\pi}$.

with no habit formation and a Cobb-Douglas production function. To this end, the parameter σ is calibrated to $\sigma = 1.8$[31]. The figure confirms the theoretical findings of Beaudry and Portier [2007]: the presence of cost complementarities generate positive co-movements between consumption, investment, output and hours. The problem arises from the fact that when the intertemporal elasticity of substitution is low, as in the case of log preferences in consumption, all variables move in the wrong direction.

Consider first the case of a high intertemporal elasticity of substitution in consumption $\gamma = 0.25$. Just as with the canonical RBC model, news about future technological progress lead to an increase in investment demand. Because of cost complementarities, however, this increase in investment renders firms more efficient at producing the consumption goods, leading to a decline in its relative price. This decline, in turns, stimulates the demand for consumption. These dynamics are such that the news is said to generate and expectation driven boom. When, in period 4, agents realize that the expected technological progress does not materialize, all variables drop, generating an economic slowdown. Consider now the case $\gamma = 1.0$. Again, one sees that with cost complementarities, all aggregates move in the same direction. With log preferences, however, the good news about future technological progress leads to a decline in all the variables. This happens because with log preferences, the wealth effect of a future increase in TFP leads to an increase in consumption demand, not an increase in investment demand. The fact that consumption ultimately falls comes from the increase in its price. On the other hand, one sees that the decline in investment is much less severe than in the model without cost complementarities. This comes from the fact that the decline in the price of investment observed in figure 3.2 dampens the drop in investment.

From these figures, it is easily seen that if one is willing to assume a high degree of intertemporal substitution in consumption, the addition of cost complementarities is sufficient for the model to generate an economic expansion in response to positive news about future technological progress. Empirically, GMM estimation of the intertemporal elasticity of substitution using aggregate data typically produces low values for γ (see Mankiw et al. [1985], Ghysels and Hall [1990] and An et al. [2007] to name a few examples). On the other hand, these estimates are usually very imprecise and quite unstable. Moreover, this finding of a high intertemporal elasticity of

[31] Recall that with a Cobb-Douglas production function, cost complementarities obtain if $\sigma \geq 1/(1-\theta)$.

substitution in consumption appears at odd with empirical evidence which suggests that agents have a considerable distaste for intertemporal substitution in consumption, Weil [1990]. As such, it would appear important that the models be able to generate an EDBC when preferences are logarithmic in consumption since this preference specification is standard in the business cycle literature.

3.3.4 Generating a boom with logarithmic preferences

The reason behind the inability of the MAC model to generate an expansion following good news about future productivity when preferences are logarithmic in consumption is that the news generates an increase in consumption demand, not an increase in investment demand. This is most clearly illustrated in the case of the canonical RBC model, where upon learning of the news, consumption increases and investment drops. One way to obtain an increase in investment following the news is to introduce the flow specification of capital adjustment costs. This is the approach followed by Jaimovich and Rebelo [2006] and Christiano et al. [2007][32]. There are some reasons why it seems desirable to stay away from this mechanism. First, the flow specification of adjustment costs does not seem to obtain strong empirical support. To compare the empirical relevance of the flow and level specification of adjustment costs, Groth and Khan [2007] construct a general adjustment costs structure which is essentially a weighted average of both specifications. They use US industry data to estimate the weight of each adjustment costs specification only to find that the weight attributed to the flow specification is very close to zero for all the industries. As such, it remains difficult to motivate the flow specification of adjustment costs. Similarly, Eberly et al. [2008] find that Hayashi-type models of investment fit firm-level data better than investment models that penalize changes in the level of investment. Second, by construction the flow specification of adjustment costs generates a smooth profile for investment. This is true even when agents learn that their expectations do not materialize. In the model of Jaimovich and Rebelo [2006], for example, consumption reacts more

[32] In theory, one could adopt a specification of adjustment costs in terms of the level of investment relative to the capital stock as in Hayashi [1982] as opposed to the change in the flow of investment, as in Jaimovich and Rebelo [2006] and Christiano et al. [2007]. However, to obtain an expansion in investment following news when adopting a level specification requires an elasticity of adjustment costs much larger than what is typically used in the literature.

severely to downward revisions of expectation than investment. In this case, it is difficult to say that these downward revisions generate the kind of investment bust that characterizes the US experience of the beginning of the years 2000. Third, this specification of adjustment costs has an implication that seems counterintuitive when one considers the case of news about future investment-specific technical progress. Investment-specific technical progress is modeled as a decline in the price of investment. As such, upon learning of a technical progress to come, firms will expect the price of investment to decline in the future. With the flow specification of adjustment costs, firms will choose to start investing immediately, even though they know the price of investment will decline in the future. In a model with a single stock of capital, this behavior appears difficult to rationalize.

This paper considers an alternative route to generate an increase in investment demand following a positive shock about future productivity when preferences are logarithmic in consumption. In particular, it departs from the usual Cobb-Douglas aggregate production function ($\mu = 0$) and considers that there is some complementarity in production between capital and labor. Empirical evidence using US and Canadian data suggests that complementarity between capital and labor is a distinct possibility. In the case of Canada, estimates obtained by Murchison et al. [2004] and Perrier [2005] suggests values for the parameter $\mu \in [-1.33, -0.82]$. Klump et al. [2007] obtain similar estimates for the US economy. Again for the US economy, Antràs [2004] confirm this number and suggests that it might even be lower than $\mu = -1.0$. A wide range of estimates obtained from surveys of the literature and reported in Chirinko [2002] suggests for the most part that μ is smaller than -1.0.

To understand why complementarity between capital and labor helps in obtaining an increase in investment demand following positive news about future productivity, one can think about the response of investment in figures 3.1 and 3.2 (for the case of log preferences) as an indication that agents have no incentive to start accumulating capital today when they learn that it will be more productive in the future. This is because with a Cobb-Douglas production function, capital and labor are substitute in production. Thus, agents can fully beneficiate from the expected technological progress by working harder only when it is realized. In a sense, substitutability allows the agent to compensate the lack of capital accumulation prior to the realization of the shock with more labor. On the other hand, if capital and labor are complement in production, then working harder will not allow the agent to fully beneficiate from the expected productivity gain unless they started accumulating capital before the realization of the shock. To illustrate, take the extreme case of a Leontief production function with labor augmenting technological progress. In this case, working harder when the shock hits will bring no benefits to agents unless they have previously accumulated the capital stock required to complement their work effort. Therefore, complementarity between productive factors can generate the necessary incentive to start accumulating capital following news about future productivity gains.

To show that complementarity in production helps in obtaining an increase in investment following the news, figure 3.3 displays the response of the MAC model when $\mu = -1.2$, a value very similar to the ones reported above. The picture displays two cases. The solid line is the case where the degree of cost complementarities $\sigma = 1.80$. The second case is when $\sigma = 3.0$. The two cases are illustrated to show that complementarity between capital and labor will generate an EDBC provided that the degree of cost complementarities be sufficiently high. In the case at hand ($\mu = -1.2$), numerical simulations show that positive news about future expected productivity will generate an expansion provided that $\sigma \geq 2.2$. In the case of a Cobb-Douglas production function, no value of σ will generate an expansion following positive news about the future.

Moreover, the model will be able to generate an EDBC with logarithmic preferences in consumption and lower values of σ if there is more complementarity (μ more negative) between capital and labor. In a sense, there exists a form of “arbitrage” between μ and σ. To demonstrate this last point, figure 3.4 shows the response of the economy for the same values of σ when $\mu = -2.0$ instead if -1.2, a plausible value given the estimates reported in Chirinko [2002]. As one can clearly see, the model can now generate an expansion following the good news even when $\sigma = 1.80$, which was not the case in the previous figure. With logarithmic preferences in consumption, more complementarity between capital and labor lowers the requirement on σ to obtain an expansion following good news about future productivity.

While cost complementarities and complementarity in production helps in obtaining the expansion even with log preferences, a closer look at figures 3.3 and 3.4 shows that the response of consumption, output and hours are quite small. Responses are small because the ongoing wealth effect of the expected productivity improvement prevents hours from rising too much. As such, aggregate production can hardly increase given that the stock of capital is fixed in the short-run and that productivity has not yet increased.

Consequently, it is difficult to accommodate an increase in both consumption and investment. This problem illustrates point (2) mentioned in the introduction about the conditions required to obtain EDBC: the increase in investment demand must be satisfied by an increase in hours. To amplify the response of the economy with log preferences, one must find a way to counter the negative impact of the wealth effect on labor. Introducing habit formation in consumption helps in achieving this[33]. To see why, consider the intratemporal decision of the consumer

$$\mathrm{MUL}_t = \mathrm{MPL}_t \cdot \lambda_t$$

where MUL is the marginal utility of leisure, MPL is the marginal product of labor and λ is the marginal utility of consumption. A rise in labor requires the marginal utility of leisure to increase. This will be possible only if λ_t increases because a rise in labor will lower the marginal product of labor given that capital and technology are fixed when the news reached the economy. Now, note that with habit persistence ($g > 0$) and log preferences, the marginal utility of consumption is given by

$$\lambda_t = \left[\frac{1}{(C_t - gC_{t-1})} - \beta g \mathbb{E}_t \frac{1}{(C_{t+1} - gC_t)} \right] \frac{1}{p_t^C}$$

In particular, it is increasing in future consumption. When agents receive news that technology will be higher in the future, they understand that they will want to consume more in the future and experience a jump in the marginal utility of consumption today. This leads agents to increase labor supply today. To show that this mechanism allows to amplify the response of the model economy to the news shock with log preferences, figure 3.5 displays the response of the MAC model with log preferences in consumption, and $\mu = -1.2$. Two cases of habit formation are presented, one case with low habit $g = 0.25$ and one case with high habit $g = 0.63$. In both examples, $\sigma = 3.0$. The choice of $g = 0.63$ is based on estimation results presented in Christiano et al. [2005] while the choice of $g = 0.25$ is used to show that

[33] To accomplish this, Jaimovich and Rebelo [2006] introduce a class of preferences which are very close to those proposed by Greenwood et al. [1988] and exhibit a weak short-run wealth effect on the labor supply so that labor supply is almost independent from the intertemporal consumption-saving choice. Thus, news about future productivity gains do not depress hours today. The spirit of capitalism hypothesis of Karnizova [2007] instead makes labor supply positively related to financial wealth. As such, when agents expect their financial wealth to improve, they see this as a good time to work and increase their labor supply

even a small degree of habit formation in consumption is enough to generate a much amplified response of the model.

One thing to note from the last figure is that with habit formation, the responses of consumption and investment are very similar, in particular when agents learn that their expectations are not realized. Since this is one of the criticism of the flow specification of adjustment costs, one might be tempted to conclude that the approach proposed in this paper does not really improve matters. This conclusion is ill founded. To show this, figure 3.6 displays the response of the economy to the same experiment when $\mu = -2.0$ instead of $\mu = -1.2$. Clearly, in this case, the response of investment is much more volatile. This happens because with more complementarity between capital and labor in production, the news shock favors more capital accumulation thus more investment. With the flow specification of adjustment costs and typical calibrations, the response of consumption and investment would generally remain equally volatile.

While adding habit formation in consumption helps to amplify the response of the economy when preferences are logarithmic in consumption, the response of the price of investment (capital) to the news shock appears at odd with empirical evidence, especially when the degree of complementarity between capital and labor is "lower" and the degree of habit formation is high. To be specific, in the model, the price of capital, expressed in terms of consumption, corresponds to the price of equity in the data. As emphasized by Christiano et al. [2007], the boom phase generated by positive news about future technological progress is typically accompanied by a sustained increase in equity prices. Then, when agents learn that their expectation is not realized, equity prices drop and there is a stock market bust. Clearly, this pattern is not observed in the current case. The price of investment in presented in figure 3.7 when $\mu = -1.2$, $\sigma = 3.0$, $g = 0.25$ and $g = 0.63$.

Even though it is true that equity prices jump immediately upon the arrival of the news, they start to decline even before agents learn that their expectation is not realized. In the case of a high degree of habit persistence, equity prices even fall below their steady state value one period before agents learn that they were overoptimistic. Note that this is not a feature related to the timing of the shock, as the same pattern is observed when the shock is expected to hit in period 8 instead of period 4. This is shown in figure 3.8.

Again, equity prices jump on impact. With low habit formation, they keep increasing until three periods before the shock is expected to hit, point at which they begin to fall. With a high degree of habit formation, equity prices decline immediately after the initial jump. This pattern results from the combination of two effects. First, when complementarity between capital and labor is low, the desire to sacrifice consumption to start accumulate capital remains low. In addition, because agents like a smooth consumption profile, it will tend to accelerate as the time the productivity gain is expected to hit gets closer. At this point, more resources are devoted to consumption and less to investment, which leads to the decline in the price of investment. The more agents want to smooth consumption, the more this decline happens quickly.

On the other hand, when complementarity between capital and labor is "higher", which favors more capital accumulation following the news shock, equity prices behave more like the boom-bust described by Christiano et al. [2007]. This is seen by looking at the response of the economy when $\mu = -2.0$, case illustrated in figure 3.9. Clearly, the tendency for equity prices to decline is much smaller in this case. With a high degree of habit formation, however, equity prices will always have a weak tendency to fall, even when μ tends to $-\infty$. Nevertheless, the behavior of equity prices in the present models is more realistic than when investment demand is generated by the flow specification of adjustment costs. Indeed, this specification will generate a decline in equity prices immediately following good news about future productivity. Christiano et al. [2007] developed a monetary version of their model precisely to avoid this counterfactual response. The flow specification will generate a decline in equity prices because the increase in investment adds an extra payoff in the form of lower future adjustment costs. This is equivalent to a reduction in the current marginal cost of capital goods which is passed on in the form of a lower price[34].

Having formally presented a new combination of mechanisms capable of generating EDBC, a natural question to ask at this point is how to discriminate between competing models. One possible channel is the response of real wages to news shocks, which is discussed in the next section.

3.4 News shocks and real wages

As mentioned in the introduction, competing models capable of generating expectation driven business cycles differ along one margin, the response of

[34] This explanation is taken from Christiano et al. [2007].

real wages to news shocks. For example, the models of Christiano et al. [2007] and Karnizova [2007] predict a decline in real wages following news shocks while the model of Beaudry and Portier [2004] predicts an increase in real wages. One interesting feature of the MAC model is that it can generate both cases for seemingly reasonable parametrization. More generally, the model can potentially generate time series where hours and wages exhibit very low correlation. This is a desirable feature of the model given that the ability to account for this empirical fact is typically one test used to evaluate the validity of existing business cycle models.

To understand how this is possible, it is important to remember that the MAC model generates fluctuations in the relative price of consumption and that the agent ultimately cares about his real wage in terms of consumption goods. This is clearly illustrated by the labor supply schedule of the agent, which is given by

$$\vartheta_0 H_t^{\eta} = \frac{w_t}{p_t^C}\left[(C_t - gC_{t-1})^{-\gamma} - \beta g \mathbb{E}_t (C_{t+1} - gC_t)^{-\gamma}\right]$$

where w_t is the real wage in terms of composite output and is given by

$$w_t = (1-\theta)A^{\mu}\left(\frac{Y_t}{H_t}\right)^{1-\mu}$$

In an expectation driven boom, output and hours will move in the same direction. Since technology has not improved yet and capital changes only slowly, hours and output will display similar fluctuations, at least in the early periods. Consequently, it is not clear how wages (in terms of composite output) will move *a priori* but one can reasonably expect this movement to be small. As such, fluctuations in the price of consumption can have an important impact on the real wage in terms of consumption, which is the relevant one from the point of view of agents.

Consider for example the case presented above with logarithmic preferences $\gamma = 1.0$, some complementarity between capital and labor $\mu = -2.0$ and a low degree of habit persistence $g = 0.25$ when $\sigma = 3.0$. In this case, we obtain an expansion with virtually no movements in the real wage expressed in terms of consumption. This is shown in figure 3.10. On the other hand, figure 3.11 shows the response of the MAC when the production function is Cobb-Douglas, there is no habit formation in consumption, the level of cost complementarities is $\sigma = 3.0$ and there is a high intertemporal elasticity of substitution in consumption $\gamma = 0.3$. In this case, one sees that the expansion generated by the news shock drives the real wage in terms of consumption up even though hours increase substantially more than output. In fact, the rise in real wages is entirely due to the decline in the price of consumption brought about by cost complementarities at the level of intermediate firms.

Finally, figure 3.12 displays the response of the MAC economy when $\gamma = 0.68$, there is a high degree of habit in consumption $g = 0.63$, $\sigma = 2.0$ and productive factors are slightly complementary $\mu = -0.2$. In this situation, because of habit formation, the shock drives the demand for consumption goods up, which in turns puts upward pressure on the price of consumption. This contributes to the decline in the real wage expressed in terms of consumption goods.

The previous section has shown that the elements required for the models to generate an expansion following good news about the future depend highly on the degree of intertemporal substitution in consumption one is willing to assume. In particular, in an economy with a high intertemporal elasticity of substitution in consumption, a news shock will generate an increase in investment demand as well as stimulate labor supply. In this case, cost complementarities in production is sufficient to generate positive co-movements between consumption, investment, output and hours. With logarithmic preferences, the wealth effect of the expected productivity gain leads to an increase in consumption and a decrease in hours and investment. To generate an expansion in this case requires two elements. The first, complementarity between productive factors, generate an incentive to start investing upon learning of the news otherwise the agent can not fully beneficiate from the (expected) productivity gain. The second element is habit formation in consumption which gives an incentive to increase labor following the news. The current section has shown that the degree of intertemporal substitution in consumption also plays a role in the response of real wages to news shocks. Specifically, with a high intertemporal elasticity of substitution, real wages will increase following the shock while a low elasticity will generally induce a decline in real wages. Given the importance of this parameter in generating the required results, the next section briefly discusses this issue in relation to the specification of preferences.

3.5 Specification of preferences

As discussed above, a low intertemporal elasticity of substitution γ helps significantly in obtaining an expectation led economic boom. This is particularly true if one does not want to rely on the flow specification of adjustment costs. This finding is not specific to the model economy presented in this paper. For example, Den Haan and Kaltenbrunner [2007] obtains an joint increase in consumption and investment only for values of γ in the range of 0.45 to 0.5. For values below 0.45, investment increases and consumption decreases whereas the responses are reversed when $\gamma > 0.5$. Given her estimates of the degree of interdependence between wealth and consumption and the status-seeking motive, Karnizova [2007] needs $\gamma < 0.5$ to obtain an expectation driven business cycle. While a low value of γ helps, it might seem inconsistent with the observed distaste for intertemporal substitution (high value of γ) mentioned in Weil [1990]. Adding habit formation can be thought of as one way to go about imposing a low value of γ while preserving a smooth profile for consumption.

There is still the possibility that the expected utility specification of preferences is itself the cause of the problem. In this setup, the intertemporal elasticity of substitution is constrained to be the reciprocal of the coefficient of relative risk aversion. This restriction is purely mechanical and is devoid of any economic content. Partly, this mechanical restriction explains the prevalence of logarithmic preferences in consumption in the business cycle literature. An interesting extension of the present paper would be to use a class of preferences which models these two attributes of consumer's taste independently. Such preferences, called nonexpected utility preferences, have been introduced in the macroeconomic literature by Weil [1990] and Epstein and Zin [1989],Epstein and Zin [1991]. In a way, the spirit of capitalism assumption used by Karnizova [2007] allows her to do just that. Examples of models of business cycles that successfully used nonexpected utility preferences include Koskievic [1999], Normandin and St-Amour [1998] and Tallarini Jr. [2000]. In the context of this paper, the use of nonexpected utility would also allow to gauge the relative contribution of risk aversion and intertemporal substitution in generating EDBC. As one might have conjectured, however, nonexpected utility would not be enough in itself to generate an economic expansion following positive news about future productivity gains.

3.6 Conclusion

Given the growing recognition of news about future productivity improvement as a source of business cycle fluctuations, it becomes important to develop models that can generate sensible economic fluctuations following such news, something typical models of the business cycle can not do. This paper proposes a model economy that can generate increases in consumption, investment, output and hours following good news about future productivity improvements. The model is a simple extension of the canonical RBC model with two types of goods, consumption and investment. To obtain this expectation driven business cycle, the good news about future productivity gain must lead to an increase in investment demand and this increase must be satisfied with an increase in labor, not a reduction in consumption. In the environment presented, three ingredients are required to obtain the desired result in a very general case. The most important ingredient is the presence of cost complementarities in production. Cost complementarities means that the marginal cost of producing one type of goods decreases as the production of the other type of goods increases. This gives an incentive to *jointly* produce both types of goods, allowing for positive co-movements between consumption, investment and output. Second, complementarity between capital and labor will lead to an increase in investment demand following good news about future productivity. This happens because unless the required amount of capital is already put in place when the expected productivity gain hits the economy, agents will not be able to fully beneficiate from it. Finally, habit formation in consumption will give an incentive to agents to start working more when they learn of the expected gain in productivity because with habit formation, the marginal utility of leisure is increasing in future consumption. This serves as an amplification mechanism in the model.

Some interesting findings are worth mentioning. First, the ability of the model to generate an expectation driven business cycle depends significantly on the intertemporal elasticity of substitution in consumption. If one is willing to assume a high intertemporal elasticity of substitution, then cost complementarities alone are sufficient to obtain the desired result. The need to include complementarity between capital and labor as well as habit formation in consumption arises when preferences are logarithmic in consumption, a standard case in the business cycle literature. This specification prevails because this literature usually adopt preferences of the expected utility type which force the intertemporal elasticity of substitution in consumption to be the reciprocal of the relative risk aversion. An interesting extension of the paper would be to use preferences which model these two concepts separately. Finally, it was shown that the model can generate an EDBC where the real wage expressed in terms of consumption either increasing or decreasing. In fact, the model can generate economic fluctuations where there is no correlation between hours and the return to labor. Of course, the relevant parametrization to be used is ultimately a matter of estimation, an exercise left for future research.

Tables and figures

Table

Table 3.1: Parameter values for MAC model

β	δ	η	θ	γ	ϑ_0	a	b
0.99	0.025	0.0	0.36	0.25/1.0	h=1/3	1.0	1.0

Figures

Figure 3.1: Response of canonical RBC model to an announcement at time 1 of a future permanent shock in technology and no realization of the shock at time 4. Solid line is $\gamma = 1.0$, dashed line is $\gamma = 0.25$.

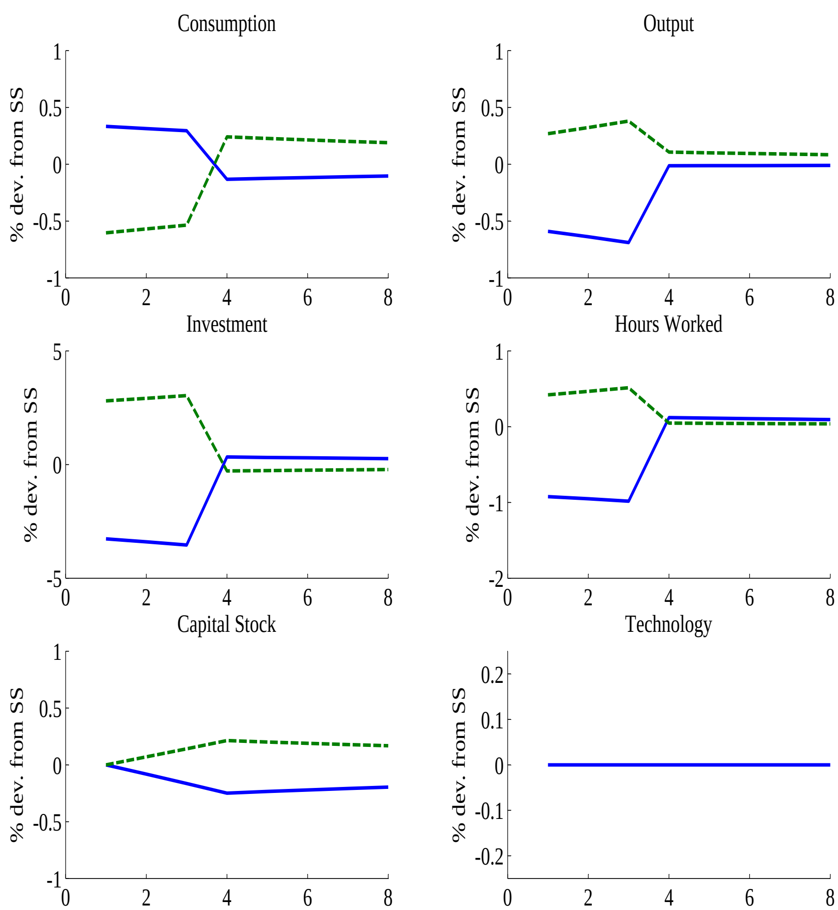


Figure 3.2: Response of MAC model to an announcement at time 1 of a future permanent shock in technology and no realization of the shock at time 4. Solid line is $\gamma = 1.0$, dashed line is $\gamma = 0.25$, $\sigma = 1.8$.

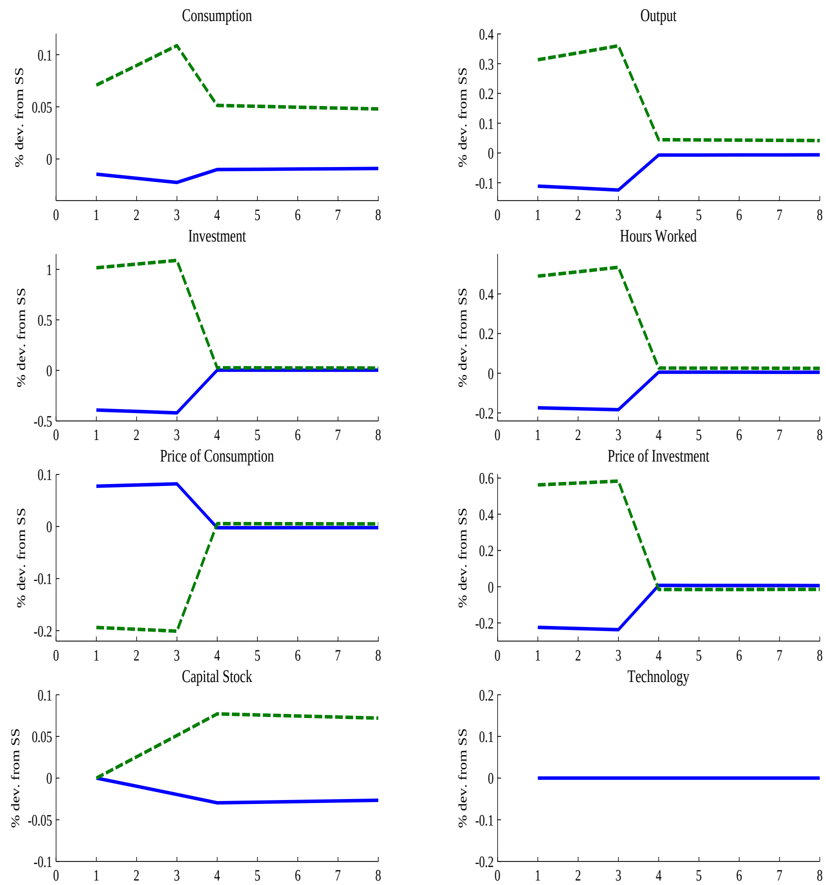


Figure 3.3: Response of MAC model with complementarity in production to an announcement at time 1 of a future permanent shock in technology and no realization of the shock at time 4. Solid line is $\sigma = 1.8$, dashed line is $\sigma = 3.0$, $\mu = -1.2$.

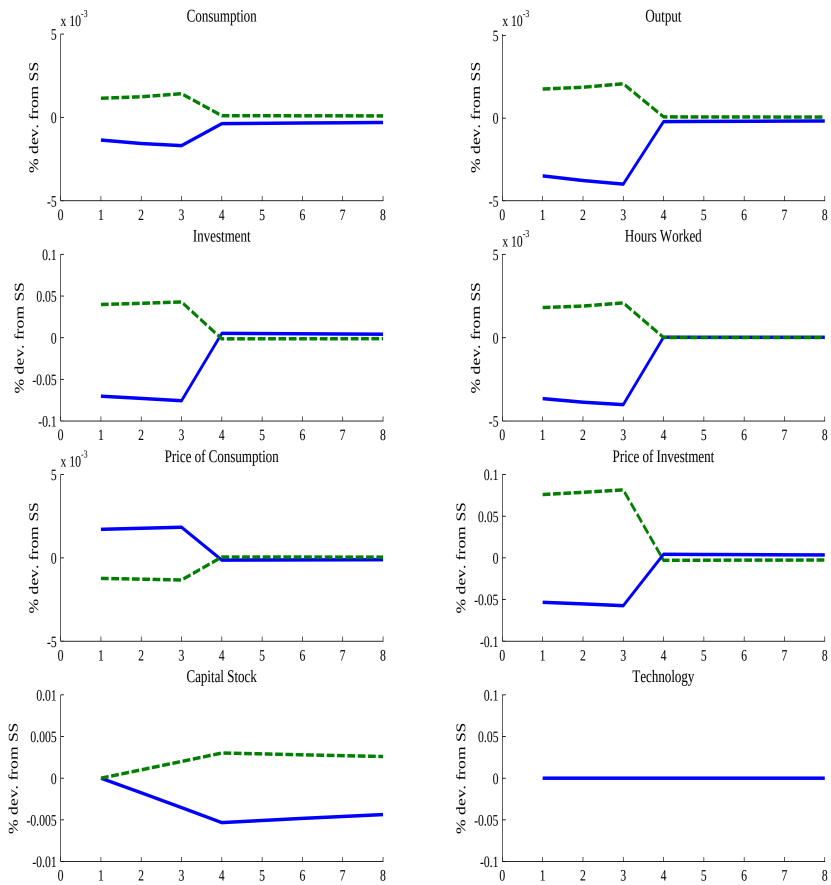


Figure 3.4: Response of MAC model with complementarity in production to an announcement at time 1 of a future permanent shock in technology and no realization of the shock at time 4. Solid line is $\sigma = 1.8$, dashed line is $\sigma = 3.0$, $\mu = -2.0$

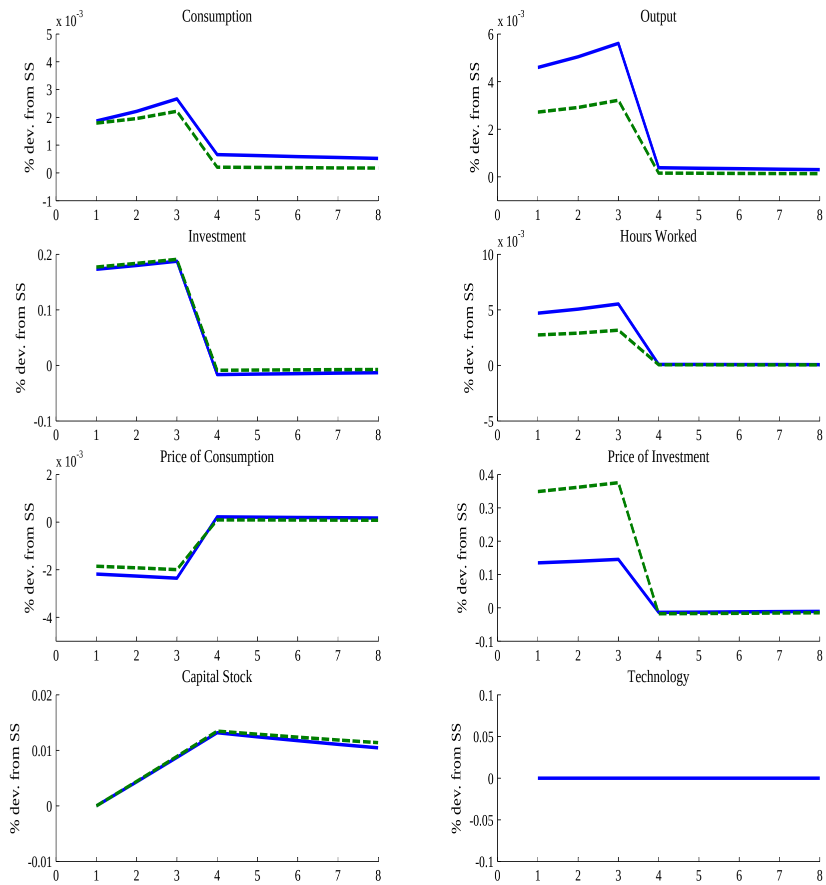


Figure 3.5: Response of MAC model with complementarity in production and habit formation in consumption to an announcement at time 1 of a future permanent shock in technology and no realization of the shock at time 4. Solid line is $g = 0.25$, dashed line is $g = 0.63$, $\mu = -1.2$. Preferences logarithmic in consumption. $\sigma = 3.0$.

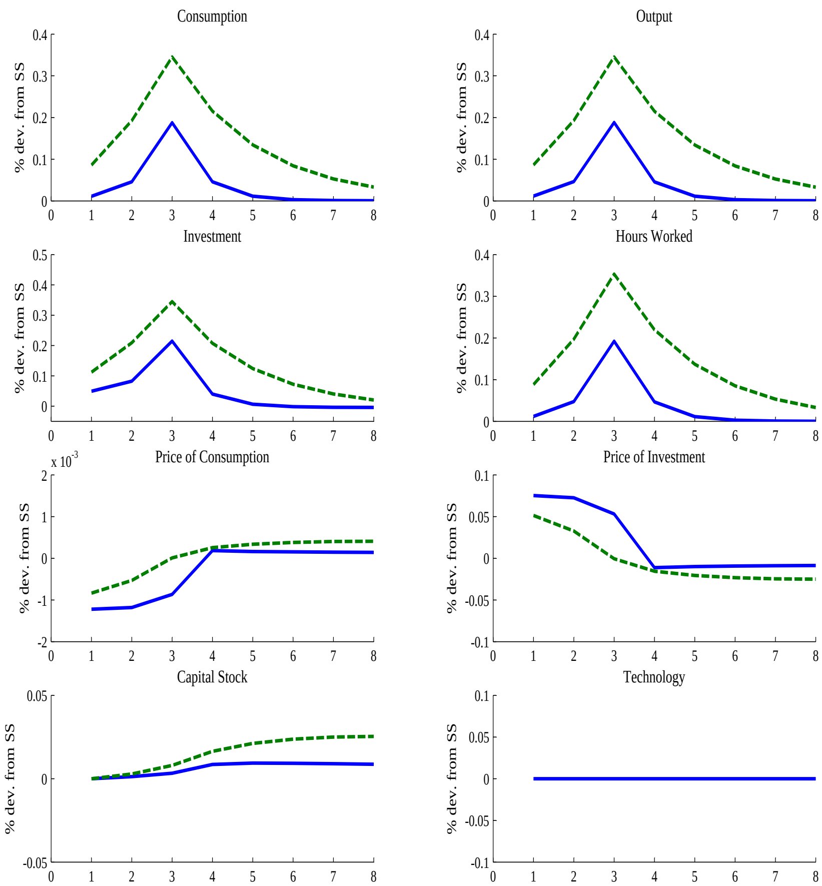


Figure 3.6: Response of MAC model with complementarity in production and habit formation in consumption to an announcement at time 1 of a future permanent shock in technology and no realization of the shock at time 4. Solid line is $g = 0.25$, dashed line is $g = 0.63$, $\mu = -2.0$. Preferences logarithmic in consumption. $\sigma = 3.0$.

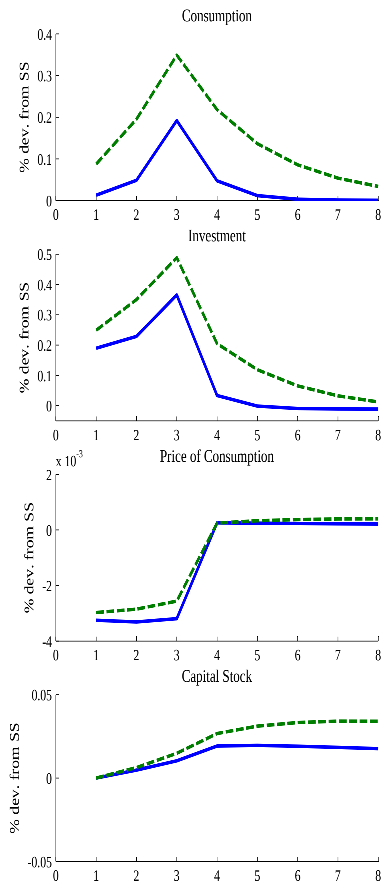


Figure 3.7: Price of capital in terms of consumption in MAC model with complementarity in production and habit formation to an announcement at time 1 of a future permanent shock in technology and no realization of the shock at time 4. Solid line is $g = 0.25$, dashed line is $g = 0.63$, $\mu = -1.2$, $\sigma = 3.0$.

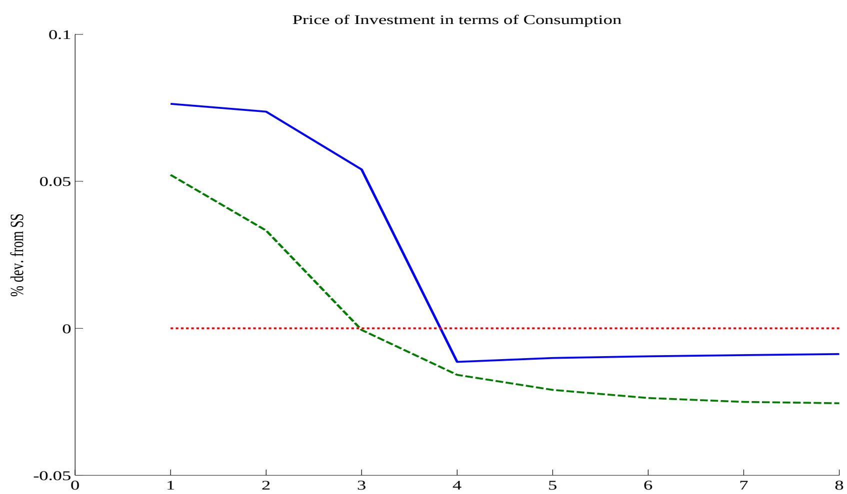


Figure 3.8: Price of capital in terms of consumption in MAC model with complementarity in production and habit formation to an announcement at time 1 of a future permanent shock in technology and no realization of the shock at time 8. Solid line is $g = 0.25$, dashed line is $g = 0.63$. $\mu = -1.2$. $\sigma = 3.0$.

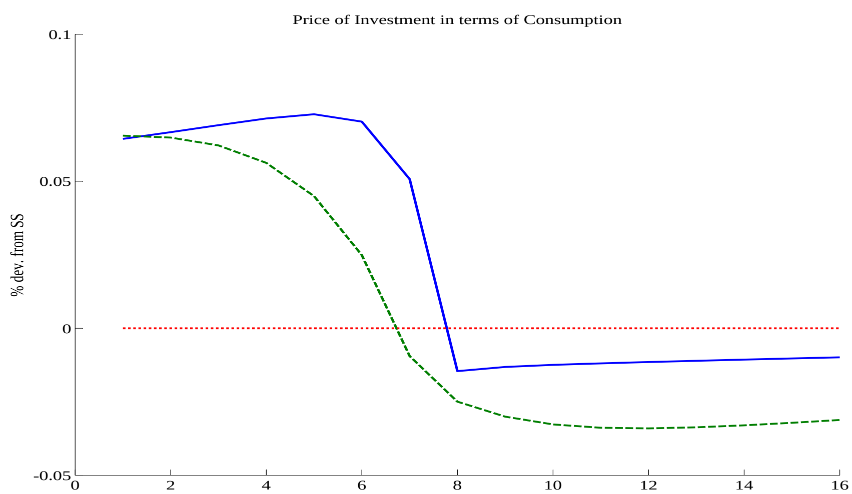


Figure 3.9: Price of capital in terms of consumption in MAC model with complementarity in production and habit formation to an announcement at time 1 of a future permanent shock in technology and no realization of the shock at time 4. Solid line is $g = 0.25$, dashed line is $g = 0.63$, $\mu = -2.0$, $\sigma = 3.0$.

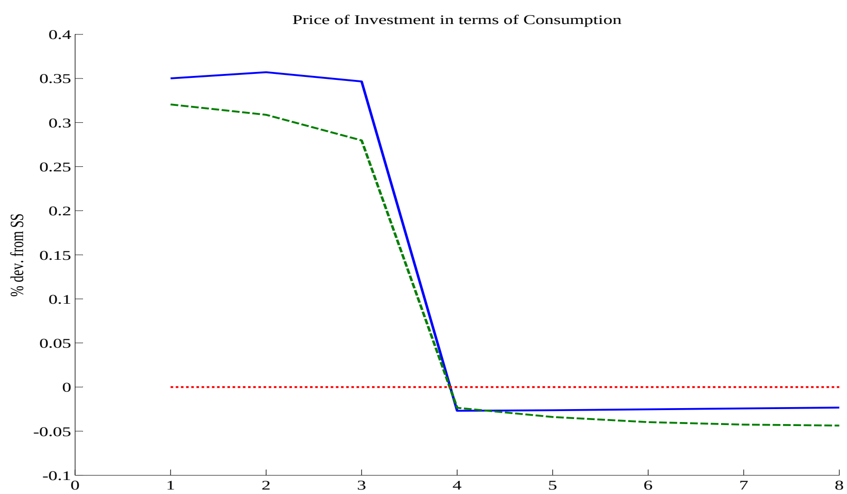


Figure 3.10: Response of MAC model to an announcement at time 1 of a future permanent shock in technology and no realization of the shock at time 4. Real wage in terms of consumption stable.

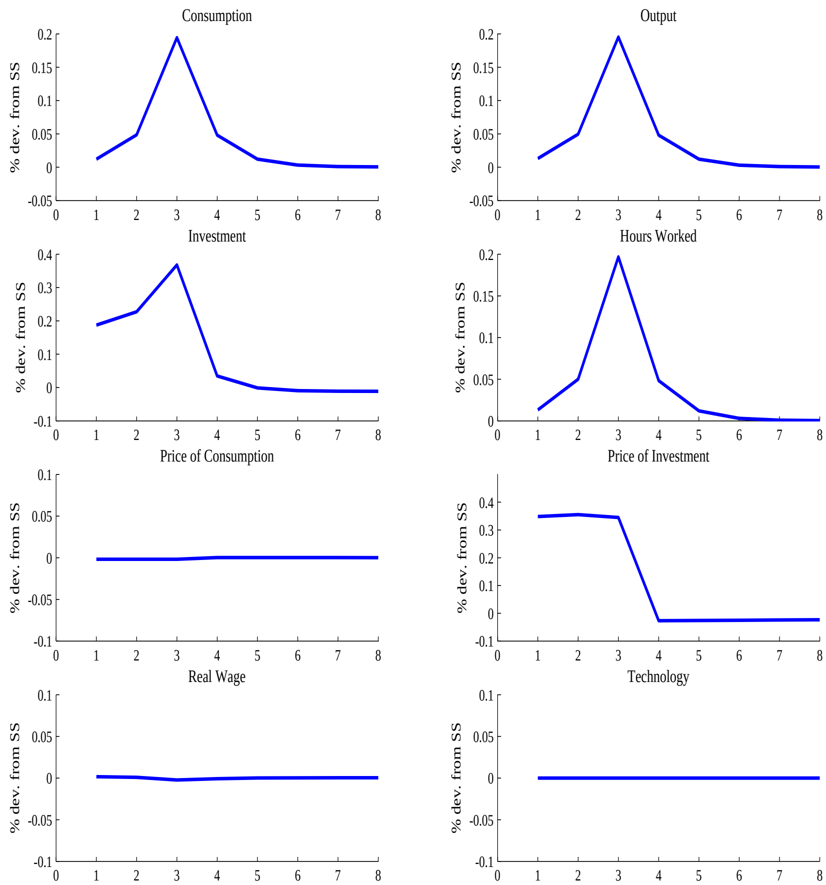


Figure 3.11: Response of MAC model to an announcement at time 1 of a future permanent shock in technology and no realization of the shock at time 4. Real wage in terms of consumption increases.

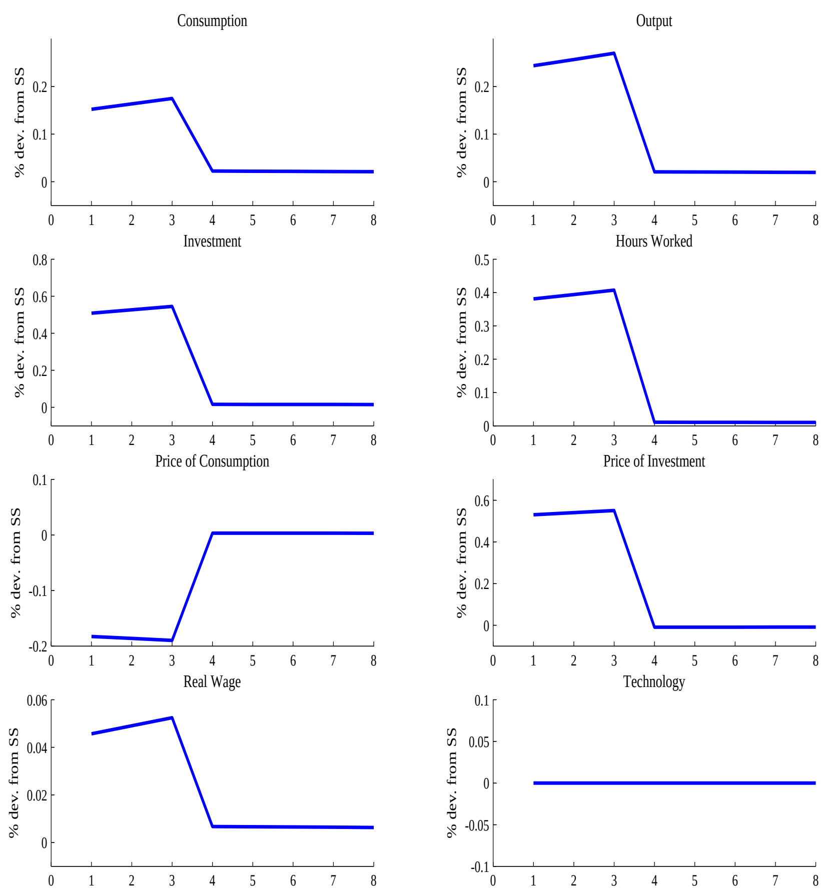
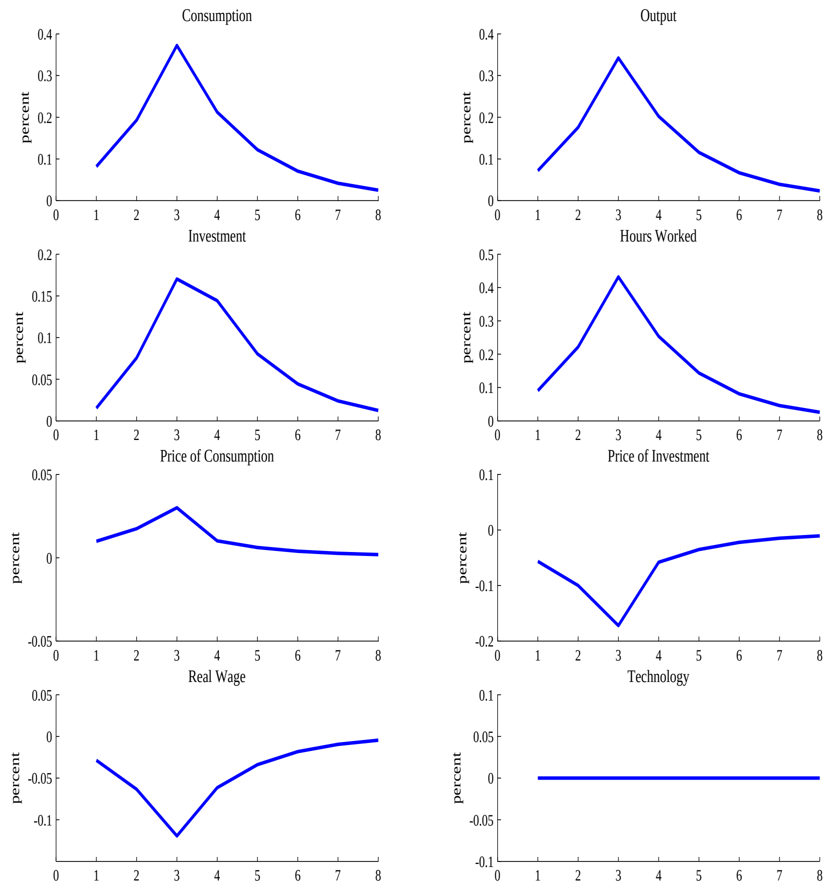


Figure 3.12: Response of MAC model to an announcement at time 1 of a future permanent shock in technology and no realization of the shock at time 4. Real wage in terms of consumption falls.



4. Distribution Systems and Expectation Driven Business Cycles.

4.1 Introduction

The investment boom and bust experienced by the United States and many other countries around the globe between 1994 and 2003 has rekindled an idea that can be traced back to Beveridge [1909] and Pigou [1926], namely that changes in expectations can spur business cycle fluctuations. More specifically, many analysts believe that the story underlying the aforementioned economic episode can be told along the following lines. Agents receive a signal that lead them to be optimistic about the future profitability of investment. This triggers an investment boom and an economic expansion. When profitability fails to live up to expectations, there is an investment bust and an economic slowdown. Karnizova [2004] shows formally that revisions in expectations about future technological progress was (at least partially) responsible for the investment bust between 2000 and 2003. Rotemberg [2003], Beaudry and Portier [2004], Beaudry and Portier [2005] and Fujiwara et al. [2008] provide evidence that changes in agents' expectations about the future are an important source of business cycle fluctuations in general. These findings provide support for what may be called the "news view" of aggregate fluctuations.

With the growing recognition of changes in expectations, or news shocks[35], as an important source of business cycle fluctuations, it seems only natural to expect any relevant model of the business cycle to be able to generate such fluctuations. More specifically, one would want models capable of gen-

[35] In a very broad sense, news shocks represent any information that helps to predict future economic fundamentals without affecting current fundamentals.

erating increases in consumption, investment, output and hours following a change in expectations about *future* productivity, even if current fundamentals remain unaltered. As shown analytically in Beaudry and Portier [2007], canonical one and two sectors neoclassical equilibrium growth models can not generate the kind of positive co-movements observed in a typical business cycle following changes in expectations about future total factor productivity[36].

To obtain pro-cyclical consumption, investment, output and hours following news shocks, the so-called expectation driven business cycle (EDBC), one needs to satisfy two conditions: (1) news about future productivity must lead to an increase in investment demand and (2) this increase in investment demand is satisfied by an increase in hours worked and not a reduction in consumption. Recently, theoretical contributions capable of generating such EDBC were developed, see for example Beaudry and Portier [2004], Christiano et al. [2007], Jaimovich and Rebelo [2006], Karnizova [2008], Nadeau [2008] and Den Haan and Kaltenbrunner [2007]. One important finding of this literature is that no single change to the canonical RBC model is generally sufficient to generate an EDBC. As emphasized by Beaudry and Portier [2004] and Den Haan and Kaltenbrunner [2007], the main challenge in building a model that can generate EDBC is to find a way to satisfy condition (2).

This paper presents and estimates a model of the business cycle augmented with a costly distribution system that is capable of generating EDBC. This distribution system represents all the necessary steps required to bring a good from its production location to its final consumption place. These steps include, for example, transportation, wholesale and retail services, financial intermediation, marketing etc. The main characteristic of the distribution system that allows the model to generate EDBC is the presence of cost complementarities in the distribution of the various goods in the economy. Cost complementarities in distribution means that the marginal cost of distributing one type of goods decreases as the distribution of the other type of goods increases. In the context of a distribution system, cost complementarities appears quite natural. For example, one can easily conceive that wholesalers distribute both types of goods using common staff or that distribution equipments such as trucks are used to distribute one type of goods in one direction and another type of goods in the other direction.

[36] Beaudry and Portier [2007] is only one example of authors having shown this result. In fact, this finding had already been anticipated by Barro and King [1984].

Betancourt and Gautschi [1988] discuss the financial incentive generated by the exploitation of economies of scope (cost complementarities) in the distribution of goods by retailers.

The idea that introducing cost complementarities through a distribution system can help in generating an EDBC was first suggested in Beaudry and Portier [2007]. There, they showed that if there is enough cost complementarities in the distribution system, news about future productivity gains can generate positive co-movements between consumption, investment, output and hours. However, Nadeau [2008] shows, in a context slightly different from the current one, that while it is true that cost complementarities generate positive co-movements between these quantities, these co-movements are generally in the *wrong* direction unless one is willing to admit a large intertemporal elasticity of substitution[37]. For example, with standard logarithmic preferences in consumption, news about future productivity gains will generate a *decline* in all the aggregates. In the current setting with a distribution system, adding complementarity between productive factors in production and preferences that are not time-separable helps in obtaining an EDBC in the more general case.

Using a distribution system to generate news driven business cycles has some advantages over alternative mechanisms found in the literature. First, distribution services are clearly required in any real life economy. The next section will provide some empirical estimates of distribution costs for the US economy. There, it will be shown that these costs can be substantial, up to 80% of the final price in the case of some agricultural products. Second, distribution systems have been used extensively in the international macroeconomics literature to help account for various phenomena. To cite some examples, Burstein et al. [2003] advocate the explicit use of a distribution system to help account for the magnitude of real exchange rate movements during periods of exchange-rate based stabilizations. They also conjecture that the introduction of a distribution system might help in explaining the fact that cross-country correlation of output is higher than that of consump-

[37]More precisely, the argument of Beaudry and Portier [2007] is that EDBC are possible if the transformation curve between the consumption and investment goods is sufficiently nonlinear. Adding a distribution system is one way to introduce this nonlinearity. An alternative mechanism is to postulate a production function with multi-sectoral adjustment costs as in Kim [2003] and Huffman and Wynne [1999] for example. Even in this alternative environment, consumption, investment, output and hours will generally co-move in the wrong direction unless there is a high intertemporal elasticity of substitution in consumption.

tion and the fact that consumption is too smooth in a small open economy with standard preferences. Although they focus on costs of distributing internationally traded goods only[38], Obstfeld and Rogoff [2000] show formally that these costs can help solve some important price and quantity puzzles such as home bias in trade, the home bias portfolio puzzle and the purchasing power parity puzzle. In contrast, to the best of the author's knowledge, the business cycle literature has not made use of distribution systems in any significant way. It is interesting to note, however, that they can help in solving one important shortcoming of this literature. There is a sense, then, in which this paper bridges, in a limited sense, a gap between these two branches of the economic literature.

Finally, if one is actually willing to accept a high degree of intertemporal substitution in consumption, adding a distribution system displaying cost complementarities is the only modification required in the canonical RBC model to be able to obtain EDBC. This is in contrast to alternatives in this new literature which typically require more elaborate combination of ingredients such as adjustment costs to capital combined with modifications on preferences for example. It is worth noting that empirically, GMM estimation of the intertemporal elasticity of substitution using aggregate data typically suggests a high degree of intertemporal substitution. See Mankiw et al. [1985], Ghysels and Hall [1990] and An et al. [2007] to name a few examples. On the other hand, these estimates are usually very imprecise and quite unstable. Moreover, this finding of a high intertemporal elasticity of substitution in consumption appears at odd with empirical evidence which suggests that agents have a considerable distaste for intertemporal substitution in consumption (Weil [1990]). Consequently, the model to be presented will comprise more ingredients that help to generate EDBC in the fully general case: 1) the model allows for complementarity between capital and labor in the aggregate production function and 2) preferences display internal habit formation in consumption. The complementarity between productive factors gives an incentive to start accumulating capital immediately following news of higher future TFP while habit formation in consumption amplifies the response of hours to news shocks since in that case, hours depend *positively* on future consumption. Note that ultimately, the relevant parameterization of the model is decided in the estimation phase.

The remainder of the paper is organized as follow. Section 4.2 presents

[38] Narrowly, transport costs but more broadly, tariffs, nontariff barriers and other trade costs.

stylized facts about the importance of distribution costs in the US economy. Section 4.3 introduces formally the model and discusses its various components. Section 4.4 presents the estimation strategy and evaluate the quantitative predictions of the estimated, in terms of business cycle statistics and in terms of responses to news shock. Finally, 4.5 concludes.

4.2 Empirical evidence on distribution costs

This section documents the importance of distribution costs in the US economy by presenting various summary statistics. To understand the data to be presented, it is useful to clarify what is meant by a distribution system. It is at first tempting to reduce a distribution system to the transportation industry, but clearly there is more to it. As emphasized by Betancourt [1993], the general function of distribution systems "is to transfer goods and services from producers to consumers in an efficient manner." In most societies, this implies that distribution systems generally include many specialized institutions that perform specific services such as wholesaling and retailing, marketing and advertising as well as local transportation services. Betancourt [1993] provides a conceptual but exhaustive discussion of distribution systems and their role in the economy. Lancioni and Pirog III [1997], by comparing US and Japan distribution systems, show that the same conceptual idea can lead to quite different real-life counterparts. This paper considers a distribution system at the level of generality proposed by Betancourt [1993].

Given that it is quite difficult to summarize such complex systems with the help of only a few simples statistics, various sources of data will be used to give an indication of the importance of distribution costs. The data presented are essentially an updated version of those presented in Burstein et al. [2000] and Burstein et al. [2003]. The section will show that distribution costs are fairly large for typical consumption goods and less so for investment goods. To measure the importance of these costs, I follow Burstein et al. [2003] and use various measures of the distribution margin defined as

$$\text{Distribution Margin} = \frac{(\text{Retail Price} - \text{Producer Price})}{\text{Retail Price}}$$

It is important to note that the distribution margin is measures as a fraction of the retail price. Thus a 50 percent margin means that half of the retail price represents production costs and the remaining 50 percent represents distribution costs. The distribution margin as defined above is calculated using the following sources 1) data on distribution margins for agricultural products, 2) the Census of Wholesale and Retail Trade data and 3) the Input-Output tables. While data on agricultural products are well suited to illustrate the point that distribution costs can be substantial, the empirical exercise of section 4.4 will rely mostly on data sources 2) and 3).

4.2.1 Distribution margin for agricultural products

Although it is clear that agricultural products represent a very small portion of a typical consumer's basket and thus are far from representative, they serve well in illustrating that distribution costs can be substantial. For a typical market basket of food bought in food stores, the United States Department of Agriculture finds that overall distribution costs represent about 80% of the retail price of the basket in 2002. Detailed data per broad category of food are presented in Table 4.1 for the same year. Moreover, a time series analysis of this data shows that overall distribution margins have tended to increase over time for all product categories.

4.2.2 US census of wholesale and retail trade

The second source of information on distribution margins is the US Census of Wholesale and Retail trade. Table 4.2 reports distribution margins for the wholesale and retail sectors for three aggregates: all goods, durable goods and nondurable goods. Margins are calculated as gross margin in percent of sales. The distribution margin is calculated for a good that goes through one wholesaler and one retailer[39]. Data reported are for the year 1998, since it is the last year for which the Census of Retail Trade reports data for durable goods and nondurable goods aggregates, which makes the comparison with the wholesale trade data possible[40]. As one can see, distribution margins are quite important, representing almost 50% of the retail price of a good. This means that almost the same amount of resources has to be spent on bringing the goods to their final consumption place than the amount of resources required to build the goods.

[39] Calling m^W the wholesale margin and m^r the retail margin, the distribution margin is calculated as $1 - (1 - m^w)(1 - m^r)$.

[40] Wholesale trade data still report margins for these aggregates

4.2.3 Input-output tables

The last source of data considered to measure the importance of distribution costs is the annual Input-Output tables for the US economy. Two different measures of the importance of distribution costs can be calculated from these tables. The first is the share of value added in the total industry output of the retail, wholesale, transportation and warehousing industries. This data is reported in table 4.3 for the year 2006. In the table, the distribution margin is calculated as (total value added - taxes and subsidies)/(total industry output - taxes and subsidies).

The table shows again that goods that need distribution experience a substantial increase in price. The distribution margin calculated for the distribution industry (last column of table 2.3) shows essentially that the price of a good doubles after going through the distribution process. These numbers are in line with those obtained using the Census of Wholesale and Retail Trade.

It is also possible to use the Input-Output matrix to calculate the distribution costs embedded in the purchaser's price values of various personal consumer expenditure and gross private fixed investment components of the National Accounts. This is especially useful because this provides a basis for evaluating whether or not the estimated distribution costs component of the price of consumption and investment obtained from the model are reasonable. For consumption expenditures, we focus on expenditures provided by agriculture, forestry, fishing and hunting, mining, manufacturing and used and second hand goods. These are the components for which explicit data are compiled. These components comprise mostly goods. In the case of services, the distribution margin reported by the BEA is typically zero, because producers of services often sell directly to consumers. However, this is not to say that services prices do not include a distribution service component in the sense adopted above. To quote Betancourt [1993], one can see service providers as a

> ... multi-product firm that produces a set of explicit items to be transferred to the consumer together or jointly with a set of distribution services that also play the role of outputs of the firm.

Relevant distribution services include, to name a few, accessibility of location, number of product lines, variety within a product line or delivery of the product at the consumer's desired time. These are all services provided by service producers, for which the money value is not explicitly accounted for. For example, banks typically offer a variety of credit cards with different characteristics, many branches with extended opening hours and mobile mortgage specialists. Real estate agents and insurance brokers will also typically offer flexible hours and be mobile to accommodate their clients' needs. As such, even though no objective quantitative measure of the distribution margin for service providers appear available, one has to recognize their existence. For the purpose of evaluating the importance of distribution costs, however, focus is centered on available data.

Table 4.4 shows the distribution margin for each consumption expenditure components aforementioned. Specifically, the table shows the value of each component evaluated at producer's prices and at purchaser's prices as well as the change in value due to transportation, wholesaling and retailing. For the manufacturing component of gross private fixed investment, the sole component of investment for which data is available, one obtains the results presented in table 4.5. From these tables, one sees that distribution costs are especially important for consumption goods, while less so for investment goods. Yet, in both cases they are non-negligible.

Altogether, the data presented above suggests that appending a distribution system to the canonical RBC model is a natural and economically relevant extension. In particular, nearly as much resources have to be spent to bring consumption goods to their final use as must be spent to produce them. When it comes to investment goods, the distribution costs is less important yet significant. This difference in distribution costs is a feature of the data that the model to be presented in the next section will attempt to reproduce.

4.3 The model

The model introduced in this section is a simple extension of the standard RBC model with one stock of capital. The consumer derives utility from consumption (C) but dislikes work (H). There is a composite output (Y) which can be used for consumption or investment (I) purposes. The main addition of the model is the presence of a distribution system required to bring goods to their final users. Since the model preserves the competitive market paradigm, it will be presented as a planner's problem.

4.3.1 Household sector

The economy is populated by an infinitely lived representative household that maximizes its expected discounted utility

$$\max\ \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{(C_t - gC_{t-1})^{1-\gamma}}{1-\gamma} - \frac{\vartheta_0}{\eta+1} H_t^{\eta+1} \right] \tag{4.1}$$

where β is the discount factor, C_t denotes consumption and H_t denotes hours worked. ϑ_0 is a positive constant. $\mathbb{E}_0 = \mathbb{E}(.|\mathcal{F}_0)$ represents the expectation operator conditional on the information set available at time 0. η is the inverse of the Frisch wage elasticity of labor supply. γ is the inverse of the intertemporal elasticity of substitution in consumption. The parameter g captures the degree of habit persistence in consumption. When $\gamma = 1$, $g = 0$ and $\eta = 0$, we have preferences of the Hansen-Rogerson type. The reason for considering the possibility of habit formation in consumption is that it amplifies the response of the economy to news shocks, as illustrated in Nadeau [2008]. This point is further discussed in section 4.4.3, when the response of the model to news shocks is analyzed. Nevertheless, it is worth noting immediately that habit formation is not necessary for this model to be able to generate expectation driven business cycles.

4.3.2 Production sector

The composite output of the economy is produced using capital K_t and labor H_t according to the production function

$$Y_t = \left(\theta^{1-\mu} K_t^{\mu} + (1-\theta)^{1-\mu} (A_t H_t)^{\mu}\right)^{\frac{1}{\mu}} \tag{4.2}$$

where $0 < \theta < 1$ and $\mu \leq 1$. The parameter μ captures the elasticity of substitution between capital and labor. The case $\mu = 0$ corresponds to the Cobb-Douglas production function[41]. A_t represents labor-augmenting technological progress. Following Christiano et al. [2007], technological progress evolves according to

$$\ln A_t = \rho \ln A_{t-1} + \xi_{t-p} + e_t \qquad 0 < \rho < 1 \tag{4.3}$$

[41] Formally, the elasticity of substitution between capital and labor is given by $1/(1-\mu)$.The Cobb-Douglas production function corresponds to the case of a unitary elasticity of substitution.

where ξ_t and e_t are uncorrelated white noise processes with respective variances s_ξ^2 and s_e^2. The presence of ξ_{t-p} means that impulses to technological progress are partly anticipated p periods in advance. This specification of technological progress can be interpreted as follow. Every period t, agents receive signals about technological progress expected p periods from now (ξ_{t-p}) and update the expectation they formed about today's technological progress p periods ago (e_t). This process is obviously a crude way to introduce news shocks in the model as agents would normally continuously update their expectations about the future. For estimation purposes, on the other hand, this parsimonious specification proves convenient.

At this point, it is worth discussing further the role played by the CES specification of the production function in generating expectation driven business cycles. As mentioned above, the presence of cost complementarities allows for positive co-movements between consumption, investment, output and hours. However, unless there is a high degree of intertemporal substitution in consumption, these quantities will generally decline following news about future productivity gain if the production function is of the typical Cobb-Douglas form. This is the case observed when preferences are logarithmic in consumption because, in this instance, news about future productivity gain would normally stimulate consumption through a wealth effect. Ultimately, consumption ends up falling because the news shock also leads to an increase in the relative price of consumption. This finding is analyzed thoroughly in Nadeau [2008].

The reason why the news shock stimulates consumption when preferences are logarithmic and the production function is of the Cobb-Douglas form is that agents can fully beneficiate from the productivity gain by simply working harder when the shock hits the economy and therefore choose to satisfy their desire for a smooth consumption profile. To obtain an economic boom even when preferences are logarithmic, the news shock must induce an increase in investment, not consumption. One way to do so is to introduce complementarity between capital and labor in production. With complementarity between productive factors, agents will fully beneficiate from the expected productivity gain only if the appropriate amount of capital is in place when the shock hits. An extreme example would be the Leontief production function. In such a case, unless the appropriate amount of capital is in place when the shock hits the economy, working harder would bring no benefits to workers. Therefore, complementarity between capital and labor gives an incentive to start accumulating capital before the productivity gain is expected to hit the economy. With enough complementarity, the news shock will induce an increase in investment, thus allowing an economic expansion. In the contributions of Christiano et al. [2007] and Jaimovich and Rebelo [2006], the incentive to accumulate capital is achieved by introducing investment adjustment costs that penalize changes in the level of investment. Section 4.4.3 discusses why this approach seems less desirable. In the end, if the estimation procedure favors a low intertemporal elasticity of substitution, the model will be able to generate EDBC if, at the same time, the estimation procedure favors a high enough level of complementarity between capital and labor.

4.3.3 Distribution costs

Before consumption and investment can take place, some of the composite output must be used to distribute these goods to their final users. As discussed in section 4.2, this distribution cost captures functions that are various in nature such as shipping, wholesaling, retailing, marketing and advertising to name a few. In this model, distribution costs are modeled in a very simplistic way and comprises three elements: the cost of building the distribution infrastructure, the cost of distributing the consumption good and the cost of distributing the investment good.

Specifically, every period a distribution infrastructure is built at a cost, in terms of composite output, equal to N_t. This infrastructure is used to distribute both the consumption and the investment goods. Since their demand is generally different, the infrastructure will be used more intensively to deliver the goods that is relatively more in demand. Denote by $\mu_{c,t}$ the intensity of use of the distribution infrastructure in delivering the consumption goods and by $\mu_{i,t}$ the intensity of use of the distribution infrastructure in delivering the investment goods. It is assumed that the cost of distributing the consumption and investment goods, in terms of composite output, is given by

$$\frac{a^{1-\sigma}}{\sigma} N_t \mu_{c,t}^{\sigma}$$

and

$$\frac{b^{1-\sigma}}{\sigma} N_t \mu_{i,t}^{\sigma}$$

respectively, where $\sigma > 1$ and $a, b > 0$. The restriction $\sigma > 1$ implies that distribution costs are convex in the intensity of use. This captures phenomena like wear and tear of the infrastructure as well as overtime pay for workers[42]. The parameters a and b allow for differing costs of delivering the consumption and investment goods, as the data presented in section 4.2 suggests. Because the consumption and investment goods must be delivered during the period in which they are produced, it is assumed that $N_t\mu_{c,t} = C_t$ and that $N_t\mu_{i,t} = I_t$. At the end of the period, the distribution infrastructure becomes obsolete. Of course, a more realistic model would include a stock of distribution infrastructure as well as investment in infrastructure. For the purpose of the present paper, however, the simpler set up presented suffices.

Thus, every period, the total composite output cost of building the distribution infrastructure and delivering the goods is given by

$$\left[N_t + \frac{a^{1-\sigma}}{\sigma}N_t\mu_{c,t}^{\sigma} + \frac{b^{1-\sigma}}{\sigma}N_t\mu_{i,t}^{\sigma}\right]\mathcal{Q} \tag{4.4}$$

under the restrictions that

$$N_t\mu_{c,t} = C_t \qquad N_t\mu_{i,t} = I_t \tag{4.5}$$

The constant $\mathcal{Q}$ is added to control for the overall size of the distribution sector in the economy. The specific role of this constant will become apparent later. Therefore, given an amount C_t and I_t to deliver, the operator of the distribution system has to make a choice between the size N_t of the distribution infrastructure and how intensively she plans to use it, $\mu_{c,t}$ and $\mu_{i,t}$.

Along an optimal path, the planner will minimize the use of resources for distribution purposes. As such, one can first find how to efficiently distribute a given amount of C and I. The minimization problem to solve is

$$\min_{N,\mu_c,\mu_i}\left[N + \frac{a^{1-\sigma}}{\sigma}N\mu_c^{\sigma} + \frac{b^{1-\sigma}}{\sigma}N\mu_i^{\sigma}\right]\mathcal{Q} \tag{4.6}$$

subject to

$$N\mu_c = C \qquad N\mu_i = I$$

From this problem, one finds that the most efficient (least cost) way to distribute a given amount of consumption and investment goods, $\Phi(C, I)$, is given by

$$\Phi(C, I) = \mathcal{T}\left(a^{1-\sigma}C^{\sigma} + b^{1-\sigma}I^{\sigma}\right)^{\frac{1}{\sigma}} \tag{4.7}$$

[42]This restriction is also what allows the nonlinearity in the transformation curve between the consumption and investment goods which, in turns, can generate cost complementarities

where

$$\mathcal{T} = \mathcal{Q}\left(\frac{\sigma-1}{\sigma}\right)^{(1-\sigma)/\sigma}$$

The parameters a, b and $\mathcal{T}$ are necessary if the model is to produce distribution costs for the consumption and investment goods that are in line with the data while keeping the overall size of the distribution sector in the economy to reasonable proportions. This is where the constant $\mathcal{Q}$ is needed, otherwise total distribution costs become too sensitive to the parameter σ. In this model, the aggregate resource constraint of the economy becomes

$$C_t + I_t = \left(\theta^{1-\mu}K_t^{\mu} + (1-\theta)^{1-\mu}(A_tH_t)^{\mu}\right)^{\frac{1}{\mu}} - \mathcal{T}\left(a^{1-\sigma}C_t^{\sigma} + b^{1-\sigma}I_t^{\sigma}\right)^{\frac{1}{\sigma}} \quad (4.8)$$

As appears clearly from the above equation, the transformation curve between consumption and investment is nonlinear when $\sigma > 1$. To gain some intuition as to why increases in the size of σ can lead to cost complementarities, figure 4.1 graphs equation (4.7) for a unit distribution cost, $\Phi(C, I) = 1$, for various values of σ. In the figure, $a = b = \mathcal{T} = 1.0$ without loss of generality. It appears easier to understand the intuition if one reads the figure horizontally. For a given level of consumption goods to deliver, it is possible to increase the amount of investment good distributed without changing the overall distribution cost when σ increases. That is, if the planner must distribute a given amount of consumption good, she can afford to deliver more of the investment good for a same overall distribution cost if σ is larger. This is equivalent to saying that, for a given level of C, the marginal cost of delivering I is lower when σ is larger. This is why a nonlinear transformation curve can potentially lead to cost complementarities.

Another consequence of a nonlinear transformation curve is that the model generates fluctuations in the relative price of consumption and investment, a desirable feature given the observed data. More precisely, using output as the numeraire and denoting $\phi_t = \left(a^{1-\sigma}C_t^{\sigma} + b^{1-\sigma}I_t^{\sigma}\right)^{\frac{1}{\sigma}}$, the relative price of consumption writes as

$$p_t^C = [1 + \mathcal{T}a^{1-\sigma}\phi_t^{1-\sigma}C_t^{\sigma-1}] \quad (4.9)$$

while the relative price of investment is given by

$$p_t^I = [1 + \mathcal{T}b^{1-\sigma}\phi_t^{1-\sigma}I_t^{\sigma-1}] \quad (4.10)$$

As shown in appendix E, this economy will display cost complementarities if

$$\frac{(1-\mu)}{(\sigma-1)}\left(\frac{\theta}{(1-\theta)}\right)^{1-\mu}\left(\frac{K}{H}\right)^{\mu} < \frac{Y\ \mathcal{T} a^{1-\sigma} b^{1-\sigma} \phi_t^{1-2\sigma} C^{\sigma-1} I^{\sigma-1}}{p^C p^I} \tag{4.11}$$

where prices are as defined above. Clearly, cost complementarities are not possible if $\sigma = 1.0$ since the left hand side of equation (4.11) tends to infinity in that case, while the right hand side of the equation is bounded from above. Increases in σ makes it possible to satisfy the condition given by equation (4.11), although it is not true that increases in σ will always lead to cost complementarities. This happens because σ affects the right hand side of the relation in a highly nonlinear fashion, in particular the steady state value of each of the variables involved in the condition[43]. Numerical simulations show that it is generally easier to satisfy the relationship for value of σ in the range of 1.8 to 5.0, although this range also depends on the values of a, b, $\mathcal{T}$ and μ.

Competitive equilibrium

A rational expectation equilibrium for this economy is a set of stochastic processes $\{C_{t+j}, H_{t+j}, I_{t+j}, K_{t+j+1}\}_{j=0}^{\infty}$ such that 1) the representative household maximizes lifetime utility and 2) all market clears. Given K_0 and a stochastic process for A_t, equilibrium allocations are found by solving the planner‘s problem

$$\max\ \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{(C_t - gC_{t-1})^{1-\gamma}}{1-\gamma} - \frac{\vartheta_0}{\eta+1} H_t^{\eta+1}\right]$$

subject to

$$C_t + I_t + \mathcal{T}\left(a^{1-\sigma}C_t^{\sigma} + b^{1-\sigma}I_t^{\sigma}\right)^{\frac{1}{\sigma}} = \left(\theta^{1-\mu}K_t^{\mu} + (1-\theta)^{1-\mu}(A_tH_t)^{\mu}\right)^{\frac{1}{\mu}} \tag{4.12}$$

$$K_{t+1} = (1-\delta)K_t + I_t \tag{4.13}$$

$$H_t \leq 1 \tag{4.14}$$

[43]In analyzing the impulse response function of the estimated model, it is customary to start the simulation at the steady state position of the model. As such, it is the steady state value of the variables that matters in determining whether or not the model will generate EDBC.

The first order conditions characterizing the equilibrium are given by

$$(C_t - gC_{t-1})^{-\gamma} - \beta g \mathbb{E}_t (C_{t+1} - gC_t)^{-\gamma} = \lambda_t p_t^C \tag{4.15}$$

$$\vartheta_0 H_t^{1+\eta-\mu} = (1-\theta)^{1-\mu} \lambda_t A_t^{\mu} Y_t^{(1-\mu)} \tag{4.16}$$

$$\lambda_t p_t^I = \beta \mathbb{E}_t \lambda_{t+1} \left[\theta^{1-\mu} \left(\frac{Y_{t+1}}{K_{t+1}} \right)^{1-\mu} + (1-\delta) p_{t+1}^I \right] \tag{4.17}$$

where

$$p_t^C = [1 + \mathcal{T} a^{1-\sigma} \phi_t^{1-\sigma} C_t^{\sigma-1}]$$
$$p_t^I = [1 + \mathcal{T} b^{1-\sigma} \phi_t^{1-\sigma} I_t^{\sigma-1}]$$
$$\phi_t = \left(a^{1-\sigma} C_t^{\sigma} + b^{1-\sigma} I_t^{\sigma} \right)^{\frac{1}{\sigma}}$$

in addition to equations (4.12), (4.13), (4.14) and the transversality condition

$$\lim_{t \to \infty} \beta^t \lambda_t K_{t+1} = 0$$

λ_t is the multiplier associated with the aggregate resource constraint. One thing to note from these conditions is that since the model generates variability in the relative price of consumption and investment, it is the conditions expressed in terms of the consumption good that matters to the agent. In particular, the labor supply decision of the agent is influenced by the real wage expressed in term of consumption. This turns out to be important because some models in this literature predicts that the real wage in terms of consumption should increase following news shocks, while others predict a decline in the real wage. Having presented the model and the conditions characterizing its equilibrium, one can now estimate the model.

4.4 Quantitative evaluation of the model

As can be inferred from equation (4.11), the capacity of the model to generate expectation driven business cycles depends on the interplay between the parameters σ, μ, a, b and $\mathcal{T}$. As such, this section will first estimate the parameters of the model. This will allow to see if the parameter combination obtained is consistent with cost complementarities and EDBC for the model with a distribution system. Then, various second moments of the estimated model are calculated analytically and compared against their empirical counterparts to evaluate the success of the model in generating appropriate business cycle statistics. Finally, the dynamic response of the estimated model to news shocks is analyzed.

4.4.1 Estimation

The strategy employed to obtain point estimates for the structural parameters of the model is to use a combination of calibration and estimation. Estimation of the model is based on the linearized version of the model around its non-stochastic steady state. Appendix F details the required linearized equations. The complete set of model parameters is given by the 16×1 vector

$$\mathcal{P} = \{\beta,\, \gamma,\, \eta,\, g,\, \vartheta_0,\, \delta,\, \theta,\, \mu,\, \sigma,\, a,\, b,\, \mathcal{T},\, \rho,\, s_e^2,\, s_\xi^2, p\}'$$

This vector is usefully decomposed into the following two vectors

$$\mathcal{P}_1 = \{\beta,\, \eta,\, \vartheta_0,\, \delta,\, \theta,\}'$$

$$\mathcal{P}_2 = \{\gamma,\, g,\, \mu,\, \sigma,\, a,\, b,\, \mathcal{T}\, \rho,\, s_e^2,\, s_\xi^2, p\}'$$

The 5×1 vector $\mathcal{P}_1$ comprises structural parameters typically found in other business cycle models and their value should not be affected by the presence of the distribution system in the model. As such, their value will be set to typical values found in the literature. In particular, β is set such that the steady state annual rate of return to capital is 3.0%. The depreciation rate $\delta = 0.025$. η is set to zero so that there is an infinite Frisch elasticity of labor supply. The parameter measuring the disutility of labor ϑ_0 is set such that the steady state level of hours is equal to one third. Finally, $\theta = 1/3$.

The 11×1 vector $\mathcal{P}_2$ comprises structural parameters who have a direct impact on the capacity of the model to generate EDBC and/or for which the literature provides little or no guidance. These parameters are estimated using a generalized method of moments (GMM) approach[44]. The idea underlying this approach is to choose the parameter vector $\mathcal{P}_2$ such as to minimize the distance between moments of the data and their model counterparts. Specifically, call $\psi_T(\mathbf{w}, \mathcal{P})$ the difference between chosen empirical moments of the data $\mathbf{w}$ and their their model counterparts for a given calibration $\mathcal{P}$ and a sample of size T. Under the null that the model is a true representation of the data generating process (DGP), $\mathbb{E}(\psi(\mathbf{w}, \mathcal{P}_0)) = 0$, where $\mathcal{P}_0$ is the true parameter vector of the DGP. The generalized method of moment estimators is given by

$$\hat{\mathcal{P}} = \arg\min_{\mathcal{P}}\, \psi_T(\mathbf{w}, \mathcal{P})'\, \mathcal{W}_T\, \psi_T(\mathbf{w}, \mathcal{P}) \tag{4.18}$$

[44] For a comprehensive description of simulation estimators, see Canova [2007].

for some positive semi-definite and symmetric matrix $\mathcal{W}_T$. As shown by Ruge-Murcia [2007], an important advantage of GMM is that it is generally more robust to misspecification than maximum likelihood procedures.

In estimating the current model, the choice is made to minimize the distance between unconditional variances and covariances of the data and their model counterparts[45]. To obtain analytically the whole set of model variances and covariances from the solution of the fully calibrated model, one proceeds as follow. For a given parameterization $\mathcal{P}$, the distribution system model can be rewritten in log-linear form as

$$A(\mathcal{P})x_t = B(\mathcal{P})x_{t-1} + C\upsilon_t + D\nu_t$$

where $\mathcal{P}$ is the vectors of structural parameters of the model and x_t is the $n \times 1$ vector of model variables expressed in percentage deviation from steady-state. x_t is by construction a zero-mean covariance stationary process. υ_t is the vector of structural shocks while ν_t is the vector of expectational errors associated with the intertemporal optimality conditions of the model. The solution to this system of expectational difference equation is given by

$$x_t = F(\mathcal{P})x_{t-1} + G(\mathcal{P})\upsilon_t$$

or, defining $e_t = G(\mathcal{P})\upsilon_t$

$$x_t = F(\mathcal{P})x_{t-1} + e_t$$

and $Q(\mathcal{P}) = \mathbb{E}(e_t e_t') = G(\mathcal{P})\Sigma_\upsilon G(\mathcal{P})'$. Thus, the solution is essentially a structural VAR(1). Calling $\Gamma_0 = \mathbb{E}(x_t x_t')$ the variance-covariance matrix of x_t and $\Gamma_j = \mathbb{E}(x_t x_{t-j}')$ the autocovariance matrix, we have that

$$\Gamma_0 = F(\mathcal{P})\Gamma_0 F(\mathcal{P})' + \Sigma_e$$

A closed-form solution for Γ_0 is given by

$$\text{vec}(\Gamma_0) = [\text{I}_{n^2} - F(\mathcal{P}) \otimes F(\mathcal{P})]^{-1}\text{vec}(Q(\mathcal{P}))$$

Thus, once numerical values are assigned to elements of $\mathcal{P}$ and Σ_υ, all the quantities in Γ_0 are readily calculated. Then, simple algebra shows that

$$\Gamma_j = F(\mathcal{P})^j \Gamma_0$$

[45] Although it is often natural to associate GMM estimation to moments based on first order conditions, it is worth mentioning that in this paper, the choice of moments in the estimation procedure does not make use of any of the first order conditions of the model.

Another advantage of a GMM approach to estimation, relative to a maximum likelihood approach, is that it is less affected by the stochastic singularity problem. Stochastic singularity arises in (linearized) dynamic stochastic general equilibrium models because they use a small number of structural shocks to generate predictions about a larger number of endogenous variables. As such, these models predict that some linear combinations of model variables should hold exactly and, as a consequence, the covariance matrix of the system is of reduced rank. A consequence of stochastic singularity is that not all moments generated by the model can be used to estimate the model parameters. In fact, only linearly independent moments can be used. In the model, the largest number of independent moments one can find is eight. For estimation purposes, then, all independent moments will be used.

Given that one can use only eight independent moments to estimate the structural parameters of the model, an appropriate choice has to be made among all the available moments generated by the model. Therefore, the selection of moments to match is guided by the objective of the model to provide an explanation of boom and bust episodes in investment such as the one observed in the 1990's. Specifically, the chosen moments center on the dynamics between output and investment. One such set of linearly independent moments comprises the volatilities of output (σ_y^2) and investment (σ_i^2), their correlation ($\sigma_{y,i}$) as well as the first order autocorrelation of output and investment ($\gamma_j(1)$, $j = y, i$). Additional moments based on the relative price of consumption and investment were added to increase the data variability used in identifying the parameters of the model, in particular the volatility of the relative price of investment σ_{pi}^2, its first order autocorrelation $\gamma_{pi}(1)$ as well as the covariance between the relative price of consumption and investment. A look at the definition of both relative prices in equations (4.9) and (4.10) shows that they are useful in identifying the parameters related to the distribution system. This provides eight moments with which one can estimate the parameters of the model.

Since there are only eight independent moments available for estimation and the vector $\mathcal{P}_2$ of structural parameters to estimate comprises 11 elements, one has to reduce the number of parameters to estimate. To this end, the following strategy is used. First, the parameters a, b and $\mathcal{T}$ proved to be difficult to identify separately. This is partly because it is always possible to rewrite the relative prices in terms of the ratio b/a. As such, the parameters $\mathcal{T}$ and a are calibrated and only the parameter b is estimated[46]. The calibrated values, $\mathcal{T} = 1.0$ and $a = 1.5$, were chosen on the basis that they produced steady state values for the relative price of consumption and the relative price of investment, which include distribution costs, that are in line with the empirical evidence presented in section 4.2.

Second, once p, the parameter measuring the time that elapses between the arrival of a signal and its expected impact on the economy, is set to an arbitrary value, there are only eight parameters left to be estimated, which matches the number of available moments. Applying the GMM procedure in this case consistently produced an estimated coefficient g of habit formation equal to zero. Given this finding, it was chosen to calibrate this parameter to zero and not estimate it, although this was technically not necessary. The benefit of doing so is that for a fixed p, there are now only seven parameters to estimate using the eight independent moments. This allows one to use of the J statistics to gauge the validity of the model.

There remains to choose an appropriate value of p. Following Beaudry and Portier [2004] and Karnizova [2008], p is chosen so as to minimize the Euclidian norm of $\psi_T(\mathbf{w}, \hat{\mathcal{P}})$. More specifically, the Euclidian norm of $\psi_T(\mathbf{w}, \hat{\mathcal{P}})$ was calculated for each of the twelve cases where p was allowed to vary from 1 to 12. The value of p deemed the most appropriate corresponds to the one that produces the lowest estimated norm. Finally, it is worth noting that for estimating purposes, the efficient weighting matrix is used. Specifically, $\hat{\mathcal{W}}_T = \hat{\mathcal{S}}_T^{-1}$ such that $\hat{\mathcal{S}}_T \xrightarrow{p} \mathcal{S} = \mathbb{E}[\psi_T(\mathbf{w}, \mathcal{P})\psi_T(\mathbf{w}, \mathcal{P})']$.

The data used for estimation covers the period 1948:1 to 2006:4. Investment is defined as the the sum of gross private domestic investment excluding inventory investment plus consumers' spending on durable goods. Consumption is the sum of consumers' spending on nondurables and services plus the imputed service flow from consumer durables with a return of 4%. Output from nonfarm business sector is used as the measure of aggregate production. The relative price of investment is the ratio of the appropriate investment deflator to the GDP deflator while the relative price of consumption is calculated as the ratio of the all-item CPI to the GDP deflator. The data are from NIPA tables published by the Bureau of Economic Analysis. Labor is measured by the hours of all people in the nonfarm business sector, obtained from the Bureau of Labor Statistics. They are converted on a per capita basis using the civilian noninstitutional population aged 16

[46] This choice is arbitrary. One could have fixed any 2 parameters and estimate the third.

and above. All second moments are calculated from the Hodrick-Prescott cyclical component of the log per capita variables setting the smoothing parameter at its usual value of 1600 for quarterly data. Table 4.6 presents the estimation results for the case $p = 5$, which corresponds to the smallest norm calculated[47].

The results obtained seem to support the idea of a nonlinear transformation curve between consumption and investment at the aggregate level. The parameter controlling the nonlinearity, σ, is estimated at 1.894, although it is not precisely estimated. In particular, it is not statistically different from unity. In addition, the estimation implies an economy in which the intertemporal elasticity of substitution is rather high at 0.300, in line with the findings of see Mankiw et al. [1985], Ghysels and Hall [1990], An et al. [2007] and Karnizova [2008]. This parameter is estimated rather precisely. As mentioned in Nadeau [2008], with such a high degree of intertemporal substitution in consumption, cost complementarities is the only required change to the canonical RBC model to generate EDBC. In particular, EDBC would be possible with a Cobb-Douglas aggregate production function, even though the estimation procedure favors an economy where capital and labor are complement (elasticity of substitution of 0.35). This coefficient is consistent with those presented in Chirinko [2002] but smaller than the results reported by Antràs [2004]. In the specific context of their model, Beaudry and Portier [2004] also obtain complementarity between capital and labor.

On a different note, the estimated model produces quite reasonable distribution costs. In steady state, the predicted relative price of consumption is 1.818 while the relative price of investment is 1.363. This implies that in the case of consumption goods, an additional 0.82 unit of the composite output must be dedicated to its distribution before one can consume it while in the case of investment goods, the additional requirement is 0.36 unit of composite output. Recall that data from tables 4.3, 4.4 and 4.5 in section 4.2.3 show that the distribution margin for consumption goods is between 45% and 56% while it is 22% for investment goods. As such, the predicted relative prices of consumption is in line with the data while the relative price of investment is slightly on the high side[48]. Although one could argue that part of this attractive result is driven by the calibration of

[47] The results were very similar for $p = 4$. This is in line with Beaudry and Portier [2004] and Karnizova [2008], who both obtained $p = 4$.

[48] Note that saying that 45% of the retail price of a good represents the distribution cost is equivalent to saying that the price of the good, in terms of composite output, is $1/(1 - 0.45) = 1.818$.

the $\mathcal{T}$ and a parameters, it should be noted that it would have been very possible to obtain estimated values for b and σ such that the relative price of consumption predicted by the model was very similar to the relative price of investment or even situations in which the relative price of investment was actually higher than the relative price of consumption. The fact that the predicted relative prices appear so much in line with the data although they were not explicitly targeted in the estimation process is thus considered a positive finding of the model.

In terms of parameters related to news shocks, the selection of $p = 5$ indicates that technology shocks can be anticipated a little more than a year in advance. Moreover, estimation results suggest that slightly more than 80% of the variance of technological progress is generated by news shocks, as opposed to contemporaneous shocks. Note however that it was somewhat difficult to disentangle the impact of contemporaneous shocks from that of news shocks, as illustrated by the relatively high standard deviation associated with the point estimate of the variances. In terms of the capacity of the model to actually generate EDBC, simple calculations show that the estimated model satisfies the condition for cost complementarities, equation (4.11). This finding, in addition to the estimated high intertemporal elasticity of substitution, allows the model to generate an economic expansion following good news about future technological progress. This will be illustrated in section 4.4.3. Finally, under the hypothesis that the model is the true data generating process and that $p = 5$, the J statistics suggests that the model fits the chosen data rather well.

4.4.2 Business cycle statistics

Turning now to the investigation of the business cycle properties of the MDS model, table 4.7 presents some model predictions relative to those targeted in the estimation procedure. To identify the role played by news shocks in this model, I follow Karnizova [2008] and also present the implied moments of the model when only contemporaneous shocks hit the economy (MDS (e only)) and when only news shocks hit the economy (MDS (ξ only)). As is clear from the table, the model replicates well the interactions between output and investment as well as the dynamic behavior of output, investment and the relative price of investment.

In table 4.8, one can find the predictions of the estimated model relative to other business cycle moments typically investigated. The performance of the model with respect to these moments is more mitigated. As estimated, the model generates too much consumption volatility relative to output volatility. Two factors contribute to this result. The first, which is directly related to the presence of the distribution system, is the estimated parameter σ which is different from unity. The second element is the estimated high intertemporal elasticity of substitution in consumption . To support this claim, if one simulates the model as estimated but with linear transformation curve $\sigma = 1.0$, the relative volatility of consumption falls from 0.974 to 0.797 while the correlation between output and consumption falls from 0.999 to 0.889. If, in addition to the linear transformation curve, one simulates the model with logarithmic preferences ($\gamma = 1.0$) then the relative volatility falls to 0.410 and the correlation falls to 0.686. On the other hand, if one simulates the model with the estimated nonlinear transformation curve but with logarithmic preferences, the decline in relative volatility is much smaller, from 0.974 to 0.921, while the correlation remains essentially unchanged. That the nonlinear transformation curve is responsible for this finding is perhaps not surprising. As the parameter governing the nonlinearity in the transformation curve rises, there is more incentive to increase jointly the production of the consumption and investment goods. Therefore, whenever production rises, it will typically be to accommodate an increase in both investment and consumption, leading to the simulated high correlation and relative volatility. Moreover, the fluctuations in the relative price of consumption induced by the nonlinear transformation curve contributes further to amplify the relative volatility of consumption.

In terms of the volatility of hours relative to output, the model performs in a fashion typical to that of the canonical RBC model in that it does not generate sufficient hours volatility. Paradoxically, this result is partly related to the estimation of a nonlinear transformation curve between consumption and investment. If one simulates the model as estimated but with a linear transformation curve $\sigma = 1.0$, the relative volatility of hours increases from 0.654 to 0.738. The model also predicts a near unity correlation between output and hours, a feature at odd with the data. This finding is mostly driven by the estimated high intertemporal elasticity of substitution in consumption. Simulating the model as estimated but with log preferences, the correlation between output and hours fall to 0.91. This finding of too high a correlation between output and hours is also typical of the canonical RBC model.

Turning to the performance of the model with respect to wages (in terms of consumption), it is seen that it predicts a much to high correlation between real wages and both output and hours. Again, this finding is related to both the nonlinear transformation curve and the high intertemporal elasticity of substitution. Simulating the model as estimated but with a linear transformation curve and log preferences, the volatility of the real wage to that of output increases to 0.410, the correlation between output and the real wage falls to 0.685 while the correlation between the real wage and hours fall to 0.390. In all three cases, the results are much more in line with the data. Overall, it can be said that the MDS model as estimated does not provide improvements over standard RBC models when it comes to explaining the labor market.

This section showed that while the estimated model can reproduce very well the dynamics of output, investment and the relative price of investment, the results are not as good when one considers business cycle moments related to consumption and the labor market. In relation to this finding, it was found that part of it can be traced to the very feature that was exploited to generate expectation driven business cycles, namely the nonlinear transformation curve between consumption and investment. To appreciate the capacity of the estimated model to generate EDBC, its dynamic adjustment to news about future TFP is presented next.

4.4.3 Dynamic responses to shocks

This section considers the response of the model economy to an anticipated 1% increase in total factor productivity. Given the results of the estimation procedure, the increase is expected to happen 5 quarters after the news is received.

Figure 4.2 displays the dynamics associated with the case where the anticipated increase is realized. As the figure shows, much of the response of the economy following the shock comes from investment. When agents learn of the news, they expect productivity to increase in the future. Since capital and labor are complementary, they know that they must start accumulating capital immediately if they want to reap all the benefits from the expected productivity gain[49]. Investment jumps on impact and experiences a further

[49] Even if the production function was of the Cobb-Douglas type, investment would also increase upon learning of the news. This is because of the high estimated intertemporal elasticity of substitution in consumption. Complementarity between capital and labor simply makes the response of investment larger. On the other hand, if preferences were logarithmic in consumption, the news shock would lead to a decline in investment if

increase when the anticipated productivity shock is realized. On the other hand, while consumption, output and hours all increase following the news, the initial response is very muted and the bulk of their response is observed when the shock hits the economy. In the strict sense, the model with a distribution system can generate expectation driven business cycles, although in the model as estimated, there is a lack of propagation from news shocks to consumption, output and hours.[50]

It is worth noting that the small responses of consumption, output and hours following news shocks in the estimated model is not a feature of this model only. In fact, the responses of the model as estimated are quantitatively very similar, with respect to these variables, to those obtained by Christiano et al. [2007] in the variant of their model without habit formation. On the other hand, it is worth questioning whether these small responses are in fact an undesirable feature of the model. To illustrate this point, figure 4.3 plots the actual data over the period 1994Q1 to 2003Q1, the period for which analysts attribute (part of) the boom and bust in investment to news about the future profitability of investment. Specifically, the data shown are linearly detrended and normalized so that they take the value of zero in the first quarter of 1994. The scale of the vertical axis is the same on all graphs, making it easier to gauge the relative size of each variable's deviation from its linear trend. Admittedly, this figure can only be considered as providing anecdotal evidence of the appropriate response of the economy to news shocks. Yet, it suggests that obtaining a small response of consumption and a much larger response of investment to news shocks is not necessarily at odd with the data. On the other hand, it appears clear that a stronger propagation from news shocks to hours would be a desirable feature. Future research will look into alternative specification of preferences such that the negative wealth effect of the shock on labor is small, such as the class of

the production function were of the Cobb-Douglas type while it generates an increase in investment if capital and labor are sufficiently complementary.

[50] This is not to say that the model can not generate a larger propagation from news shocks to the latter three variables. In fact, the observed small responses arise because the model as estimated does not support habit formation in consumption. As illustrated in Nadeau [2008], the presence of habit formation in consumption increases the response of hours and thus consumption and output following the arrival of news shocks. This happens because with habit formation, the marginal utility of leisure is increasing in future consumption. Thus, when agents receive news that technology will be higher in the future, they understand that they will want to consume more in the future. This gives an incentive for agents to increase labor supply today which, in turns, increase aggregate production, allowing for more consumption even if investment expands following the news shock.

utility function proposed by Jaimovich and Rebelo [2006].

More interesting in the context of the current paper is to consider the dynamic behavior of the model when agents learn they were too optimistic and that technology does not improve in period 6, as anticipated. The response of the model is illustrated in figure 4.4. In this case, the news shock generates an expansion as consumption, investment, output and hours all increase. Up to period 5, the response of the economy is identical to the case presented in figure 4.2. In period 6, agents observe actual TFP, realize that their expectation does not materialize and that there is an over-accumulation of capital. In response to this, investment experiences a sharp decline, falling below its steady state value before starting a slow recovery. Firms lay off workers, leading to a decline in output. Finally, as the expected wealth gain arising from the productivity improvement does not materialize, consumption slowly returns to its steady state value. As the figure shows, then, the economy experiences a boom followed by a bust without ever having experienced a change in technology.

It is worth mentioning some additional features of the model's response to an unrealized TFP shock that are desirable. First, investment experiences a much sharper decline than consumption following the realization that expectations are not fulfilled. This is qualitatively consistent with the behavior of the US economy during the boom-bust episode illustrated in figure 4.3. Competing models using investment adjustment costs in terms of the change in the flow of investment to generate EDBC, such as those of Christiano et al. [2007] or Jaimovich and Rebelo [2006], generate a larger decline in consumption than in investment because of the need to smooth investment to avoid paying large costs. This behavior appears counterintuitive because it is the over-accumulation of capital induced by the unrealized productivity gain that mostly requires a correction. There is a sense, in these models, that the boom and bust is more in consumption than in investment. Second, the capacity of the model to generate EDBC is not sensitive to the length of the anticipation period p. That is, the model generates an EDBC even when the shock is expected to happen later than 5 periods in the future. Figure 4.5 shows the response of the model in the case when TFP is expected to increase in 10 periods from the time of the news, instead of 5 periods as estimated. In models that rely on investment adjustment costs in terms of the change in the flow of investment, the capacity of the model to generate EDBC can be sensitive to the length of the anticipation period.

It is also of interest to analyze the behavior of the relative price of investment (or capital). As in Christiano et al. [2007] and Karnizova [2008], the price of capital is identified with asset prices in the data. Given this interpretation, the model as estimated suggests that news about future productivity gains will lead to a stock market boom, while the realization that the expectation will go unfulfilled leads to a stock market crash. This is consistent with the behavior of the US stock market over the 1994-2003 period. Again, not relying on the flow of investment specification of adjustment costs allows for a sharp response of asset prices, as opposed to smooth fluctuations. Finally, it is worth noting that the model as estimated suggests a very muted response of the real wage in response to news shocks. In fact, the model generates an expansion without any significant movements in wages. By opposition, Christiano et al. [2007] and Karnizova [2008] predict a drop in real wages following news shocks while the model of Beaudry and Portier [2004] predicts an increase. As discussed more thoroughly in Nadeau [2008], evaluating the response of real wages to news shocks is one way by which one could discriminate between the existing competing models. This is left for future research.

4.5 Conclusion

This paper presented a standard business cycle model augmented with a distribution system that has the capacity, under a parameter restriction, to generate a boom in consumption, investment, output, hours and asset prices following positive news about future technology improvement. This is something that standard models can not achieve, yet is an important feature to satisfy if one accepts, as many analysts now do, that the boom and bust episode experienced in the Unites States between 1994 and 2003 was partly driven by such news. The main feature of the model that permits the expansion is the presence of a nonlinear transformation curve between consumption and investment at the aggregate level, which captures the potential presence of cost complementarities in the distribution system.

The parameters of the model are estimated and found to support the existence of cost complementarities. The model reproduces well the usual business cycle statistics related to output and investment. Moreover, it generates distribution costs that are quite in line with the data. On the other hand, the very parameter that generates cost complementarities and hence the capacity of obtaining expectation driven business cycles is also responsible for producing some counterfactual model statistics. In particular, it generates too much volatility of consumption relative to output, too high a correlation between consumption and output as well as too high a correlation between consumption and investment. These results are obtained almost by construction, as cost complementarities gives an incentive to produce both goods simultaneously. Paradoxically, the estimation of a nonlinear transformation curve is in part responsible for the volatility of hours being too small relative to the volatility of output.

One advantage of using cost complementarities as a mechanism to generate expectation driven business cycles is that it allows investment and asset prices to experience larger fluctuations than consumption in response to news about future technological progress, something that appears consistent with the 1994-2003 US episode. The opposite is typically obtained when one uses the change in investment specification of adjustment costs to generate EDBC. An area of future work is to consider alternatives that would amplify the response of hours, and hence output, to news shocks. This could take the form of labor adjustment costs or alternative specifications of preferences such as those considered by Jaimovich and Rebelo [2006] or Karnizova [2008]. Finally, as the rank of models capable of generating EDBC are growing, attention will be required to try to differentiate between the various explanations proposed. This is important because while the model proposed in this paper suggests that news driven economic expansions are a real-side phenomenon, Christiano et al. [2007] suggests instead that they are mostly the result of monetary policy. Hence, for policy design, it becomes important to identify the most relevant explanations.

Tables and figures

Tables

Table 4.1: Distribution margin for US agricultural products, 2002

Category	Dist. Margin
Meat products	68%
Poultry	67%
Eggs	66%
Dairy products	72%
Fats and oils	84%
Fresh fruit	84%
Fresh vegetables	80%
Processed fruit and vegetables	84%

Source: USDA economic research service

Table 4.2: Wholesale, retail and total distribution margin, 1998, percentage

	Wholesale margin	Retail margin	Distribution margin
All goods	20.5	32.1	46.0
Durable goods	23.3	25.6	42.9
Nondurable goods	17.2	36.7	47.6

Table 4.3: Share of value added in total industry output, 2006, billions of $ at producer's prices

	Wholesale (1)	Retail (2)	Transp & Warehouse (3)	Distribution (1)+(2)+(3)
Intermediate Inputs	396.5	504.7	371.4	1272.6
Labor Income	411.2	477.8	243.1	1132.1
Taxes less subsidies	168.8	186.7	20.1	375.6
Gross Operating Surplus	182.2	183.5	122.2	487.9
Total Value Added	762.2	848.0	385.4	1995.6
Total Industry Output	1158.7	1352.6	756.9	3268.2
Distribution Margin	59.9%	56.7%	49.6%	56.0%

Source: I-O accounts, Use of commodities per industry table

Table 4.4: Consumption expenditures on goods at producer's prices and purchaser's prices, 2002

	Prod. prices (1)	Trans. margin (2)	Wholesale margin (3)	Retail margin (4)	Purch. price (5)	Distrib. margin (5-1)/5
Agric., forest., fish. and hunt.	48655	5659	11820	25304	91438	46.8%
Mining	118	136	2	101	356	66.8%
Manufacturing	1248059	40646	281063	685645	2255414	44.7%
Used and second-hand goods	68346	5723	2999	47347	124415	45.1%

Source: Benchmark 2002 I-O accounts, available from BEA website.

Table 4.5: Investment expenditures on goods at producer's prices and purchaser's prices, 2002

	Prod. prices (1)	Trans. margin (2)	Wholesale margin (3)	Retail margin (4)	Purch. price (5)	Distrib. margin (5-1)/5
Manufacturing	565745	16360	77617	29952	689674	21.9%

Source: Benchmark 2002 I-O accounts, available from BEA website.

Table 4.6: GMM estimation results, $p = 5$,st. err. in parenthesis

μ	σ	b	ρ	s_e	s_ξ	γ
-1.855	1.894	0.173	0.804	0.0010	0.0049	0.300
(0.706)	(0.830)	(0.069)	(0.035)	(0.0068)	(0.0030)	(0.128)

J statistics: 3.314
p-value: 0.069

Table 4.7: Predicted vs targeted moments

Moment	US Data	MDS	MDS (e only)	MDS(ξ only)
σ_y	2.200	2.191	0.415	2.151
σ_i	4.688	4.649	0.903	4.560
σ_{pi}	0.730	0.738	0.134	0.725
$\sigma_{y,i}$	0.836	0.837	0.907	0.835
$\gamma_y(1)$	0.837	0.836	0.822	0.837
$\gamma_i(1)$	0.856	0.841	0.743	0.845
$\gamma_{pi}(1)$	0.836	0.885	0.739	0.890

Table 4.8: Other business cycle statistics

Moment	US Data	MDS	MDS (e only)	MDS(ξ only)
σ_c/σ_y	0.362	0.974	0.966	0.974
$\sigma_{y,c}$	0.802	0.999	0.999	0.999
$\gamma_c(1)$	0.830	0.839	0.830	0.839
σ_h/σ_y	0.853	0.654	0.651	0.654
$\sigma_{y,h}$	0.870	0.999	1.000	0.999
$\gamma_h(1)$	0.892	0.847	0.827	0.848
σ_w/σ_y	0.410	0.292	0.279	0.292
$\sigma_{y,w}$	0.187	0.999	1.000	0.999
$\sigma_{h,w}$	-0.021	0.999	1.000	0.999

Figures

Figure 4.1: $(C^\sigma + I^\sigma)^{\frac{1}{\sigma}} = 1$ for various values of σ. For a given distribution cost and quantity of C, one can increase the quantity of I distributed as σ increases. This is the source of cost complementarity in the distribution system.

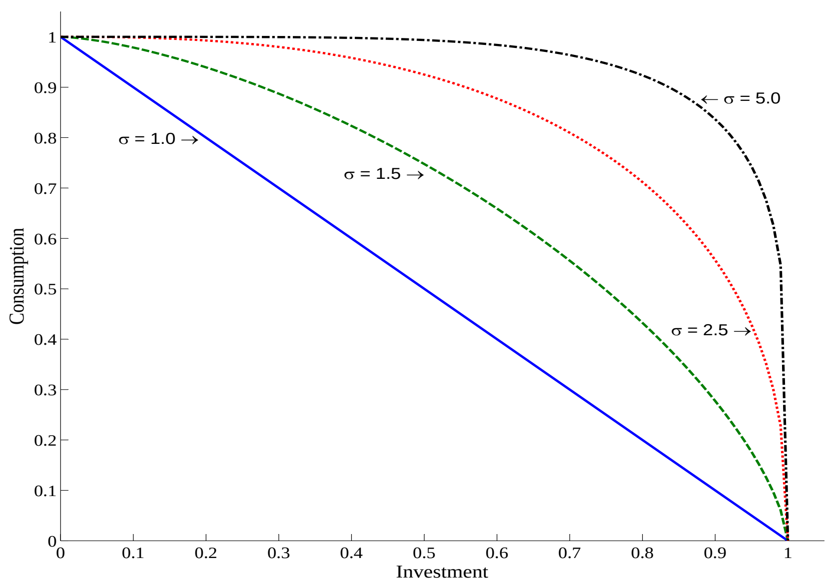


Figure 4.2: Response of the MDS economy to a period 1 announcement of a 1% increase in productivity and a realization of that shock in period 6.

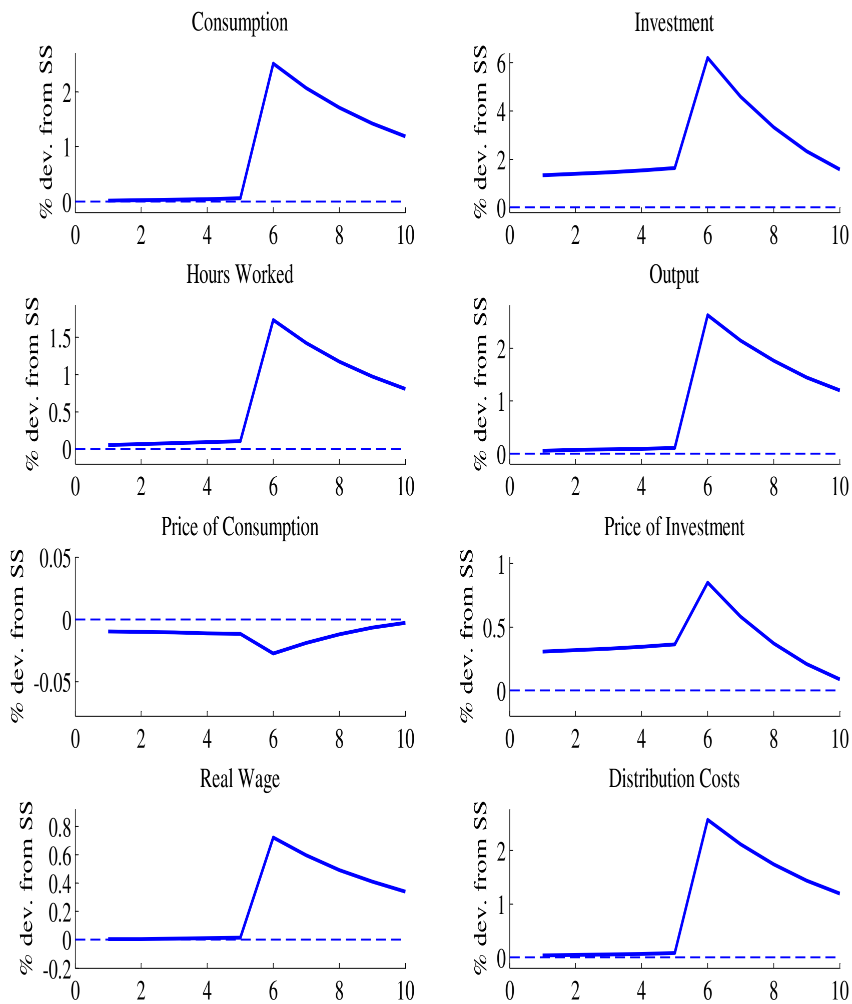


Figure 4.3: Relative size of deviation from linear trend, 1994Q1 to 2003Q1. The figure shows the log deviation of each variable from its linear trend calculated over the 1994Q1 to 2003Q1 period. Deviations normalized to equal zero in 1994Q1.

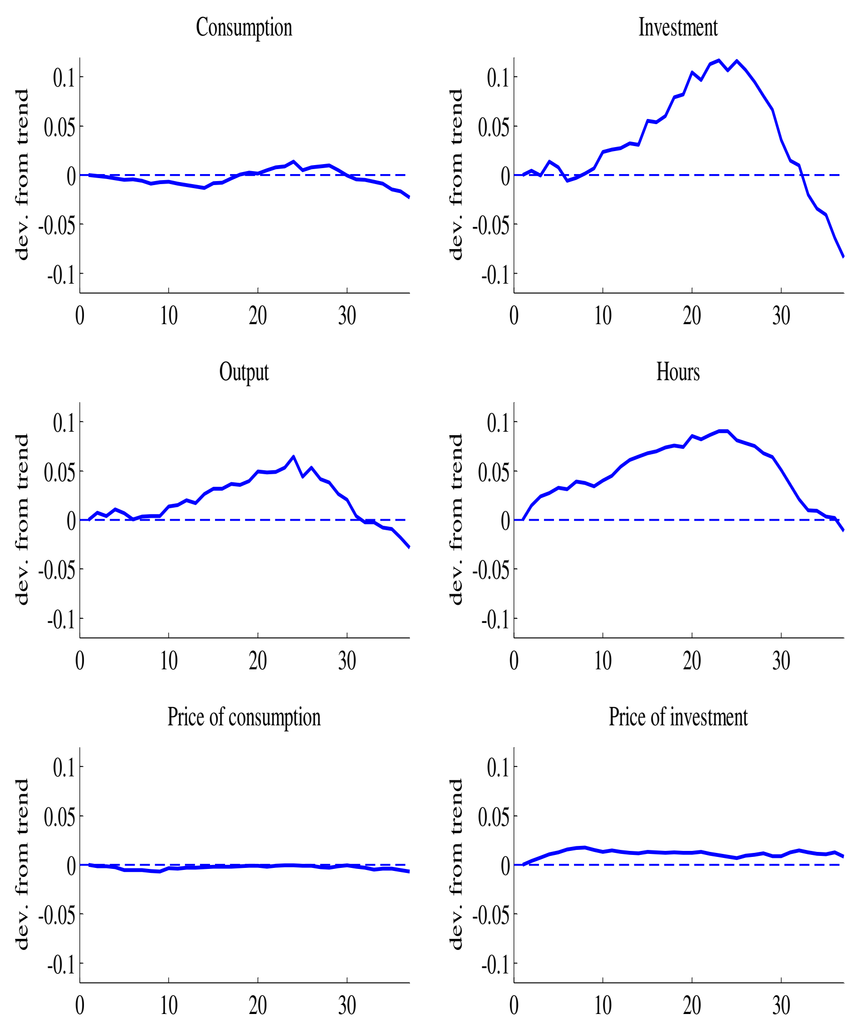


Figure 4.4: Response of the MDS economy to a period 1 announcement of a 1% increase in productivity and no realization of that shock in period 6.

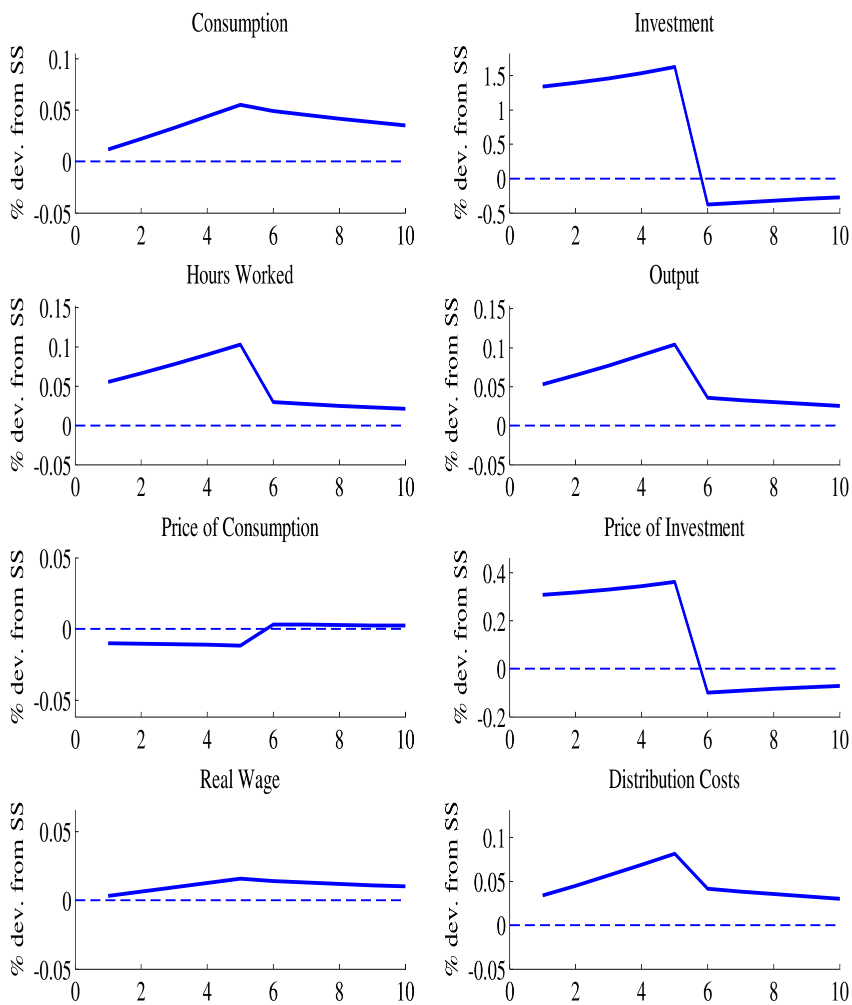
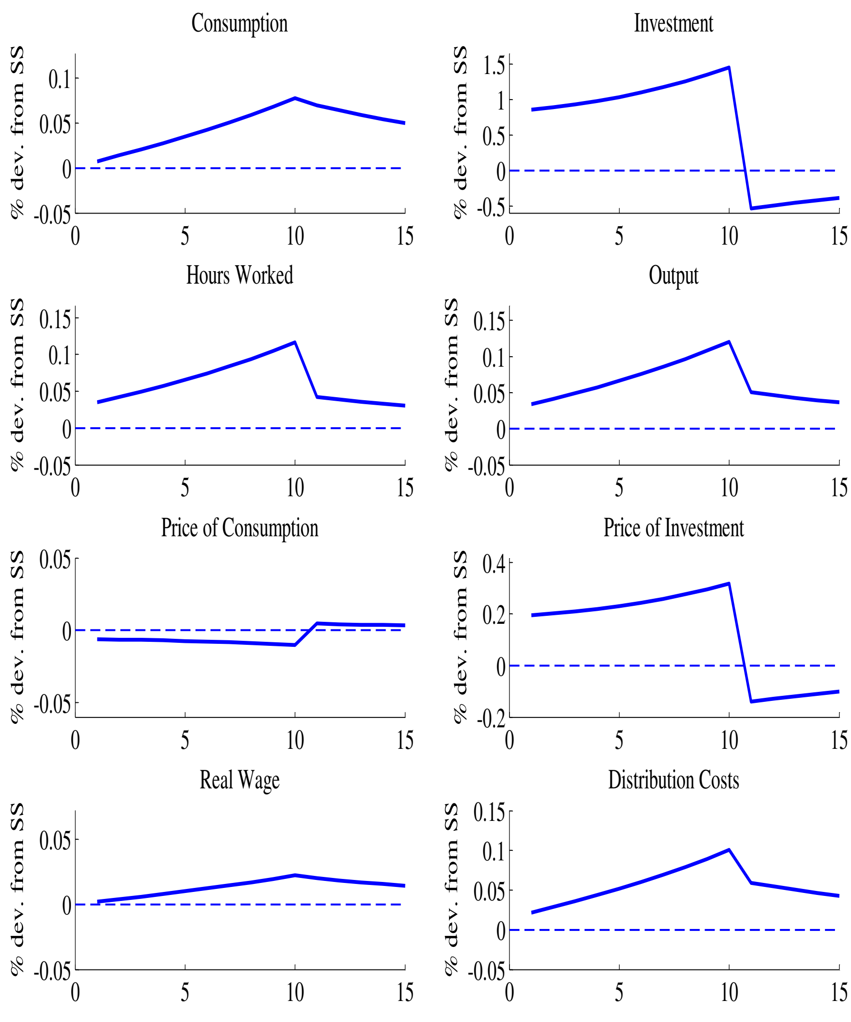


Figure 4.5: Response of the MDS economy to a period 1 announcement of a 1% increase in productivity and no realization of that shock in period 11.



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A. Data Source and Construction

The dataset used in the estimation of chapter 2 is based on Chari *et al* Chari et al. [2005]. Note that since data from US national accounts are in billions of Chained 2000 dollars, they are not strictly additive. We therefore construct real aggregates using the Fisher of Fishers method described in Chevalier Chevalier [2003]. The sample data is from 1959Q1 to 2004Q4. The end of the appendix describe the sources for all the data.

A.1 Measures

A.1.1 Consumption

Consumption is defined as follow

> Consumer spending on nondurables and services
> + government consumption expenditures
> + service flow from consumer durables with a return of 4%
> + depreciation from consumer durables
> - sales tax × share of nondurables and services in PCE

Real depreciation from consumer durables is obtained by deflating the nominal consumption of fixed capital for durable goods by the PCE deflator for consumer durables. To remove sales taxes from consumption, I use the nominal share of nondurables and services in total consumption expenditures and I use the deflator for total consumption expenditures. The real service flow from the stock of consumer durables is obtained by dividing the nominal service flow by the deflator for consumer durables. This data is transformed in per capita terms using non-institutional population, ages 16-64.

A.1.2 Investment

Investment is defined as follow

Gross private domestic investment (fixed investment + inventory investment)
+ government gross investment
+ consumer spending on durables
- sales tax $\times$ share of durables in PCE

To remove sales taxes from investment, I use the nominal share of durables in total consumption expenditures and I use the deflator for total consumption expenditures.

A.1.3 Output

To respect the theoretical model, output is defined as the sum of nominal consumption and nominal investment, to which nominal net exports are removed. Real output is then obtained by dividing nominal output by the GDP deflator.

A.1.4 Hours

Per capita hours is defined as follow

Total hours from the current population survey
+ military hours

They are transformed on a per capita basis using the non-institutional population aged 16-64.

A.2 Sources

National Income and Products Accounts (NIPA) tables are available on the Bureau of Economic Analysis' website. All data are quarterly, in billions of dollars. The detailed sources of the data presented above are

1. NIPA table 1.1.2
   a) nominal national income

b) nominal compensation of employees

2. NIPA table 1.1.5

   a) nominal spending on consumer durables

   b) nominal spending on consumer nondurables

   c) nominal spending on consumer services

   d) nominal gross private domestic investment

   e) nominal exports of goods and services

   f) nominal imports of goods and services

3. NIPA table 1.1.9

   a) deflator for consumer durables

   b) deflator for consumer nondurables

   c) deflator for consumer services

   d) deflator for consumer expenditures

4. NIPA table 3.9.4

   a) deflator for government consumption expenditures

   b) deflator for government gross investment

5. NIPA table 3.9.5

   a) nominal government consumption expenditures

   b) nominal government gross investment

6. NIPA table 3.2

   a) nominal federal excise taxes

7. NIPA table 3.3

   a) nominal state and local sales taxes

   b) nominal state and local other taxes

Data on the stock of consumer durables and the consumption of fixed capital are published by the Federal Reserve. All data are quarterly.

1. Flow table 10 in millions of dollars

a) consumption of fixed capital, consumer durables

2. Level table 100 in billions of dollars

    a) current-cost net stock of consumer durables

Data on hours and population are taken from Prescott, Ueberfeldt and Cociuba (2005). Specifically, I use from this document the non-institutional hours from the current population survey and the non-institutional population aged 16-64.

B. Alternative Data Set

This alternative dataset used for estimation of chapter 2 is a simplified version of the one used in the main text. The sample period is from 1959Q1 to 2004Q4. Data sources are the same as for the main text's dataset.

B.1 Consumption

Nominal consumption is the sum of consumer spending on nondurables and services . Real consumption is obtained by dividing nominal consumption by the appropriate National Account deflator. Alternatively, one can divide nominal consumption by a CPI-based price deflator. This does not alter the findings in any substantial ways.

B.2 Investment

Nominal investment is the sum of nominal gross private domestic investment and nominal spending on durable goods. Real investment is obtained by deflating nominal investment by the appropriate National Account deflator.

B.3 Output

Output is Gross Domestic Product from National Account. Real output is obtained by dividing nominal output by the GDP deflator.

B.4 Hours

Per capita hours is defined as in the main text's dataset, that is, total hours from the current population survey + military hours. They are transformed on a per capita basis using the non-institutional population aged 16-64.

C. Cost Complementarities in MAC Model

This appendix derives the condition that must be satisfied for the model with multi-sectoral adjustment costs to generate cost complementarities. By definition, a short-run cost function displays cost complementarities when its cross-derivative is negative. The short-run cost function $C(H|K, X, Z, w)$ solves

$$\Xi(H|K, X, Z, w) = \min_{H} wH \tag{C.1}$$

subject to

$$(X^{\sigma} + Z^{\sigma})^{\frac{1}{\sigma}} = (\theta K^{\mu} + (1-\theta)H^{\mu})^{\frac{1}{\mu}} = Y$$

where w is the real wage. The cost function is given by

$$\Xi(H|K, X, Z, w) = w(1-\theta)^{-\frac{1}{\mu}} \left[(X^{\sigma} + Z^{\sigma})^{\frac{\mu}{\sigma}} - \theta K^{\mu}\right]^{\frac{1}{\mu}} \tag{C.2}$$

Then, the marginal cost of X is given by

$$\Xi_X = D\left[(X^{\sigma} + Z^{\sigma})^{\frac{\mu}{\sigma}} - \theta K^{\mu}\right]^{\frac{1-\mu}{\mu}} (X^{\sigma} + Z^{\sigma})^{\frac{\mu-\sigma}{\sigma}} \tag{C.3}$$

where $D = w(1-\theta)^{-\frac{1}{\mu}} X^{\sigma-1}$. The cross derivative is then

$$\begin{aligned} \Xi_{X,Z} \;=\; & DZ^{\sigma-1}\Big\{(1-\mu)\left[(X^{\sigma} + Z^{\sigma})^{\frac{\mu}{\sigma}} - \theta K^{\mu}\right]^{\frac{1-2\mu}{\mu}} (X^{\sigma} + Z^{\sigma})^{\frac{2\mu-2\sigma}{\sigma}} \\ & +(\mu-\sigma)\left[(X^{\sigma} + Z^{\sigma})^{\frac{\mu}{\sigma}} - \theta K^{\mu}\right]^{\frac{1-\mu}{\mu}} (X^{\sigma} + Z^{\sigma})^{\frac{\mu-2\sigma}{\sigma}}\Big\} \end{aligned}$$

Cost complementarity requires that $\Xi_{X,Z} < 0$. Since D and Z^{σ} are necessarily positive, $\Xi_{X,Z}$ can be negative if and only if

$$\begin{aligned} & (1-\mu)\left[(X^{\sigma} + Z^{\sigma})^{\frac{\mu}{\sigma}} - \theta K^{\mu}\right]^{\frac{1-2\mu}{\mu}} (X^{\sigma} + Z^{\sigma})^{\frac{2\mu-2\sigma}{\sigma}} \\ < \; & (\sigma-\mu)\left[(X^{\sigma} + Z^{\sigma})^{\frac{\mu}{\sigma}} - \theta K^{\mu}\right]^{\frac{1-\mu}{\mu}} (X^{\sigma} + Z^{\sigma})^{\frac{\mu-2\sigma}{\sigma}} \end{aligned}$$

that is

$$\frac{(1-\mu)}{(\sigma-\mu)} < \left[(X^\sigma + Z^\sigma)^{\frac{\mu}{\sigma}} - \theta K^\mu\right]^{\frac{1-\mu-1+2\mu}{\mu}} (X^\sigma + Z^\sigma)^{\frac{\mu-2\sigma-2\mu+2\sigma}{\sigma}}$$

$$\frac{(1-\mu)}{(\sigma-\mu)} < \left[(X^\sigma + Z^\sigma)^{\frac{\mu}{\sigma}} - \theta K^\mu\right] (X^\sigma + Z^\sigma)^{\frac{-\mu}{\sigma}}$$

$$\frac{(1-\mu)}{(\sigma-\mu)} < \frac{(X^\sigma + Z^\sigma)^{\frac{\mu}{\sigma}} - \theta K^\mu}{(X^\sigma + Z^\sigma)^{\frac{\mu}{\sigma}}}$$

Recalling from the constraint that

$$(X^\sigma + Z^\sigma)^{\frac{\mu}{\sigma}} = Y^\mu$$

the last inequality simplifies to condition (3.2)

$$\frac{(1-\mu)}{(\sigma-\mu)} < 1 - \theta \left(\frac{K}{Y}\right)^\mu$$

D. Linearized MAC Model

This section list the the main equations of the model with multisectoral adjustment costs and presents the linearized equations used to simulate the various experiments of section 3.3.

D.1 Planner's problem

$$\max \; \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{(C_t - gC_{t-1})^{1-\gamma}}{1-\gamma} - \frac{\vartheta_0}{\eta+1} H_t^{\eta+1} \right]$$

subject to

$$(aC_t^\sigma + bI_t^\sigma)^{\frac{1}{\sigma}} = (\theta K_t^\mu + (1-\theta)(A_t H_t)^\mu)^{\frac{1}{\mu}}$$

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

$$0 \leq H_t \leq 1$$

The first order necessary condition (FONC) with respect to consumption is given by

$$(C_t - gC_{t-1})^{-\gamma} - \beta g \mathbb{E}_t (C_{t+1} - gC_t)^{-\gamma} = \lambda_t p_t^C$$

where

$$p_t^C = a \left(\frac{C_t}{Y_t} \right)^{\sigma - 1}$$

is the price of consumption in terms of the composite output and λ_t is the multiplier on the aggregate resource constraint. λ gives the marginal utility of an extra unit of composite output so that λp^C gives the marginal utility of an extra unit of output evaluated in terms of the consumption good.

The FONC with respect to investment is

$$q_t = \lambda_t p_t^I$$

where

$$p_t^I = b\left(\frac{I_t}{Y_t}\right)^{\sigma-1}$$

and q_t is the multiplier associated with the capital accumulation equation. The FONC with respect to capital K_{t+1} is

$$q_t = \beta\mathbb{E}_t\left(\theta\lambda_{t+1}\left(\frac{Y_{t+1}}{K_{t+1}}\right)^{1-\mu} + (1-\delta)q_{t+1}\right)$$

while that with respect to hours is

$$\vartheta_0 H_t^{1+\eta-\mu} = (1-\theta)\lambda_t A_t^\mu Y_t^{(1-\mu)}$$

Note that since labor is paid its marginal product, the real wage in terms of the composite output is given by

$$w_t = (1-\theta)A^\mu\left(\frac{Y_t}{H_t}\right)^{1-\mu}$$

As such, the FONC for labor can be rewritten as

$$\vartheta_0 H_t^\eta = \frac{w_t}{p_t^C}\left[(C_t - gC_{t-1})^{-\gamma} - \beta g\mathbb{E}_t(C_{t+1} - gC_t)^{-\gamma}\right]$$

which shows that the agent cares about the real wage in terms of consumption goods only.

In addition to the FONCs, the equilibrium allocation is characterized by the following equations

$$p_t^C C_t + p_t^I I_t = Y_t$$

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

$$Y_t = (\theta K_t^\mu + (1-\theta)(A_t H_t)^\mu)^{\frac{1}{\mu}}$$

$$p_t^C = a\left(\frac{C_t}{Y_t}\right)^{\sigma-1}$$

$$p_t^I = b\left(\frac{I_t}{Y_t}\right)^{\sigma-1}$$

D.2 Steady-state determination

Finding steady state values for the model with Multisectoral Adjustment Costs is relatively simple. First, from the capital accumulation equation

$$K = (1-\delta)K + I$$

$$I = \delta K$$

Then, from the FONC for investment, we have that

$$\frac{\lambda}{q} = \frac{1}{p^I}$$

and that in steady state,

$$p^I = b\left(\frac{I}{Y}\right)^{\sigma-1} = b\left(\frac{\delta K}{Y}\right)^{\sigma-1}$$

Now, from the FONC for capital

$$q = \beta\left(\theta\lambda\left(\frac{Y}{K}\right)^{1-\mu} + (1-\delta)q\right)$$

Dividing through by q and using the above relation for p^I

$$1-\beta(1-\delta) = \beta\theta\frac{1}{p^I}\left(\frac{Y}{K}\right)^{1-\mu} = \frac{\beta\theta}{b\delta^{\sigma-1}}\left(\frac{Y}{K}\right)^{\sigma-\mu}$$

then the output to capital ratio is given by

$$\frac{Y}{K} = \left(\frac{b(1-\beta(1-\delta))\delta^{\sigma-1}}{\theta\beta}\right)^{\frac{1}{(\sigma-\mu)}}$$

From this ratio and the fact that the steady state level of hours H is set to 1/3, one can find the level of all remaining variables.

D.3 Linear approximation

This section lists the linearized equations required to simulate the model. To simplify notation, I denote $\hat{x}_t = (\ln x_t - \ln x)$ the percentage deviation of a variable x_t from its steady state value x.

$$(1 + \eta - \mu)\hat{H}_t - \hat{\lambda}_t - \mu\hat{A}_t - (1 - \mu)\hat{Y}_t = 0$$

$$\theta \left(\frac{K}{Y}\right)^{\mu} \hat{K}_t + (1 - \theta) \left(\frac{H}{Y}\right)^{\mu} \hat{H}_t + (1 - \theta) \left(\frac{H}{Y}\right)^{\mu} \hat{A}_t - \hat{Y}_t = 0$$

$$a \left(\frac{C}{Y}\right)^{\sigma} \hat{C}_t + b \left(\frac{I}{Y}\right)^{\sigma} \hat{I}_t - \hat{Y}_t = 0$$

$$(\sigma - 1)(\hat{C}_t - \hat{Y}_t) - \hat{p}_t^C = 0$$

$$(\sigma - 1)(\hat{I}_t - \hat{Y}_t) - \hat{p}_t^I = 0$$

$$\hat{\lambda}_t + \hat{p}_t^I - \hat{q}_t = 0$$

$$(1 - \delta)\hat{K}_t + \delta\hat{I}_t - \hat{K}_{t+1} = 0$$

$$\beta\gamma g \mathbb{E}_t \hat{C}_{t+1} - \gamma(1 + \beta g^2)\hat{C}_t + \gamma g \hat{C}_{t-1} - (1 - g)(1 - \beta g)(\hat{\lambda}_t + \hat{p}_t^c) = 0$$

$$(1 - \beta(1 - \delta))\mathbb{E}_t \left[\hat{\lambda}_{t+1} + (1 - \mu)\hat{Y}_{t+1} - (1 - \mu)\hat{K}_{t+1}\right] + \beta(1 - \delta)\mathbb{E}_t \hat{q}_{t+1} - \hat{q}_t = 0$$

$$\rho_A \hat{A}_{t-1} + \xi_{t-p} + e_t - \hat{A}_t = 0$$

E. Cost Complementarities in MDS Model

This appendix derives the condition that must be satisfied for the model with multi-sectoral adjustment costs to generate cost complementarities. By definition, a short-run cost function displays cost complementarities when its cross-derivative is negative. Denote by $\Xi(H|K, C, I, w)$ the short-run cost function. For the model with a distribution system, the short-run cost function is given by

$$\Xi = w(1-\theta)^{\frac{\mu-1}{\mu}} \left[\left\{ C + I + \mathcal{T}(a^{1-\sigma}C^{\sigma} + b^{1-\sigma}I^{\sigma})^{\frac{1}{\sigma}} \right\}^{\mu} - \theta^{1-\mu}K^{\mu} \right]^{\frac{1}{\mu}} \quad \text{(E.1)}$$

Then, the marginal cost of C is given by

$$\Xi_C = D\left[Y^{\mu} - \theta^{1-\mu}K^{\mu}\right]^{\frac{1-\mu}{\mu}} \{C + I + \mathcal{T}\phi_t\}^{(\mu-1)} \left(1 + \mathcal{T}a^{1-\sigma}\phi^{1-\sigma}C^{\sigma-1}\right)$$

where

$$D = w(1-\theta)^{\frac{\mu-1}{\mu}}$$

$$\phi = \left(a^{1-\sigma}C^{\sigma} + b^{1-\sigma}I^{\sigma}\right)^{\frac{1}{\sigma}}$$

and recalling that

$$C + I + \mathcal{T}(a^{1-\sigma}C^{\sigma} + b^{1-\sigma}I^{\sigma})^{\frac{1}{\sigma}} = Y$$

Then, the cross-derivative is given by

$$\Xi_{C,I} = D(1-\mu)p^I p^C \left(\left[Y^{\mu} - \theta^{1-\mu}K^{\mu}\right]^{-1} \frac{Y^{\mu}}{Y} - \frac{1}{Y} \right) + D(1-\sigma)\mathcal{T}a^{1-\sigma}b^{1-\sigma}\phi^{1-2\sigma}C^{\sigma-1}I^{\sigma-1}$$

where p^C and p^I are defined in equation (4.9) and (4.10) respectively. This condition simplifies to

$$\Xi_{C,I} = D(1-\mu)p^I p^C \left(\frac{\theta^{1-\mu}K^{\mu}}{(1-\theta)^{1-\mu}H^{\mu}Y} \right) + D(1-\sigma)\mathcal{T}a^{1-\sigma}b^{1-\sigma}\phi^{1-2\sigma}C^{\sigma-1}I^{\sigma-1} \quad \text{(E.2)}$$

using the facts that

$$(1-\theta)^{1-\mu} H^{\mu} = Y^{\mu} - \theta^{1-\mu} K^{\mu}.$$

Again, to obtain cost complementarities, one need $\Xi_{CI} < 0$. Therefore, manipulating (E.2) and noting that D is strictly positive, the condition for cost complementarities reduces to

$$\frac{(1-\mu)}{(\sigma-1)} \frac{\theta^{1-\mu}}{(1-\theta)^{1-\mu}} \left(\frac{K}{H}\right)^{\mu} < \frac{Y\, \mathcal{T} a^{1-\sigma} b^{1-\sigma} \phi^{1-2\sigma} C^{\sigma-1} I^{\sigma-1}}{p^C p^I} \tag{E.3}$$

In the specific case of a Cobb-Douglas production function $\mu = 0$, we have

$$\frac{1}{(\sigma-1)} \frac{\theta}{(1-\theta)} < \frac{Y\, \mathcal{T} a^{1-\sigma} b^{1-\sigma} \phi^{1-2\sigma} C^{\sigma-1} I^{\sigma-1}}{p^C p^I}$$

F. Linearized MDS Model

This section list the the main equations of the model with a distribution system and presents the linearized equations used to simulate the various experiments of section 4.4.

F.1 Planner's problem

$$\max\ \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{(C_t - gC_{t-1})^{1-\gamma}}{1-\gamma} - \frac{\vartheta_0}{\eta+1} H_t^{\eta+1} \right]$$

subject to

$$C_t + I_t + \mathcal{T}(a^{1-\sigma} C_t^{\sigma} + b^{1-\sigma} I_t^{\sigma})^{\frac{1}{\sigma}} = \left(\theta^{1-\mu} K_t^{\mu} + (1-\theta)^{1-\mu} (A_t H_t)^{\mu}\right)^{\frac{1}{\mu}}$$

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

$$0 \leq H_t \leq 1$$

The first order necessary condition (FONC) with respect to consumption is given by

$$(C_t - gC_{t-1})^{-\gamma} - \beta g \mathbb{E}_t (C_{t+1} - gC_t)^{-\gamma} = \lambda_t p_t^C$$

where

$$p_t^C = 1 + \mathcal{T} a^{1-\sigma} (a^{1-\sigma} C_t^{\sigma} + b^{1-\sigma} I_t^{\sigma})^{\frac{1-\sigma}{\sigma}} C_t^{\sigma-1}$$

is the price of consumption in terms of the composite output and λ_t is the multiplier on the aggregate resource constraint. λ gives the marginal utility of an extra unit of composite output so that λp^C gives the marginal utility of an extra unit of output evaluated in terms of the consumption good.

The FONC with respect to investment is

$$q_t = \lambda_t p_t^I$$

where

$$p_t^I = 1 + \mathcal{T} b^{1-\sigma}(a^{1-\sigma}C_t^\sigma + b^{1-\sigma}I_t^\sigma)^{\frac{1-\sigma}{\sigma}} I_t^{\sigma-1}$$

and q_t is the multiplier associated with the capital accumulation equation. The FONC with respect to capital K_{t+1} is

$$q_t = \beta \mathbb{E}_t \left(\theta^{1-\mu} \lambda_{t+1} \left(\frac{Y_{t+1}}{K_{t+1}} \right)^{1-\mu} + (1-\delta) q_{t+1} \right)$$

while that with respect to hours is

$$\vartheta_0 H_t^{1+\eta-\mu} = (1-\theta)^{1-\mu} \lambda_t A_t^\mu Y_t^{(1-\mu)}$$

Note that since labor is paid its marginal product, the real wage in terms of the composite output is given by

$$w_t = (1-\theta)^{1-\mu} A^\mu \left(\frac{Y_t}{H_t} \right)^{1-\mu}$$

As such, the FONC for labor can be rewritten as

$$\vartheta_0 H_t^\eta = \frac{w_t}{p_t^C} \left[(C_t - gC_{t-1})^{-\gamma} - \beta g \mathbb{E}_t (C_{t+1} - gC_t)^{-\gamma} \right]$$

which shows that the agent cares about the real wage in terms of consumption goods only.

F.2 Steady-state determination

Finding steady state values for the model requires one to solve a root finding problem because of the definition of relative prices. First, from the FONC for investment, we have that

$$\frac{\lambda}{q} = \frac{1}{p^I}$$

Now, from the FONC for capital

$$q = \beta \left(\theta^{1-\mu} \lambda \left(\frac{Y}{K} \right)^{1-\mu} + (1-\delta) q \right)$$

Dividing through by q and using the above relation

$$1 - \beta(1-\delta) = \beta \theta^{1-\mu} \frac{1}{p^I} \left(\frac{Y}{K} \right)^{1-\mu}$$

then the output to capital ratio is given by

$$\frac{Y}{K} = \left(\frac{p^I(1-\beta(1-\delta))}{\theta^{1-\mu}\beta}\right)^{\frac{1}{(1-\mu)}}$$

Since in steady state, $I = \delta K$, we have that

$$\frac{Y}{I} = \frac{Y}{\delta K} = \frac{1}{\delta}\left(\frac{p^I(1-\beta(1-\delta))}{\theta^{1-\mu}\beta}\right)^{\frac{1}{(1-\mu)}}$$

Now, from the aggregate resource constraint, we have

$$p^C\frac{C}{I} + p^I = \frac{Y}{I} = \frac{1}{\delta}\left(\frac{p^I(1-\beta(1-\delta))}{\theta^{1-\mu}\beta}\right)^{\frac{1}{(1-\mu)}} \tag{F.1}$$

Now, one can express p^C and p^I in terms of the ratio I/C as follow

$$p^C = 1 + \mathcal{T}a^{1-\sigma}(a^{1-\sigma}C^\sigma + b^{1-\sigma}I^\sigma)^{\frac{1-\sigma}{\sigma}}C^{\sigma-1}$$

$$p^C = 1 + \mathcal{T}a^{1-\sigma}(C^\sigma[a^{1-\sigma} + b^{1-\sigma}(I/C)^\sigma])^{\frac{1-\sigma}{\sigma}}C^{\sigma-1}$$

$$p^C = 1 + \mathcal{T}a^{1-\sigma}C^{1-\sigma}(a^{1-\sigma} + b^{1-\sigma}(I/C)^\sigma)^{\frac{1-\sigma}{\sigma}}C^{\sigma-1}$$

that is

$$p^C = 1 + \mathcal{T}a^{1-\sigma}(a^{1-\sigma} + b^{1-\sigma}(I/C)^\sigma)^{\frac{1-\sigma}{\sigma}}$$

Using a similar approach, one finds that

$$p^I = 1 + \mathcal{T}b^{1-\sigma}(a^{1-\sigma} + b^{1-\sigma}(I/C)^\sigma)^{\frac{1-\sigma}{\sigma}}(I/C)^{\sigma-1}$$

Using the last two relations, equation (F.1) writes as

$$\left[1 + \mathcal{T}a^{1-\sigma}\left(a^{1-\sigma} + b^{1-\sigma}\left(\frac{I}{C}\right)^\sigma\right)^{\frac{1-\sigma}{\sigma}}\right]\left(\frac{I}{C}\right)^{-1}$$

$$+$$

$$\left[1 + \mathcal{T}b^{1-\sigma}\left(a^{1-\sigma} + b^{1-\sigma}\left(\frac{I}{C}\right)^\sigma\right)^{\frac{1-\sigma}{\sigma}}\left(\frac{I}{C}\right)^{\sigma-1}\right]$$

$$=$$

$$\left[1 + \mathcal{T}b^{1-\sigma}\left(a^{1-\sigma} + b^{1-\sigma}\left(\frac{I}{C}\right)^\sigma\right)^{\frac{1-\sigma}{\sigma}}\left(\frac{I}{C}\right)^{\sigma-1}\right]^{\frac{1}{1-\mu}}\frac{1}{\delta}\left(\frac{(1-\beta(1-\delta))}{\theta^{1-\mu}\beta}\right)^{\frac{1}{(1-\mu)}}$$

Now, note that once all the parameters are calibrated, the only unknown quantity is the I/C ratio. Therefore, this last equation can be used to determine this ratio. This is a root finding problem for which the solution is found numerically[51]. With the solution for I/C, it is straightforward to find the remaining steady-state quantities.

F.3 Linear approximation

This section lists the linearized equations required to simulate the model. To simplify notation, I denote $\hat{x}_t = (\ln x_t - \ln x)$ the percentage deviation from the steady state value of variable x. Variables without a subscript represent variables at their steady state value. Moreover, I have defined the variable $\phi_t = (a^{1-\sigma} C_t^\sigma + b^{1-\sigma} I_t^\sigma)^{1/\sigma}$ which is used in the definition of relative prices. The set of linearized equation is

$$(1 + \eta - \mu)\hat{H}_t - \hat{\lambda}_t - \mu\hat{A}_t - (1 - \mu)\hat{Y}_t = 0$$

$$\theta^{1-\mu} \left(\frac{K}{Y}\right)^\mu \hat{K}_t + (1 - \theta)^{1-\mu} \left(\frac{H}{Y}\right)^\mu \hat{H}_t + (1 - \theta)^{1-\mu} \left(\frac{H}{Y}\right)^\mu \hat{A}_t - \hat{Y}_t = 0$$

$$\frac{p^C C}{Y}\hat{C}_t + \frac{p^I I}{Y}\hat{I}_t - \hat{Y}_t = 0$$

$$a^{1-\sigma}\hat{C}_t + b^{1-\sigma} \left(\frac{I}{C}\right)^\sigma \hat{I}_t - \left[a^{1-\sigma} + b^{1-\sigma} \left(\frac{I}{C}\right)^\sigma\right] \hat{\phi}_t = 0$$

$$\frac{(p^C - 1)}{p^C}(1 - \sigma)(\hat{\phi}_t - \hat{C}_t) - \hat{p}_t^C = 0$$

$$\frac{(p^I - 1)}{p^I}(1 - \sigma)(\hat{\phi}_t - \hat{I}_t) - \hat{p}_t^I = 0$$

$$\hat{\lambda}_t + \hat{p}_t^I - \hat{q}_t = 0$$

$$(1 - \delta)\hat{K}_t + \delta\hat{I}_t - \hat{K}_{t+1} = 0$$

$$\beta\gamma g\mathbb{E}_t\hat{C}_{t+1} - \gamma(1 + \beta g^2)\hat{C}_t + \gamma g\hat{C}_{t-1} - (1 - g)(1 - \beta g)(\hat{\lambda}_t + \hat{p}_t^c) = 0$$

$$(1-\beta(1-\delta))\mathbb{E}_t \left[\hat{\lambda}_{t+1} + (1 - \mu)\hat{Y}_{t+1} - (1 - \mu)\hat{K}_{t+1}\right] + \beta(1-\delta)\mathbb{E}_t\hat{q}_{t+1} - \hat{q}_t = 0$$

$$\rho_A\hat{A}_{t-1} + \xi_{t-p} + e_t - \hat{A}_t = 0$$

[51] For example, one can use the function `fsolve` in Matlab.