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The New Keynesian Business Cycle Achievements and Challenges

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Abstract

The New-Keynesian (NK) business cycle model has presented itself as a potential "workhorse" model for business cycle analysis. This paper seeks to assess afresh the performance of the baseline NK model and its various extensions. The main theme of the paper is that although the dynamic NK literature has secured a robust defence to criticism arising, *inter alia*, on account of lack of microfoundations, it still has a long way to go in terms of providing a fully satisfactory model of the business cycle. In this regard, it is conjectured that explicitly accounting for the role of heterogeneity in business-cycle dynamics could lead towards a viable solution.

1 Introduction

The New-Keynesian model has, in recent times, emerged as the dominant analytical framework for monetary policy discussions among the broad class of dynamic stochastic general equilibrium (DSGE) models. Building upon the New Classical and Keynesian literatures it seeks to provide a theoretically acceptable and empirically plausible framework within which to address business cycle and optimal policy questions. While the Keynesian features like nominal inertia yield empirically attractive predictions such as real effects of monetary policy, the New Classical intertemporal optimisation framework enables a rigorous analysis of expectations and forward-looking behaviour. Importantly,

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it has provided microeconomic foundations for the traditional IS-LM type analyses and put dynamic macroeconomic analysis on a sounder theoretical footing.[1]

However, from a quantitative perspective, the model has had considerable difficulty in matching the actual moments of aggregate macroeconomic data, especially in regard to persistence of variables. So much so that there is a substantial literature devoted to the task to generating sufficient endogenous persistence in the DSGE model to match the data.

Macroeconomic aggregates are constituted of arguably diverse individual components. The most important examples of such heterogeneity are the GDP and the aggregate price level. Individual commodities as well as prices have heterogeneous dynamics on account of a variety of specific behavioural and institutional factors such as variable input and transactions costs and demand structures. Recognising the dynamic heterogeneity of the constituents of macroeconomic aggregates leads to a number of questions. What are the implications of heterogeneity for the modelling of aggregate dynamics? Would much of significance be lost by failing to take explicit account of heterogeneity? How would heterogeneity affect our interpretation of results based on aggregates?

This paper argues that although aggregates are a natural point of departure for business cycle analysis, an explicit recognition of heterogeneity is essential for understanding properly the dynamic behaviour of aggregates in response to exogenous shocks, without wrongly imputing such behaviour to unreasonable preference or technology parameters. It attempts to build a case for a more explicit analysis of heterogeneity in sticky-price DSGE models by looking at the conventional New-Keynesian model and its several extensions, all of which have a modest performance in terms of endogenous business-cycle propagation. Following this, I try to motivate introduction of heterogeneity in the New-Keynesian context by looking at a simpler partial-equilibrium model of heterogeneous price setting.

The paper is organised as follows. Section 2 looks at some data and data-based stylised facts concerning macroeconomic persistence. A discussion of theoretical questions and the associated literature accompanies this. Section 3 describes the canonical New-Keynesian model along with its various extensions and analyses its performance by means of impulse response functions, which show that the predicted responses are neither as gradual nor as persistent as in the data. Against this background, Section 4 presents a simple partial equilibrium model of price setting where there is sectoral heterogeneity characterised by exogenous sectoral marginal costs and relative prices. Simulations show that the persistence of aggregate inflation is much greater when sectoral inflation rates have heterogeneous dynamics on account of heterogeneity in sectoral marginal costs and relative prices. Section 5 concludes.

[1] Among others, McCallum and Nelson (1999) show how an IS-LM type model can be derived from a fully-micro-founded stochastic general equilibrium model.

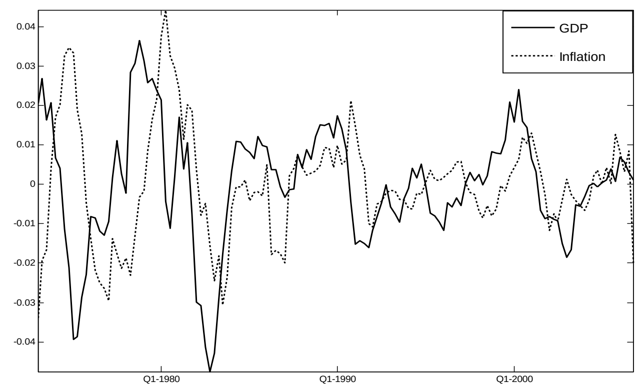

Figure 1: HP Filtered US GDP and CPI Inflation

2 The Persistence of Macroeconomic Aggregates

Even though the "dominant macroeconomic fact in developed economies...is that of output growth" (Blanchard and Fischer, 1989), data show that there are substantial and persistent fluctuations in the aggregate output, inflation and the real exchange rate over time. Figure 1 plots the Hodrick-Prescott (Hodrick and Prescott, 1997)[2] filtered US GDP and year-on-year CPI inflation for the post-war period from 1947 Q1 to 2006 Q3.

The persistence of GDP and inflation is evident in Figure 1. Also, inflation is procyclical, though its path often follows that of GDP with time-varying lags. Particularly, the contemporaneous correlation between the two variables is quite low (equal to 0.069 in the above sample). The sample first-order autocorrelation of the GDP and inflation series are, respectively, 0.86 and 0.84 and, on average, their journey back to equilibrium takes about three years.

There are two main questions posed in the context of a series like those in Figure 1. The first is what causes it to deviate from the long-run equilibrium path? There are two main competing views on this: (*i*) the real business cycle (RBC) school that ascribes most fluctuations to productivity shocks (Prescott, 1986)[3] and (*ii*) the new-Keynesian school which considers a range of exogenous shocks including monetary, productivity and preference shocks, but emphasises largely monetary policy shocks as the main source of business cycles [see, among many others, Rotemberg and Woodford (1997), Clarida, Gali and Gertler (1999, 2000) and Gali (1999, 2002)]. A lively debate has

[2]Hodrick and Prescott first developed this filter as a working paper in 1980, which was finally published in a journal in 1997.

[3]Prescott claimed that around 75% of business cycle fluctuations are caused by productivity shocks.

raged in the NK literature recently on this subject following Gali's (1999) provocative analysis concluding that the role of technology shocks in propagating business cycles is negligible. Gali and Rabanal (2004) review this literature and provide extensive evidence supporting this view. In the light of these developments, this paper takes the view that monetary shocks, rather than technology shocks, have a significant role in business-cycle propagation and, therefore, in the DSGE models considered below, responses to shocks to the monetary-policy instrument will be the centre of focus.

It is customary in the literature to study the impact of monetary shocks using identified vector autoregressions (VARs) [see Christiano, Eichenbaum and Evans (1999)]. The stylised facts are usually summarised through impulse response functions. For US data from 1973Q1 till 2006Q4, Figure 2 plots the impulse response functions from a four-variable VAR in GDP, CPI inflation[4], trade-weighted dollar and the effective federal funds rate[5]. Figure 2 summarises the stylised facts that the New-Keynesian literature seeks to deal with. A positive one standard deviation innovation to the federal funds rate causes a gradual fall in the real GDP, with the maximal impact of the innovation attained much later than the occurrence of the shock, which is reflected in the hump-shaped response of output. Also, the response of output is highly persistent. Upon impact, CPI inflation rises, before falling very sluggishly. Another noteworthy feature is that the peak response of inflation occurs somewhat after the peak response of output. This is consistent with the delayed catch-up of inflation with output in Figure 1. Trade-weighted dollar appreciates in response to the positive interest rate shock, perhaps adding to the list of explanations for why uncovered interest parity (UIP) hypothesis is violated over short horizons[6].

The average persistence of the US economy as captured by the VAR impulse responses is somewhere between three and five years. The task for theory is to provide structural models that can replicate this behaviour, so that policy analysis can be carried out without incurring the Lucas critique [Lucas (1976)].

The second question is: why are aggregate series and other series that depend on them so persistent. The real business cycle school has had limited success in this context[7], as most of their models are incapable of producing much endogenous persistence.

[4]Quarter-on-quarter, rather than year-on-year, CPI inflation has been used because in the DSGE models calibrated to quarterly data, we shall work with one-period inflation, rather than four-period inflation.

[5]The US data has been obtained from the Federal Reserve Bank of St Louis' FRED Database. The lag length chosen for the VAR is 4 and is based upon the Bayesian (Schwarz) information criterion. The impulse responses are based upon a triangular decomposition of the error covariance matrix. Using a Cholesky decomposition gives very similar results. The VAR output has been generated using E-Views 4.1.

[6]See Sarno and Taylor (2002) or Mark (2001) for a discussion of UIP and Eichenbaum and Evans (1995) for a discussion of the *monetary-policy induced UIP puzzle*.

[7]Rebelo (2005) is a most up-to-date review on the performance of RBC models, coming from one of the key architects of the baseline RBC theory. A more detailed discussion of the issue of lack of

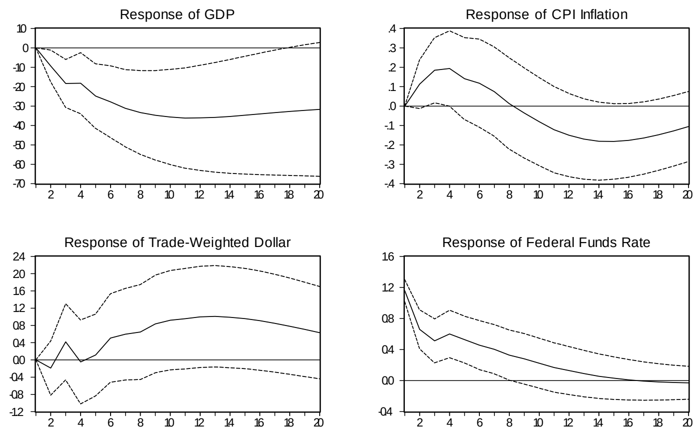

Figure 2: Impulse Responses to a Shock to the Federal Funds Rate

Interestingly, the only form of endogenous persistence that appears in real business cycle models is due to some form of heterogeneity. For example, Christiano, Eichenbaum and Evans (2005) find that the notion of variable capital utilisation, first developed by Basu (1996) and Burnside, Eichenbaum and Rebelo (1996), has important implications for the persistence of output and inflation in their structural DSGE model. As a general principle, King and Rebelo (1999) show that factor variability, capital or labour, can lead to significant business cycle propagation within an RBC model.

The New-Keynesian school has, on the other hand, relied heavily on the Keynesian idea of short-term nominal rigidity in a monopolistic-competitive framework as a source of endogenous persistence. Chari, Kehoe and McGrattan (2000, 2002) and Bergin and Feenstra (2000, 2001) have, however, concluded that models with reasonable degrees of nominal inertia (sticky prices or wages or both) are unable to replicate the persistence behaviour of output, inflation and the real exchange rate.

Very recently, building on the New-Keynesian tradition, a new line of research has opened up into some of the questions posed in this paper. This literature introduces sectoral heterogeneity in price/wage stickiness explicitly in the New-Keynesian framework. Dixon and Kara (2005) develop what they term a Generalised Taylor Economy, where there are multiple sectoral wage-contract lengths. They show that even a small proportion of longer-term wage contracts can lead to significant enhancement in endogenous persistence. Carvalho (2006) performs a similar exercise in a multi-sector Calvo economy and provides analytical as well as numerical results showing that heterogeneous economies have endogeneous persistence several orders of magnitude larger than "single-sector" economies.

endogenous persistence in RBC models appears in King and Rebelo (1999).

3 The Baseline New-Keynesian Model

In this section, we look briefly at the baseline New-Keynesian model. The model comprises a representative household maximising expected discounted utility over an infinite time horizon and supplying the labour input to firms[8], a continuum of monopolistically competitive intermediate firms indexed along the unit interval by $s \in [0, 1]$ and setting prices in a staggered fashion à la Calvo (1983)[9], and an independent central bank following an interest-rate Taylor (1993) rule. The household owns all firms and is entitled to all residual profits of the firms. It is common in the persistence literature to model monetary policy using an exogenous process for the supply of nominal money. However, this does not represent a very good approximation to how monetary policy is conducted in practice. As Taylor (1993) and Gali and Gertler (1999) show, Taylor-style rules provide a reasonably good approximation of the actual conduct monetary policy in the US.

3.1 The Representative Consumer Household

The representative consumer household maximises expected utility over an infinite time horizon where the intertemporal utility function is twice continuously differentiable and time separable. It is assumed that consumption C_t, real cash balances $m_{d,t} \equiv M_{d,t}/P_t$ and leisure $-L_t$ yield utility to the consumer and that the utility function is separable in these three arguments. The household's problem, therefore, is to maximise

$$E_t \sum_{\tau=t}^{\infty} \beta^{\tau-t} \left(\frac{C_\tau^{1-\sigma}}{1-\sigma} + \frac{m_{d,\tau}^{1-\sigma}}{1-\sigma} - \frac{L_\tau^{\sigma_L}}{\sigma_L} \right) \tag{1}$$

where $\beta \in (0, 1)$ is a subjective discount factor, $\sigma > 0$ is the relative risk aversion parameter and $\sigma_L > 0$ is the labour-supply elasticity parameter. C_t is a constant elasticity of substitution (CES) index of aggregate consumption, comprised of monopolistically produced intermediate outputs $C_t(s)$, $s \in [0, 1]$ each of which has price $P_t(s)$. C_t has a corresponding price index P_t derived from a unit-cost minimisation problem. These quantities are related as follows:

[8] It is also common in the literature to assume that there is a continuum of households indexed along the $[0, 1]$ interval with the same utility function and that there is a set of complete state-contingent claims, so all risks may be insured against. Then a representative household and a continuum of households give equivalent formulations.

[9] Alternative price-setting mechanisms have been considered in the literature such as Taylor's (1980) overlapping contracts model [e.g. Chari, Kehoe and McGrattan (2000), Bergin and Feenstra (2000), Dixon and Kara (2005)] and fixed-cost models [e.g. Rotemberg (1982, 1987) and Ireland (2001)]. Roberts (1995) shows that all of these models give rise to a similar supply side relation which relates inflation to its own conditional expectation and marginal costs or output gap.

$$C_t = \left[\int_0^1 C_t(s)^{\frac{\nu-1}{\nu}} ds\right]^{\frac{\nu}{\nu-1}}, \quad C_t(s) = P_t(s)^{-\nu} P_t^{\nu} C_t, \quad P_t = \left[\int_0^1 P_t(s)^{1-\nu}\right]^{\frac{1}{1-\nu}} \tag{2}$$

which are respectively aggregate consumption, the demand function for an individual consumption good and the aggregate price level. Maximisation of (1) is subject to the following intertemporal budget constraint:

$$M_{d,t} + \frac{B_t}{R_t} + P_t C_t = B_{t-1} + W_t L_t + \Pi_t + M_{d,t-1} + T_t \tag{3}$$

where B_t is the net stock of one-period riskless bonds at the end of period t, W_t is the nominal wage, R_t the gross (i.e. 1 + net) nominal rate of return on B_t, Π_t the total profits received by the household from producers and T_t a nominal transfer received by the household from the monetary authority. The first-order conditions are a bond Euler equation, a labour supply equation and a money demand function given, respectively, by

$$\beta E_t \left[C_{t+1}^{-\sigma} R_t \left(P_t / P_{t+1}\right)\right] = C_t^{-\sigma}, \quad L_t^{\sigma_L - 1} = C_t^{-\sigma}\left(W_t / P_t\right), \quad m_{d,t}^{-\sigma} = C_t^{-\sigma}\left[1 - 1/R_t\right] \tag{4}$$

Also, in order to ensure that the intertemporal consumption-possibilities set is bounded and there exists a unique solution to the utility maximisation problem, the relevant transversality (no-Ponzi game or no-bubbles) condition on bonds is imposed.

3.2 Production and Pricing

Intermediate good $s \in [0, 1]$ is produced using the following simple linear technology:

$$Y_t(s) = A_t L_t(s) \tag{5}$$

where $L_t(s)$ is the labour input used by firm s and A_t is an economy-wide technology shock that affects all firms in the same way. Analogously to aggregate consumption, the aggregate output of the economy is a CES aggregate of the individual goods $Y_t(s)$ given by

$$Y_t \equiv \left(\int_0^1 Y_t(s)^{\frac{\nu-1}{\nu}}\right)^{\frac{\nu}{\nu-1}} \tag{6}$$

In the canonical New-Keynesian model, price stickiness is commonly modelled using Calvo's (1983) formulation where every period firms are chosen randomly to set their price with a given probability[10].

Profit maximisation subject to the Calvo constraint on price setting and subject to the satisfaction of the demand function in (2) for good s yields the first order condition

$$P_t(s) = \left(\frac{\nu}{\nu - 1}\right) \frac{\sum_{\tau=t}^{\infty} \omega^{\tau-t} E_t S_\tau C_\tau {P_\tau}^{1+\nu} mc_\tau}{\sum_{\tau=t}^{\infty} \omega^{\tau-t} E_t S_\tau C_\tau {P_\tau}^{\nu}} \tag{7}$$

where $(1-\omega)$ is the price-resetting probability, $mc_\tau \equiv W_\tau/(P_\tau A_\tau)$ is the real marginal cost of all monopolists in period $\tau \geq t$ and $S_\tau \equiv \left(\frac{\beta^{\tau-t} C_\tau^{-\sigma}}{C_t^{-\sigma}} \frac{P_t}{P_\tau}\right)$ is a stochastic discount factor that is equal to the intertemporal marginal rate of substitution of the representative consumer between date t and date τ consumption. Only symmetric equilibria are considered, so that all firms setting their price in period t choose the same price. Therefore, the aggregate price level evolves according to the following recursive relation

$$P_t^{1-\nu} = (1-\omega) P_t(s)^{1-\nu} + \omega {P_{t-1}}^{1-\nu} \tag{8}$$

3.3 Market Clearing and Equilibrium

To close the model, a policy side is specified where an independent central bank sets the nominal interest rate in response to inflation and output. The following Taylor (1993) style interest-rate rule is considered

$$R_t = R_{t-1}^{\phi} \left(\left(\frac{P_t}{P_{t-1}} \right)^{\phi_p} Y_t^{\phi_Y} \right)^{1-\phi} \epsilon_{r,t} \tag{9}$$

The lagged interest-rate term captures interest-rate smoothing behaviour [see Clarida, Gali and Gertler (1999)].[11] It is assumed that the central bank sets the money supply in order to hit a target level of interest rate. Since real money balances enter the period

[10] The Calvo model has an unattractive property that the number of periods for which the price has remained constant has no bearing whatsoever on the likelihood of the price being changed in the current period. Wolman (1999) considers a modification of the Calvo model which implies a higher probability of price change for prices that were set in the more distant past. Also, as Dixon (2006) points out, in the Calvo model, it is possible that a (possibly negligibly) small proportion of firms have prices set for arbitrarily long periods of time.

[11] There has been some recent controversy about such a rule with Rudebusch (2005) arguing that evidence from the term structure of interest rates points against any purposive smoothing behaviour and that the apparent smoothing behaviour arises because the influences on policy makers (i.e. shocks) are themselves persistent. The debate is ongoing and unresolved. Moreover, observationally, the two formulations do not appear to be very different. Since rules embodying explicit smoothing are quite dominant in the mainstream monetary policy literature and their empirical performance is reasonably good, we choose the specification in Clarida et al (1999).

utility separably, the money demand function in (4) is redundant from the perspective of solving for equilibrium.

Since the economy is closed and has no capital accumulation and government spending, in equilibrium, aggregate output is equal to aggregate consumption, i.e. $C_t = Y_t$. Owing to the non-linear (CES) aggregation relation (6), it is not straightforward to aggregate firm-level production functions (5) in order to derive an explicit relation between aggregate output Y_t and aggregate labour L_t. However, for local analysis (in the neighbourhood of a deterministic steady state) it is customary to use a linear aggregation over production functions, i.e. $Y_t = \int_0^1 Y_t(s)ds$, which enables the following aggregate relation

$$Y_t = A_t L_t$$

where $L_t = \int_0^1 L_t(s)\, ds$. Finally, in the bond market, net nominal bond holdings are zero in equilibrium.

Imposing these conditions and using by-now standard methods of loglinearisation (see Uhlig (2001)), the above nonlinear economy can be reduced to the following first-order system:

$$
\begin{aligned}
\hat{Y}_t &= E_t[\hat{Y}_{t+1}] - \frac{1}{\sigma}(\hat{R}_t - \hat{\pi}_{t+1}) && (10)\\
\hat{L}_t &= \frac{1}{(\sigma_L - 1)}(\hat{W}_t - \hat{P}_t - \sigma \hat{Y}_t) && (11)\\
\hat{\pi}_t &= \frac{(1-\omega)(1-\omega\beta)}{\omega}\widehat{mc}_t + \beta E_t[\hat{\pi}_{t+1}] && (12)\\
\widehat{mc}_t &= \hat{W}_t - \hat{P}_t - \hat{A}_t && (13)\\
\hat{Y}_t &= \hat{L}_t + \hat{A}_t && (14)\\
\hat{\pi}_t &= \hat{P}_t - \hat{P}_{t-1} && (15)\\
\hat{R}_t &= \phi \hat{R}_{t-1} + (1-\phi)(\phi_p \hat{\pi}_t + \phi_Y \hat{Y}_t) + \xi_t && (16)
\end{aligned}
$$

where hats above the symbols represent the log-deviations from the steady state values of the relevant variables and inflation $\hat{\pi}_t$ is defined in log-deviation terms in equation (15). The logarithm of the productivity shock $\hat{A}_t$ is assumed to follow a first-order stationary autoregressive process and $\xi_t \equiv \log(\epsilon_{r,t})$ is a white-noise shock. The equations in (10), (11), (12), (13), (14), (15) and (16) constitute a system of seven equations in seven unknowns $\hat{Y}_t$, $\hat{L}_t$, $\hat{P}_t$, $\hat{\pi}_t$, $\hat{W}_t$, $\widehat{mc}_t$ and $\hat{R}_t$. A rational-expectations equilibrium for the seven control variables with the two state variables $\hat{R}_{t-1}$ and $\hat{P}_{t-1}$ and two exogenous shocks to monetary policy and economy-wide productivity can be computed using any standard algorithm[12] [13]. The algorithm used to solve the model is that described in Klein (2000) and implemented using the MATLAB software. For calibration, standard values for the policy-invariant parameters are chosen such as those described in Walsh (2003). They are as follows: $\beta = 0.99$ (implying a steady state interest rate of about 1 per cent), $\sigma = 1$ and $\sigma_L = 1.5$, $\phi = 0.8$, $\phi_p = 2$ (must be greater than one for existence of a unique equilibrium) and $\phi_Y = 0.01$. The choice of the Calvo parameter ω deserves some comment. In the literature, it is customary to choose $\omega = 0.75$ in order to model an average four quarters (steady-state) duration of fixed-price contracts. However, as Dixon (2006) argues, the concept of average duration of contracts is not the same as the concept of average contract age across firms at a point of time, which is something one models using Taylor's (1980) overlapping-contracts structure. Failing to recognise this distinction leads researchers like Kiley (2002) to conclude that the Calvo model generates greater persistence than the Taylor model, where, in fact, what they are actually comparing are different concepts[14]. The idea is that whereas in the Taylor model, the length of an individual contract is explicitly stated, say, T periods, in the Calvo model, we only have a reset probability, $(1 - \omega)$, of a contract in the steady state. In the Taylor model, the average age of contracts at a point of time is given by $(T+1)/2$,[15] whereas, in Calvo, it is given by $1/(1 - \omega)$. So the implied relationship between the reset probability and the contract length is $T = (2 - (1 - \omega))/(1 - \omega)$. Now, if one were to compare like for like, then the appropriate choice for the Calvo parameter for a four-quarters' average-length of price contracts would be $\omega = 0.6$, rather than $\omega = 0.75$, which is the standard choice of calibration in the literature.

3.4 Impulse Responses

Once the model equilibrium has been computed, it is straightforward to perform an impulse-response analysis similar to that for the VAR above. Figure 3 plots the impulse response functions for output, employment, price level, nominal wage, real wage, real interest rate and real marginal cost in response to a one standard-deviation shock to the monetary-policy rule.

We start by looking at the economics of the model and then come to an examination

[12] There are by now several algorithms in the macroeconomics literature for solving first-order linear systems including those introduced by Blanchard and Kahn (1980), Klein (2000) and Uhlig (2001).

[13] It is common for monetary policy analysis to reduce the system to three equations in output y_t (or a related measure called output gap), inflation π_t and the interest rate r_t. However, since the principal objective here is business cycle analysis, all the relevant variables of the model are solved for.

[14] See Dixon and Kara (2006) for a comment on Kiley (2002) and a clarification of the two differing concepts.

[15] To see this, note that, in the Taylor world, at any point in time, there are T cohorts of firms and $1/T$ of them set prices every period, so that there are T different contract ages in force, namely $1, 2, ...T$ periods. Averaging the ages across the T cohorts, the average age is $(1+2+...+T)/T$, which gets simplified to $T(T+1)/2T = (T+1)/2$.

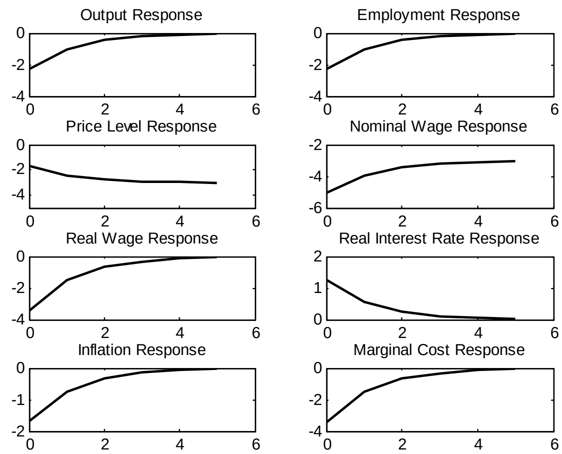

Figure 3: Impulse Responses to a Shock to Monetary Policy in the Baseline Model

of its adequacy for business cycle analysis. The model predicts that a positive shock to monetary policy (causing the central bank interest rate to rise) will cause a temporary fall in output, employment, inflation and marginal costs. The output effect works directly through the IS equation (10). In response to a positive shock to the nominal interest rate, it rises instantly. Because prices are sticky in the short run, the real interest rate also rises. This leads to an instant fall in output. The effect on all other variables is through this effect on output. For example, employment falls because output does (equation (14)). Because of the temporary fall in employment, there is a temporary fall in the real wage $\hat{W}_t - \hat{P}_t$, which causes marginal costs to fall temporarily, as productivity does not change. Both the nominal wage $\hat{W}_t$ and the aggregate price level $\hat{P}_t$ finally reach a new equilibrium level which is permanently lower than their initial equilibrium levels, but identical for the two variables (which is reflected in the fact that both employment and marginal costs reach their original equilibrium levels at the end of the adjustment period). However, there is an important difference in the way the nominal wage and the price level adjust. While the nominal wage jumps immediately in response to the shock and overshoots its new equilibrium level initially, the price level, after an initial jump, falls gradually to its new equilibrium. Particularly, there is no overshooting for the price level, on account of the short-run fixity of prices, while the wage rate overshoots because it is assumed flexible. Finally, there is also a temporary fall in inflation because of the fall in marginal costs and price level.

Intuitively as well as empirically, the model correctly describes the impact of a contractionary monetary policy shock. Also, as seen from the impulse responses, inflation and employment are procyclical, which is consistent with the empirical evidence on business-cycle co-movements. This feature is not shared by the baseline RBC model with flexible prices and no other frictions. Given the evidence in Gali (1999) and Gali and Rabanal (2004) and the stylised facts about cyclical co-movements in the data [see Walsh (2003), Chapter 1], the model provides motivation for the hypothesis that business cycles are indeed propagated to a large extent by monetary shocks.

3.5 Achievements and Challenges

At one level, by providing microfoundations for the Keynesian theories of business cycles, the NK model has overcome some of the most virulent criticism levelled in the history of macroeconomics. Lucas' (1976) attack on the traditional Keynesian econometric models had created enormous pessimism in the literature regarding the Keynesian philosophy of the business cycle. The NK literature has not only mitigated that pessimism substantially, but also provided a theoretically elegant and empirically realistic framework for business-cycle analysis. The system of equations from (10) to (16) is essentially a Keynesian-model but one that is not subject to the Lucas critique. The model is fully micro-founded and structural. Formation of expectations is clearly characterised and their role in equilibrium as well as disequilibrium dynamics well understood.

The achievement of the NK model is reflected in the impulse-response analysis above. The baseline RBC model fails to predict many of the features of the data, especially the pro-cyclicality of employment and inflation. These features are among the main predictions of the NK model above describing the monetary transmission mechanism.

However, from the perspective of being an adequate description of business cycles, there are two key shortcomings of the model. First, the response of all variables to shocks is in the nature of a jump. Output and inflation, for example, respond instantly to a shock to the interest rate and the maximal impact of the shock on them is immediate. Unlike the VAR impulse responses to a shock to the Federal funds rate, there is no hump in the response. This is an extremely important phenomenon of the business cycle and is relevant from the perspective of not only optimal policy but also issues like financial market efficiency. The optimal policy considerations are obvious. If the model has to be a useful device for the analysis and conduct of optimal policy, then it must provide a reasonably good description of the actual time paths of aggregate variables following a policy impulse. The financial-market efficiency angle is less obvious and relatively little explored in the DSGE literature until recently. It may be argued that this delayed response of macroeconomic aggregates is crucial to understanding the short-run failures of market-efficiency theories such as uncovered interest parity (UIP). The main idea is captured in the VAR impulse response of the trade-weighted dollar above, where in response to a positive interest-rate shock, the exchange rate does not appreciate instantly and then depreciate gradually to a new equilibrium (very much in violation of the UIP hypothesis which predicts that an instant appreciation would be followed by a depreciation over the near term). Indeed, in response to the policy shock, the exchange rate continues to appreciate over a few quarters and responds in the same "hump-shaped" manner as output[16]. Fuhrer (2000) has addressed the issue of hump-shaped responses using a special kind of preference structure, namely habit formation. We look at this issue presently.

The second very important difference between the VAR responses and the model responses is that the model responses are much less persistent than the VAR responses. Whereas the average persistence is at least three years in the data, the model generated persistence in response to monetary policy shocks is even less than one year. This has been termed the *persistence puzzle* by Chari, Kehoe and McGrattan (2000, 2002). The persistence of the model would rise if the Calvo parameter ω were higher for the obvious reason. The more the price stickiness, the greater the persistence. However, in the basic price-stickiness model, there is no other mechanism that would generate higher persistence for reasonable values of calibrated parameters.

The analysis of a number of studies including those by Erceg, Henderson and Levin (2000), Ascari (2000) and Huang and Liu (2002) suggests that adding sticky wages may improve the endogenous-persistence performance of the NK model. The next section takes a look a model that has wage stickiness in addition to price stickiness.

3.6 Adding Wage Stickiness

In order to introduce wage stickiness using the Calvo model, it is customary to start with the assumption of a continuum of households indexed along the unit interval $[0,1]$ and assume that there exists a complete set of state contingent claims. Then each household is modelled as supplying a differentiated labour service to firms [see, for example, Erceg, Henderson and Levin (2000) or Canzoneri, Cumby and Diba (2006)]. The existence of complete markets ensures that the households are homogeneous in terms of their consumption decisions but heterogeneous in terms of their labour supply decisions. Aggregate labour L_t and wage W_t are now composites of individual labour types $L_t(i)$ and wage rates $W_t(i)$, $i \in [0,1]$. These quantities are related as follows, where derivations follow essentially the same arguments as for aggregate consumption and price level in (2):

$$L_t = \left(\int_0^1 L_t(i)^{\frac{\nu_L - 1}{\nu_L}} di\right)^{\frac{\nu_L}{\nu_L - 1}}, \quad L_t(i) = W_t(i)^{-\nu_L} W_t^{\nu_L} L_t, \quad W_t = \left(\int_0^1 W_t(i)^{1-\nu_L} di\right)^{\frac{1}{1-\nu_L}}$$

The derivation of the optimal wage setting equation is now through a similar consumer optimisation problem where now a "Calvo" constraint is imposed along with the

[16] McCallum (1994) and Eichenbaum and Evans (1995) provide arguments and evidence (but not a well-articulated macro model) for why violations of UIP are closely related to business-cycle dynamics. Bansal and Dahlquist (2000) provide evidence that rejections of UIP are systematically related to business cycle dynamics in different countries, with UIP being much more strongly rejected for low-inflation countries than for high-inflation ones, where its performance is quite good.

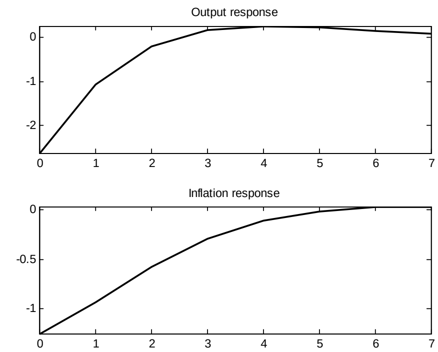

Figure 4: Impulse Responses to a Shock to Monetary Policy in the Sticky-Price Sticky-Wage Model

demand function for the labour services of individual types, such as the one given in the last equation. In loglinear terms, the result for optimal nominal wage setting, in analogy with equation (12) is the following wage-inflation New Keynesian Phillips curve

$$\hat{\pi}_t^w = \frac{(1-\omega_L)(1-\omega_L\beta)}{\omega_L}(\widehat{mrs}_t - \hat{w}_t) + \beta E_t \hat{\pi}_{t+1}^w$$

where $\omega_L \in (0,1)$ is the Calvo parameter for wage setting, $\hat{\pi}_t^w \equiv \hat{W}_t - \hat{W}_{t-1}$ is the wage inflation, $\widehat{mrs}_t \equiv (\sigma_L - 1)\hat{L}_t + \sigma\hat{C}_t$ is the marginal rate of substitution between labour and consumption (output) and $\hat{w}_t$ is the real wage. The deviation of the marginal rate of substitution from the real wage represents a cost to the household, since, if wages were flexible, then equality between these two quantities would hold.

The impulse responses for output and inflation are shown in Figure 4. A comparison of Figures 3 and 4 reveals that there is some improvement in endogenous persistence with the addition of sticky wages, especially for inflation, but also to an extent for output. However, the difference is not significant enough to make us change our view of the model regarding its adequacy as a descriptive device. The gain in persistence is at best marginal, though sticky wages is a sufficiently realistic and useful assumption to retain in the model.

3.7 Habit, Indexation and Hump

In neither of the models above is there any hump-shaped response of output or inflation, which is quite a distinctive feature of the VAR impulse responses commonly observed. The literature has explored two solutions for each of these variables. First, for a hump in output, Fuhrer (2000) has argued that habit formation (or habit persistence[17]) in

[17]The idea of habit formation or persistence originated in the context of the equity-premium puzzle literature in financial economics, but it has been applied in good measure for business cycle analysis

consumer preferences could be a plausible resolution of the "hump problem". Recent studies, including the influential paper by Christiano, Eichenbaum and Evans (2005), have assumed period-utility preferences of the type (ignoring arguments other than consumption):

$$U(C_t) = \frac{(C_t - bC_{t-1})^{1-\sigma}}{1-\sigma}$$

where the parameter b captures the intensity of habit formation ($b = 0$ corresponds to the baseline model). What this utility function implies is that marginal utility of consumption in the current period is a function of both today's and yesterday's consumption. More specifically, an increase in today's consumption lowers marginal utility of consumption today and increases the marginal utility of consumption tomorrow. Past consumption C_{t-1} represents the consumer's stock of habit.

As for the hump in inflation, in the context of the Calvo model, the main recourse has been to the assumption that firms that do not set their prices in a particular period index them to past inflation, i.e. increase prices at the rate of inflation in a previous period[18]. This gives rise to the following law of motion for any one of the fraction ω of the firms that do not set their price in the current period

$$\log P_t(s) = \log P_{t-1}(s) + \kappa \log(1 + \pi_{t-1})$$

where $\pi_{t-1} \equiv (P_{t-1}/P_{t-2}) - 1$ and $\kappa \in [0, 1]$ is the degree of indexation. The law of motion followed by the price level (8) must be modified to reflect this added structure as follows:

$$P_t^{1-\nu} = (1-\omega)P_t(s)^{1-\nu} + \omega \left(P_{t-1} \left(1 + \pi_{t-1}\right)^{\kappa}\right)^{1-\nu}$$

With this modification, the (loglinearised) Phillips curve (aggregate supply) equation (12) now becomes:

$$\hat{\pi}_t - \kappa\hat{\pi}_{t-1} = \frac{(1-\omega)(1-\omega\beta)}{\omega}\widehat{mc}_t + \beta E_t \left(\hat{\pi}_{t+1} - \kappa\hat{\pi}_t\right)$$

which, with full indexation (i.e. $\kappa = 1$), becomes

$$\hat{\pi}_t = \frac{(1-\omega)(1-\omega\beta)}{\omega(1+\beta)}\widehat{mc}_t + \frac{\beta}{1+\beta}E_t\hat{\pi}_{t+1} + \frac{1}{1+\beta}\hat{\pi}_{t-1}$$

Similar changes feature in the wage New-Keynesian Phillips curve as well.

too. See Schmidt-Grohe and Uribe (2007) for an up-to-date review of the habit-persistence literature.

[18] Notable examples for this approach are Smets and Wouters (2002) and Christiano, Eichenbaum and Evans (2005). Woodford (2003, Chapter 3, Section 3.2) provides an exposition of the general approach.

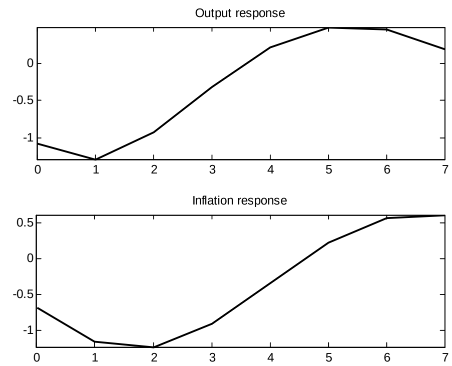

Figure 5: Impulse Responses to a Shock to Monetary Policy in the Model with Habit Persistence and Indexation in Price and Wage Setting

The impulse responses of output and inflation from a modification of the baseline model incorporating habit formation and indexation are plotted in Figure 5. There is a clear gain in the persistence of output, quite apart from some delay induced in the shock achieving its maximal impact. Both modifications seem to have taken the model closer to realism. However, the persistence of the model is still way too less as compared to the data. Moreover, the timing of the humps also fails to match the data by a large measure, though, to the model's credit, it does capture the fact that inflation peaks after output. However, both peaks are much earlier than in the VAR impulse responses.

4 Heterogeneity and Inflation Persistence

Previous sections have attempted to take the NK model closer to realism. However, we have seen that a number of enrichments of the structural model fail to improve its quantitative performance. In this section, we analyse the effects of heterogeneity in partial equilibrium and suggest that this could potentially make the NK framework rich enough to be a satisfactory description of the business cycle propagated by monetary shocks. A small number of studies have recently attempted this line of attack on the persistence problem. A mention has already been made of Dixon and Kara (2005, 2006) who introduce heterogeneity in nominal-wage inertia by modelling a distribution of contract lengths. In the RBC tradition, Christiano et al (2005) have modelled what may be viewed as real-side heterogeneity by way of assuming variable capital utilisation by firms. In both of these cases, heterogeneity has the effect of making real marginal costs and, therefore, relative prices different across firms. They show that inflation persistence generated by their models is significantly higher than that generated by models without these features.

Short-run inflation dynamics can be influenced by both demand- and supply-side factors. Especially, both excess demand and positive (supply-side) cost shocks put upward pressure on inflation. Fuhrer and Moore (1995) provide evidence that variations in inflation arise independently of excess demand, which must be on account of ex-demand-side (i.e. supply side) shocks. Clarida, Gali and Gertler (1999) term these cost-push shocks. Interestingly, in the baseline model considered by Clarida et al (1999), the cost-push shock proves to be essential for any short term trade-off between inflation and output variability, which is arguably what enables monetary policy to influence short-run inflation.

Against this backdrop, this section presents a simple partial equilibrium model of price-setting behaviour where there is heterogeneity in marginal costs and relative prices across sectors. In order to focus sharply on heterogeneity, the demand and policy sides are not modelled. Therefore, both sectoral inflation rates and economy-wide inflation are entirely determined by costs. Long run inflation is assumed to be zero. Therefore, the presence or otherwise of money growth is irrelevant. This supply side model is, to an extent, inspired by Wolman's (1999) partial equilibrium model of inflation.

The economy still has measure 1, but, in order to model heterogeneity, the indexing interval $[0,1]$ is partitioned into N connected subintervals $\{I_n\}_{n=1}^{N}$ such that $I_n \bigcap I_m = \emptyset$ for $m \neq n$ and $\bigcup_{n=1}^{N} I_n = [0,1]$. The measure of each interval I_n is given by $\mu(I_n) = \lambda_n$. Monopolisitic-competitive producers indexed along each subinterval produce a unique non-storable good and set prices in a staggered way. Factor markets are not modelled and therefore any description of the production technology is also omitted. There is a competitive final-good producer that combines sectoral composite intermedaite goods $Y_{n,t}$, which in turn are a composite of sectoral intermediate inputs $Y_{n,t}(s)$, $s \in I_n$. These quantities are given by

$$Y_t = \left(\sum_{n=1}^{N} \lambda_n^{\frac{1}{\xi}} Y_{n,t}{}^{\frac{\xi-1}{\xi}} \right)^{\frac{\xi}{\xi-1}}, \quad Y_{n,t} = \left(\int_{I_n} Y_{n,t}(s)^{\frac{\nu-1}{\nu}} \right)^{\frac{\nu}{\nu-1}}, \tag{17}$$

$$Y_{n,t} = P_{n,t}^{-\xi} P_t^{\xi} Y_t, \quad Y_{n,t}(s) = P_{n,t}(s)^{-\nu} P_{n,t}^{\nu} Y_{n,t} \tag{18}$$

where ξ, $\nu > 1$ and the aggregate price index P_t and the sectoral price indices $P_{n,t}$ are given by:

$$P_t = \left(\sum_{n=1}^{N} \lambda_n P_{n,t}{}^{1-\xi} \right)^{\frac{1}{1-\xi}}, \quad P_{n,t} = \left(\lambda_n^{-1} \int_{I_n} P_{n,t}(s)^{1-\nu} \right)^{\frac{1}{1-\nu}}, \tag{19}$$

Every period a fraction $(1-\omega)$ of firms in each sector n is chosen at random to set their prices. Within each sector, all firms that are chosen to set their price choose the same price. The real marginal costs $mc_{n,t}$ vary across sectors and so do sectoral relative prices $P_{n,t}/P_t$. The maximisation problem for a typical sector n firm is stated as:

$$\max_{P_t(n)} E_t \sum_{\tau=t}^{\infty} S_\tau [\{\omega^{\tau-t} [P_t(n) - P_\tau mc_{n,\tau}] Y_\tau(n)\}] \tag{20}$$

where S_τ is a nominal discount factor defined by $S_\tau \equiv \prod_{j=1}^{\tau}(1+i_{t+j})^{-1}$ where i_{t+j} is the nominal interest rate in period $t+j$ assumed to be exogenous. The first-order condition gives the following solution for the optimal price set by sector n firms:

$$P_t(n) = \left(\frac{\nu}{\nu-1}\right) \frac{\sum_{\tau=t}^{\infty} \omega^{\tau-t} E_t S_\tau Y_\tau (P_{n,\tau})^{1+\nu} (P_\tau / P_{n,\tau})\, mc_{n,\tau}}{\sum_{\tau=t}^{\infty} \omega^{\tau-t} E_t S_\tau Y_\tau (P_{n,\tau})^{\nu}} \tag{21}$$

and the sectoral price indices evolve according to

$$(P_{n,t})^{1-\nu} = (1-\omega) P_t(n)^{1-\nu} + \omega (P_{n,t-1})^{1-\nu} \tag{22}$$

Loglinearisation of (21) and (22) around a deterministic zero-inflation steady state gives the following "sectoral New Keynesian Phillips curves":

$$\hat{\pi}_{n,t} = \frac{(1-\omega)(1-\beta\omega)}{\omega} \left(\widehat{mc}_{n,t} + \hat{P}_t - \hat{P}_{n,t}\right) + \beta E_t \hat{\pi}_{n,t+1} \tag{23}$$

where $\beta \equiv 1/(1+i)$ with i being the steady-state nominal as well as real interest rate, since inflation is assumed to be zero in the steady state.

What differentiates one sector from another is the dynamics of sectoral real marginal costs and relative prices. $\hat{D}_{n,t} \equiv \widehat{mc}_{n,t} - (\hat{P}_{n,t} - \hat{P}_t)$, the driving process for sectoral New-Keynesian Phillips curves, is assumed to follow the following stationary first-order autoregressive processes:

$$\hat{D}_{n,t} = \rho_n \hat{D}_{n,t-1} + \varepsilon_{D,t} \tag{24}$$

In a fully-specified model, sectoral real marginal costs will vary with sectoral real wages, real capital rentals or shocks to production technology. In particular, for this kind of heterogeneity to be credible, it would be critical to model heterogeneity in factor markets. For example, real marginal costs in two sectors would have different dynamics if wage stickiness between the two sectors was different by some order of magnitude.

Assuming $i > 0$, we have $\beta \in (0,1)$. Given that $D_{n,t}$ is exogenous, we can solve (23) forwards for $\pi_{n,t}$. The solution is

$$\pi_{n,t} = \zeta(\rho_n) D_{n,t} \tag{25}$$

where $\zeta(\rho_n) \equiv \frac{(1-\omega)(1-\beta\omega)}{\omega(1-\beta\rho_n)}$. Equation (25) shows that, in this simple model, the dynamic behaviour of $\pi_{n,t}$ is completely determined by that of $D_{n,t}$. Finally, sectoral inflations can be aggregated to get the economy-wide inflation as follows:

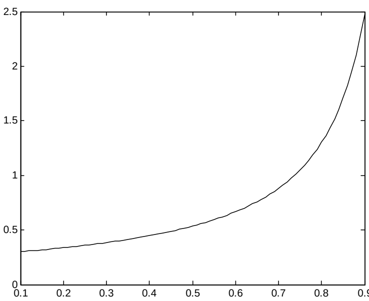

Figure 6: The Weights Function $\zeta(\rho_n)$

$$\pi_t = \sum_{n=1}^{N} \lambda_n \pi_{n,t} = \sum_{n=1}^{N} \lambda_n \zeta(\rho_n) D_{n,t} \tag{26}$$

By simulating time paths for $D_{n,t}$ the properties of the implied time path of economy-wide inflation can be derived using equations (24) and (26). Before doing that, it would be in order to examine carefully the constant $\zeta(\rho_n)$. Differentiating $\zeta(\rho_n)$ twice with respect to ρ_n shows that $\zeta(\rho_n)$ is increasing in ρ_n and at an increasing rate. Figure 6 plots this "weights" function $\zeta(\rho_n)$. A couple of interesting features of this function are noteworthy. First, clearly, the aggregation scheme places greater weights on high-persistence sectors. Secondly, the convex nature of $\zeta(\rho_n)$ shows that the distribution of persistence across sectors is crucial to understanding aggregate persistence. In particular, for heterogeneity to generate significant persistence, it is crucial to have at least a few high-persistence sectoral marginal costs. For example, if sectoral marginal cost persistence varied between 0.2 and 0.5, it would add little to overall persistence. On the other hand, even if most of sectoral costs were in the low persistence region, but there were only a small number of high-persistence sectors, then also the impact on overall persistence would be significant on account of the increasing weights. In this sense, higher-persistence sectors have a disproportionate effect on the aggregate and dominate lower-persistence sectors[19].

For simplicity, let us assume that the persistence coefficients are uniformly distributed over the interval $(0, 1)$. The open interval is required for the stationarity of the driving process $\hat{D}_{n,t}$. The mean persistence is, therefore, 0.5.

Figure 7 plots the sample autocorrelation functions (ACFs) of the individual sectoral inflations and aggregate inflation. In the left panel, the ACF given by the green curve

[19] This disproportionate effect arising for example on account of a handful of very long-term wage or pricing contracts is the central theme of the recent studies like Dixon and Kara (2005a) and Carvalho (2006).

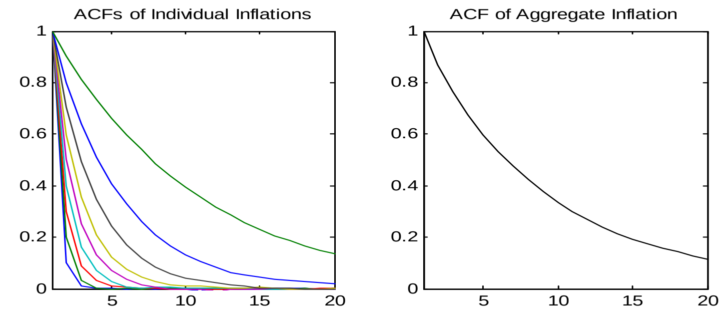

Figure 7: Autocorrelation Functions of Sectoral Inflations (left panel) and aggregate inflation (right panel).

furthest away from the origin corresponds to a marginal cost persistence parameter of 0.9, whereas the ACF curve closest to the origin corresponds to a marginal cost persistence parameter of 0.1. The curves in between correspond to the intermediate persistence parameters each differing by 0.1 from its predecessor so that there is a total of nine sectors in this example. As is clear from Figure 6 (left panel), the ACFs are not equidistant from each other and the distance between any two successive curves widens as we move away from the origin. This is due to the nature of the weights function $\zeta(\rho_n)$ which increases at an increasing rate with ρ_n. The effect of aggregation is evident in the sample ACF of the aggregate in the right panel, which is much closer to the ACF corresponding to $\rho_n = 0.9$ than to any other ACFs in the left panel.

The analysis above brings into sharp relief the role of heterogeneous dynamics of constituent variables for the dynamics of aggregates like inflation. By isolating price-setting in a heterogeneous environment from any other effects arising on account of demand pressures or policy impulses, we have been able to single out the persistence gain arising solely on account of heterogeneity in individual dynamics.

It is the argument of the present paper that, in a DSGE context, explicit modelling of such heterogeneity in sectoral aggregates could not only improve our understanding of the implications of heterogeneity for aggregate dynamics, but also provide a more realistic model for business-cycle and policy analysis.

5 Conclusion

This paper has taken a fresh look at the textbook New-Keynesian model and assessed its performance as a tool for business-cycle analysis. We have seen that the New-Keynesian approach is richer and more comprehensive in its description of the business cycle and broadly consistent with the findings of the empirical business-cycle literature.

However, quantitatively, the New-Keynesian approach has faced major obstacles in being an accurate description of the business cycle. Various modifications and enhancements of the baseline model do serve to take the model closer to the data. But none of the augmented versions produce time paths of aggregates that are comparable to the actual time paths in terms of timing of maximal impact and, more importantly, persistence.

Against this backdrop, it is suggested that an explicit account of heterogeneity in the dynamics of the individual quantities that aggregates are made of could go a long way towards providing an adequate tool for business-cycle and policy analysis. A few studies have taken this approach. However, we are still far from a complete understanding of how and why heterogeneity may be so important, even though we know that aggregates made of heterogeneous components are more persistent. Especially, the precise economic mechanisms at work may need to be characterised more clearly. Also, heterogeneity, like staggered price setting, may need to be better motivated in a DSGE model. Lastly, it would be desirable to have a model that incorporates heterogeneity, but, at the same time, is simple enough to be used for an analysis of optimal policy.

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