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The theoretical framework of monetary policy revisited

Abstract

The three-equation New-Keynesian model advocated by Woodford (2003) as a self-contained system on which to base monetary policy analysis is shown to be inconsistent in the sense that its long-run static equilibrium solution implies that the interest rate is determined from two of the system's equations, while the price level is left undetermined. The inconsistency is remedied by replacing the Taylor rule with a standard money demand equation. The modified system is seen to possess the key properties of monetarist theory for the long run, i.e. monetary neutrality with respect to real output and the real interest rate and proportionality between money and prices. Both the modified and the original New-Keynesian models are estimated on US data and their dynamic properties are examined by impulse response analysis. Our research suggests that the economic and monetary analysis of the European Central Bank could be unified into a single framework.

JEL classification: E40, E47; E52, E58

Keywords: Monetary theory; Central banking; New-Keynesian model; Impulse response analysis

1. Introduction

The New-Keynesian model as laid out by Rotemberg and Woodford (1997) and Goodfriend and King (1997) and developed in detail by Woodford (2003) appears to be today's mainstream approach to monetary analysis. As pointed out by McCallum (2010), "it has become the bible for a generation of young scholars who will likely dominate monetary economics for the next couple of decades". Requiring only a small number of equations and variables, the model has proved very helpful in deriving certain important principles for the conduct of monetary policy. However, a notable feature of this model, which is highly debated, is that monetary aggregates play no direct role in the transmission of monetary policy to output and inflation. Thus, inflation is no longer considered to be "always and everywhere a monetary phenomenon" according to Friedman's famous dictum (Friedman, 1963, p.17). Given that monetary policy decisions are made by most central banks with regard to the interest rate, changes in this rate, by influencing aggregate demand and the gap between actual output and its potential level, impact on inflation via the New-Keynesian Phillips curve. Interest rate policy, no matter whether it is optimal or not, may be thus characterized without any reference to monetary aggregates. These are determined from the equilibrium condition in the money market as the stock of money balances, which is sufficient to satisfy the demand for money at a particular level of the interest rate.

The importance of monetary aggregates has declined in central bank practice. The Federal Reserve already de-emphasized the role of monetary aggregates in its strategy in the early 1990s, although arguably this was due to empirical problems that originated from factors such as financial innovation, currency substitution, divergent developments in income and wealth etc, rather than new theories. An exception to this trend is the European Central Bank (ECB), whose monetary policy strategy is based on two analytical perspectives referred to as the "two pillars": the economic analysis and monetary analysis. The former focuses on a short- to medium-term horizon and analyzes price developments, which over this horizon are thought to be influenced largely by the interplay of demand and supply in the output market. The monetary analysis, on the other hand, is important enough to deserve a special consideration in the ECB's strategy and focuses on the medium- to long-term link between money and prices. However, the ECB's monetary policy strategy "was often derided by observers as lacking a

theoretical foundation” (Blanchard et al., 2010, p.5). For this reason, merging the two analytical pillars of the ECB’s strategy would appear to be a quite attractive and rewarding possibility. This would require a unified treatment of essential monetary and non-monetary determinants of inflation in a consistent framework (Papademos, 2008). Lucas (2007) raised a similar point, criticizing the increasing reliance of central bank research on New Keynesian modeling. He suggests that New Keynesian models “are formulated in terms of deviations from trends that are themselves determined somewhere off stage”. Thus, according to Lucas, these models should be reformulated to give a unified account of trends, including trends in monetary aggregates, but so far they have not been. In a similar vein, Pesaran and Smith (2011) argued that the long-run steady state, around which most New-Keynesian DSGE models are log-linearized, is estimated by deterministic trends or by purely statistical methods like the HP filter, a fact indicating a low degree of belief in long-run economic relations. It would instead be preferable to use the theory to get the steady state, which would give the model transparent long-run properties that offer themselves to a theoretical interpretation.

In this paper, we revisit the New-Keynesian model and examine its implications for the role of monetary aggregates in the conduct of monetary policy. Using the concept of static long-run equilibrium, we show that the New-Keynesian model, including a New-Keynesian Phillips curve, an aggregate demand equation and a Taylor rule, is internally inconsistent. In particular, when the endogenous variables of interest are real output, the interest rate and the price level, the latter is left undetermined, while two of the model’s equations provide long-run static equilibrium solutions for the same variable, namely the interest rate.

This problem can be remedied by inserting a standard money demand equation (instead of the Taylor rule) in the original New-Keynesian model. We confirm that in this modified model, real output and the real interest rate are determined from the New-Keynesian Phillips curve and the aggregate demand equation, respectively, while the money demand equation determines the price level. This model maintains all the desirable features of the original New-Keynesian macroeconomic system: first and foremost the main structural equations are still directly derived from the optimizing behavior of individual rational agents. The model can be solved for all three endogenous variables (output, interest rate and price level) using standard statistical techniques. Further, the time path of the endogenous variables, as obtained from

impulse response analysis, confirms that the modified model possesses the key long-run monetarist features, namely (i) monetary neutrality with respect to real output and the real interest rate and (ii) proportionality between money and prices (Abel and Bernanke, 1992).

Moreover, the modified three-equation model follows Pesaran and Smith's (2011) suggestion in the sense that a static long-run equilibrium is established. Importantly, from a policy perspective, this model enables the integration of the two pillars of the ECB's monetary policy strategy, i.e. the economic and monetary analyses. According to the model, consistent with the ECB analysis, the main (but not exclusive) short-run influences on the price level come from the interplay between the demand and the supply of output but the only lasting influence can come from the supply of money.

The rest of this paper is organized as follows. Section 2 discusses the original model (used as a benchmark for comparison) and the modified model as well as the role of monetary aggregates in these models. Section 3 describes theoretically the long-run properties and consistency of the models. In section 4 we present our empirical analysis. First, we estimate the two models and, subsequently, we examine their dynamics using impulse-response analysis. Section 5 concludes the paper.

2. Monetary policy: the current debate

A lively debate has developed recently within the field of monetary economics in the context of New-Keynesian dynamic stochastic general equilibrium (DSGE) models. This modeling framework is currently the dominant school of thought, both in academic circles and in actual central banking practice. It consists of only three structural relationships and does not include a money demand equation or, indeed, any monetary aggregates at all. Nonetheless, academic discussions and monetary policy decision-making are often grounded on this basis. Christiano et al. (2007) note that "the current consensus is that money and credit have essentially no constructive role to play in monetary policy".

2.1. *The benchmark model*

This paper revisits this popular framework with a view to reexamining its characteristics and consistency. We first set out the benchmark New-Keynesian DSGE model. Its main

equations are derived from the optimization problems of individual economic agents and its parameters are explicit functions of the underlying structural parameters of the consumer's utility function and the price-setting process, the latter involving nominal rigidities. Rational expectations and a forward-looking behavior are also incorporated into the model. Frequently cited references include Rotemberg and Woodford (1997, 1999) Goodfriend and King (1997) and McCallum and Nelson (1999). A standard version of such a model comprises the following three equations:

$$\Delta p_t = a_1 E_t \Delta p_{t+1} + a_2 (y_t - \bar{y}_t) + e_{\pi t} \quad (1)$$

$$y_t = b_0 + b_1 (i_t - E_t \Delta p_{t+1}) + E_t y_{t+1} + e_{yt} \quad (2)$$

$$i_t = i_t^* + c_1 (\Delta p_t - \pi^*) + c_2 (y_t - \bar{y}_t) + e_{it}, \quad (3)$$

where $\Delta p_t = \pi_t$ is inflation; π^* is the monetary authority's inflation target; y_t denotes output; \bar{y}_t is the flexible-price (natural) level of y_t ; i_t is the short-term interest rate; i_t^* is the sum of the central bank's view of the economy's equilibrium (or natural) real rate of interest r^* and inflation π_t ¹; $e_{\pi t}$ is a supply shock; e_{yt} is a demand shock; e_{it} is a monetary policy shock, and $0 < a_1 < 1$, $a_2, c_1, c_2 > 0$ and $b_1 < 0$ are parameters to be estimated. With the exception of the interest rate, all variables are in natural logarithms. The first equation has come to be known as the New-Keynesian Phillips curve (NKPC). The second is an "expectational" or "forward-looking" aggregate demand equation (AD). The third is a standard formulation of Taylor's interest rate rule, an increasingly popular tool among central bankers in recent years.

We briefly recall the intuition behind each of these equations. The NKPC is derived from the representative firm's optimization problem, under monopolistic competition. The standard formulation presented above is based on a Calvo-type framework (Calvo, 1983), i.e. one involving nominal price rigidities such that, in each period, a fraction of the firms re-optimize their price, while the remaining firms keep their prices fixed. Price-changing probabilities are independent of the time elapsed since the last adjustment, i.e. prices are

¹ See McCallum (2008). In Woodford (2008) the inflation component of i_t^* is the central bank's inflation target, while in McCallum (2001) it is expected inflation $E_t \Delta p_{t+1}$. Whichever definition is adopted, this does not alter the analysis that follows.

adjusted at exogenous random intervals. According to the specification derived from the above optimization problem, inflation depends on how much real marginal cost deviates from its frictionless level as well as on what the future inflation rate is expected to be, the latter reflecting the forward-looking nature of firms' behavior. As it can be shown that, under certain restrictions, the real marginal cost is proportional to the output gap,² in its most commonly used form the NKPC relates inflation to expected future inflation and to the deviation of output from the potential level that could have been attained under flexible prices. It is the assumption of nominal price rigidities that generates the real effects of monetary policy in the benchmark model.

The AD equation in the most basic model, i.e. that for a closed economy without a public sector, reflects the optimizing behavior of the representative consumer and the equilibrium in the goods market. It is derived from the Euler equation of a representative agent's optimization problem and relates output to expected future output and the real interest rate. Changes in the interest rate brought about by monetary policy affect the real short-term interest rate,³ altering the optimal consumption path. Thus, the aggregate demand function encapsulates the degree of control over the economy available to the central bank.

The third equation is a Taylor-type monetary policy rule, which stipulates how the monetary policy authority should move the nominal interest rate in response to a divergence of the actual inflation rate from its target or of output from its flexible-price natural level. The policy action implied by this rule is an upward adjustment of the nominal (and real, under the Taylor principle) interest rate in response to inflationary pressures.

A fourth equation is occasionally appended to the other three, namely a money demand (MD) equation such as the following:

$$m_t - p_t = d_0 + d_1 y_t + d_2 i_t + e_{mt}, \quad (4)$$

where $m_t - p_t$ represents log real money balances; $d_1 > 0$, $d_2 < 0$ are parameters; and e_{mt} is a money demand shock. However, the exact role, if any, of a money demand equation in the

² See Gali et al. (2001) and Rotemberg and Woodford (1997).

³ Assuming a stable relationship between the short-term interest rate and the monetary policy rate, the two terms are used interchangeably in this paper. In less basic models, the monetary policy rate influences the short-term interest rate, which in turn affects the long-run interest rate on which aggregate demand depends.

context of the New-Keynesian macroeconomic model has been and remains a subject of controversy.

2.2. The role of money in the benchmark model

Current analysis often disregards this last equation, considering it as not integral to the functioning of the model. Instead, it is viewed as an add-on relationship, which yields the level of money balances compatible with the inflation target set by the monetary policy authority. Indeed, the money demand equation is seen as superfluous in the sense that it does not affect the behavior of y_t , Δp_t or i_t . Its only function would be to specify the amount of money that is needed to implement the policy rule (3). Thus, policy analysis involving the above three variables could be carried out without even specifying a money demand function. According to Woodford (2008), “there is nothing structurally incoherent about a model that involves no role whatsoever for measures of the money supply”. The central bank influences the real economy only through the interest rate and, given the money demand relationship, it supplies money at the interest rate set.

The question which arises then is whether money could be given a causal or structural role in the "cashless" New-Keynesian framework. As Woodford (2003) indicates, there are various ways of introducing money into the model without altering its core characteristics. Most commonly, it is assumed that money is used to reduce transaction costs, and therefore it enters the household utility function. Under the assumption of separability of the utility function, the aggregate demand equation, as derived from household optimization, remains unaffected – money does not appear in this equation. Moreover, this optimization yields a standard money demand equation such as equation (4). In this way, money has no role to play from a policy perspective in determining the rate of inflation, still the money demand equation itself implies a long-run correlation between money and inflation. How reasonable is the separability assumption and what are the consequences of removing it? With the separability assumption lifted, real money balances enter into the aggregate demand equation⁴ and a causal link between money on the one hand and output and inflation on the other is introduced. McCallum (2001)

⁴ Money may also enter the discount factor of the price-setting firms and thus the New- Keynesian Phillips curve, see Berger et al. (2008).

notes that separability is an implausible assumption and considers as more likely a negative partial derivative of consumption with respect to money, implying that the marginal benefit of holding money, i.e. the reduction in transaction costs, increases with the volume of consumption spending. However, when McCallum tests whether the exclusion of money from the model is of quantitative importance, he finds that the magnitude of the error introduced thereby is extremely small, a finding consistent with the insignificance of money in empirical studies of the aggregate demand equation (e.g., Ireland, 2004; Andrés et al., 2009). This may reflect the fact that although money influences the marginal utility of consumption, it is usually needed for only a small fraction of transactions (Berger et al., 2008). Thus, the possible effects of money stemming from the non-separability of the utility function can be neglected.⁵

Turning to the derivation of the equilibrium solution, including that for inflation, Woodford (2008) advocates that this can indeed be obtained from the self-contained three-equation system. He indicates that, as implied by the solution of these three equations, in the long run inflation equals its policy target (or its long-run anchor) π^* , output equals its natural (flexible-price) level y^* and the short-term interest rate is equal to sum of the exogenous real rate of interest and steady-state inflation ($r^* + \pi^*$). Consequently, Woodford's premise is that, while monetary policy determines inflation not only in the short run but also in the long run via the interest rate, money balances play no role in this process.

2.3. *The debate on the role of money*

Several authors have questioned this view, arguing to the contrary that, in the context of New-Keynesian models, long-run inflation is in fact determined by the rate of money growth alone (see e.g., Nelson, 2003; Christiano et al., 2007; Ireland, 2004). Bernanke (2003) stated that the expectational Phillips curve is fully consistent with inflation being determined by monetary forces in the long run. Nelson (2008) and McCallum (2008) in particular responded directly to Woodford's critique, arguing in a different direction. Their disagreement essentially amounts to a shift of emphasis, rather than an algebraic correction. As Nelson highlights,

⁵ However, Andrés et al. (2009) demonstrate that when one allows for portfolio adjustment costs for holding real money balances, this implies a forward-looking character of these money balances that conveys on money an important role for monetary policy. Their estimates confirm the forward-looking character of money demand.

Woodford perceives the short-term interest rate as an effective policy instrument, even in the long run. This may be overrating the central bank's capabilities and, moreover, does not follow from the model's assumptions. In the steady state, the monetary policy authority has no power to affect real variables, despite its continuing ability to affect nominal variables. Hence, according to Nelson, the position that the nominal interest rate may be viewed as a policy instrument and the third equation as a policy rule, even in the steady-state version of the model, is not a tenable one, unless one explicitly explains how the central bank enforces its inflation target in the long run. The formal foundation of this argument lies in the fact that the role of the interest rate as a policy instrument in New-Keynesian models stems from a short-run deviation from monetary neutrality, arising from temporary nominal rigidities. This effect completely dissipates in the long run and monetary neutrality prevails. Conversely, open market operations do continue to affect the nominal money stock, even in the long run. Hence, in the long run, prices move by the same percentage as the money stock, the money demand equation thus becoming pivotal in understanding this long-run relationship.

McCallum (2008) also argues along the same lines, explaining that, when implementing monetary policy by means of an interest rate rule, the central bank automatically commits to supplying money at a particular average growth rate consistent with the selected target. As empirical evidence he cites his own research (McCallum, 2000) in support of the idea that narrow monetary aggregates, such as the monetary base, may in fact be superior to interest rates as a policy tool. Furthermore, he disagrees with Woodford's contention that within the New-Keynesian framework the central bank could control the interest rate even assuming the economy is cashless.

Nelson, McCallum and Woodford debate the necessity of a money demand equation in the presence of an inflation rule or, in other words, the exact sense in which money may still determine inflation in the long run, given that inflation is directly targeted, and hence defined, via the use of the interest rate as a policy instrument in open market operations. To quote McCallum (2008), "there is hardly any issue of a more fundamental nature, with regard to monetary policy analysis, than whether such analysis can coherently be conducted in models that make no explicit reference whatsoever to any monetary aggregate". Indeed, in view of the absence of monetary aggregates from mainstream monetary policy analysis, one may wonder

whether something fundamental has been overlooked in this debate and, hence, whether something may be gained from examining the long-run properties of the New-Keynesian model. Having done so, one could consider inverting the original question and asking instead whether there is any need for a policy rule, once a well-defined money demand equation, linking real output and the nominal interest rate to real money balances, is in place. In other words, an interesting question is whether it may be the Taylor rule that is in fact rendered redundant in such a model. It is with this perspective in mind that we reconsider the above benchmark monetary policy framework.

3. Theoretical discussion

The benchmark New-Keynesian DSGE macroeconomic model is set out in equations (1) through (3) and repeated in the first three equations in column 1 of Table 1, which presents the alternative policy frameworks to be discussed. This small system comprising the NKPC, the “expectational” AD curve and the standard Taylor rule appears, at first glance, to be a very straightforward log-linear one. Here we discuss the long-run properties of this model that point to an internal inconsistency.

3.1. Long-run properties of linear models

Before discussing this inconsistency, it may be instructive to revisit the key macroeconomic concept of long-run static equilibrium. Although estimation and policy analysis is more often based on short-run systems, economists should be equally interested in long-run properties and the long-run effects of economic shocks. In this paper it is precisely the long-run behavior of the benchmark New-Keynesian model on which we focus. We reiterate that in the static long-run or steady-state equilibrium all aggregates, be it stock or flow variables, are constant over time and, it thus follows, all growth rates are zero. In other words, the long-run static equilibrium of a model is obtained by suppressing all time subscripts. Moreover, in linear or log-linear dynamic systems, such as the one at hand, the total effects of a shock or, equivalently, the total impulse responses, are given by the solution of the corresponding static

form of the model, i.e. of the time-invariant form obtained in the absence of time subscripts (cf. Hamilton, 1994; Wallis and Whitley, 1987).⁶

It is also important to highlight that for a model, i.e. a system of equations, to be internally consistent, both its short-run and its long-run static form should be internally consistent. With the above in mind, it is straightforward to show that the benchmark model is inconsistent in the sense that, with inflation being zero in equilibrium, its static counterpart has three equations but only two endogenous variables. In other words, the interest rate appears to be defined from two separate equations, rendering the system overidentified. This point shall be clearly outlined below.

3.2. Standard solution of the benchmark model

We first look at what is viewed as the standard treatment of the model. Following Woodford (2008), there are three unknowns, i.e. the endogenous variables y_t , Δp_t and i_t , and three equations. Hence, each of these three unknowns can be solved for in terms of the exogenous variables, to give what is presented in Table 1, column 2, as the equilibrium solution. According to this solution, and assuming that the central bank, acting sensibly, will set the real interest rate r^* in the Taylor rule equal to the average real interest rate $-b_0/b_1$ implied by the aggregate demand equation, output is equal to its natural level,⁷ steady-state inflation is equal to the policy-determined inflation target and the interest rate is given by the steady-state Fisher condition. Indeed, on the basis of this logic, the system is self-contained as regards equilibrium, rendering the further addition of a money demand function redundant. To quote Nelson (2008), “the money demand equation adds one equation and one unknown, so it can be dropped altogether...”.

[Please insert Table 1 here]

⁶ Similar conclusions would follow from the analysis of dynamic multipliers, which is known to yield identical formulas to those for the impulse responses in the case of linear dynamic systems (see Brissimis, 1976; Gill and Brissimis, 1978).

⁷ McCallum (2001, pp. 147) is puzzled by the observation that in the steady state the NKPC implies that $y - \bar{y} > 0$, which violates the natural rate hypothesis. However, he attributes this to a flaw in the usual formulation of the model, which, under rational expectations, cannot capture the persistence found in inflation data.

3.3. Long-run static equilibrium of the benchmark model

The above is a very simple -and hence compelling- analysis of the “matching equations and unknowns” type (Woodford, 2008). However, in its simplicity, it fails to bring forth that, even within the above three-equation framework, one equation is redundant, at least in terms of the system’s long-run static equilibrium; that equation is the Taylor rule. Referring to the above solution, Woodford (2008) states that the inflation rate is “determined within the system: it corresponds to the central bank’s target rate, incorporated into the policy rule”. However, following our earlier discussion, it is a misunderstanding that such a statement reflects part of the model’s solution. To the contrary, such a statement in itself presupposes the existence of a Taylor rule and, thus, imposes the resulting long-run solution for inflation, i.e. that inflation is equal to the policy target. In fact, the static equilibrium value of inflation is by definition zero, since in this equilibrium the price level remains unchanged. That given, the two micro-founded equations, i.e. the NKPC and the dynamic AD curve, suffice for the calculation of the static equilibrium values of the two variables y_t and i_t in what is now a two-equation system. By suppressing the time subscripts in these two equations we obtain their static equilibrium form. For the NKPC, given that inflation is zero, we come to the same solution for output, shown in column 3 of Table 1, i.e.:

$$y = \bar{y} \quad (5)$$

By replacing this solution in the dynamic AD curve and setting inflation equal to zero, we arrive at the long-run equilibrium for the interest rate:

$$r^* = -b_0 / b_1 \quad (6)$$

It should be noted that, in the long-run static equilibrium, the third equation of the system, i.e. the Taylor rule, also implies a solution for the interest rate, namely $i = r^*$ (see also column 3 of Table 1). From this perspective, the benchmark New-Keynesian macroeconomic model would now appear to be inconsistent, in the sense that its static version, with inflation being by definition zero, has three equations but only two variables. In particular, the interest rate appears to be defined from two separate equations, the “expectational” aggregate demand

curve and the Taylor rule, rendering the system, in its static form, overidentified.⁸ It should be stressed that nowhere in this system is the long-run equilibrium price level determined, i.e. this model is characterized by price level indeterminacy in the sense of McCallum (2001).⁹ This indeterminacy remains even if, by pure coincidence, the real interest rates defined by the above two equations are equal to each other or if it is assumed, as for instance in McCallum (2001), that the central bank chooses r^* to be equal to b_0/b_1 .

3.4. Modifying the benchmark model: long-run consistency

Having highlighted and clarified the internal inconsistency of the current monetary policy framework in the long run, we can now consider augmenting the system of equations (1) and (2), i.e. the NKPC and the AD equations, by a money demand equation. The very simple specification of equation (4) is suitable and can be solved to yield the static equilibrium price level:

$$p = m - d_0 - d_1 y - d_2 i \tag{7}$$

⁸ An alternative way of presenting the same point is to view the standard three-equation formulation as a special case of the more general formulation presented here, i.e. a case where a policy rule is superimposed on the general model dynamics and inflation is forced to have a steady-state value of π^* rather than 0. The enforceability of the rule relies on the existence of the Calvo-type rigidities embedded in the New-Keynesian Phillips curve. These however are present only at a short-run horizon. Consequently, the claim that the Taylor rule's effects and implications can be thought to follow through to the medium- and long-term horizon remains contentious.

⁹ The notion of price level indeterminacy used here is different from the one that involves a multiplicity of equilibrium solutions in terms of real variables. The distinction has been drawn by McCallum (2001), who nevertheless noted that solutions other than the one he defines as the unique minimum-state-variable rational expectations solution may be considered as empirically irrelevant. Cochrane (2007), on the other hand, argued that the Taylor principle applied to Neo-Keynesian models does not guarantee inflation or price level determinacy (defined as the existence of a single solution that is dynamically stable) but showed instead that New-Keynesian models are typically consistent with the existence of solutions with explosive inflation rates. This inflation indeterminacy, according to Cochrane, means that the New-Keynesian model does not, in the end, determine the price level or the inflation rate and one has to resort to other theoretical possibilities. One possibility would be to use money as a nominal anchor but, as noted by Cochrane, central banks appear to say that they use monetary aggregates as one of their many indicators but not as the key nominal anchor and, moreover, the problem of solving the indeterminacy issues with interest-elastic money demand still has not been solved. Thus, Cochrane chooses the fiscal theory as the only currently available economic model that can solve the indeterminacy problems. The required assumption for this solution is that governments follow a fiscal regime that is at least partially non-Ricardian. However, Cochrane admits that the fiscal theory does not yet have a compelling empirical counterpart. Finally, McCallum (2009a) argued that least-squares learnability advocated by Evans and Honkapohja (2001) can save New-Keynesian models from indeterminacies (see also Cochrane, 2009 and McCallum, 2009b). Cochrane's (2007) conclusion suitably sums up this discussion: "One may argue that when a model gives multiple equilibria, we need additional selection criteria. I argue instead that we need a different model."

This equation is a function of output (equal to its natural level), the rate of interest (equal to the natural real rate) and the exogenous money supply. Thus, all variables of interest have now been defined in the static equilibrium of this new three-equation macroeconomic model and are shown in column 4 of Table 1.

In summary, all desirable features of the standard New-Keynesian macroeconomic system have been maintained, with first and foremost the fact that the main structural equations are directly derived from the optimization problem of individual rational economic agents. Hence, the appealing features of the New-Keynesian Phillips curve and the dynamic aggregate demand curve follow through to this differentiated setup. However, instead of the ad hoc imposition of equality between the inflation rate and the target inflation rate in the steady state, and the resulting inconsistency problems, we complete the above two-equation system with a micro-founded money demand equation. This allows us to define not only inflation, but also the price level which prevails once prices have fully adjusted to monetary policy actions and which corresponds to the static equilibrium at each level of the exogenously given money supply.¹⁰ Note that, in this context, the monetary authority may use monetary aggregates rather than the policy rate as a tool. Hence, our framework is internally consistent and additionally it possesses the key properties of monetarist theory for the long run, namely (i) monetary neutrality with respect to real output, (ii) proportionality between money and prices and (iii) no effect of money on the real interest rate (Abel and Bernanke, 1992). However, these standard monetarist properties are derived from a general equilibrium model, which does not require the assumption of perfectly competitive markets, as models of the monetarist tradition do. Instead, it is based on the assumption of imperfect competition in product markets, where prices remain fixed for some time rather than being instantaneously adjusted to reflect market conditions (see Woodford, 2009). Moreover, the much quoted proposition that inflation is always and everywhere a monetary phenomenon, intended to reflect a long-run property (Nelson, 2003), is indeed reinstated within this framework.

¹⁰ It should be noted that, a comparative static analysis of our model yields the result that for the central bank to allow a sustained change in inflation by x percent (as for example does the ECB, with its objective of an inflation rate close to or below 2% in the medium term), the money supply must also be allowed to change at the same rate *ceteris paribus*. It also shows that for $d_1=1$, if the rate of money growth is required to be equal to the growth rate of steady state output, reflecting e.g. technological change, this would result in zero inflation (cf. Inoue and Tsuzuki, 2011).

On a final note, the proposed modified framework can describe the behavior of the price level both in the long run and the short run¹¹. In particular, in the short run, price dynamics are determined primarily by the aggregate demand curve and the New-Keynesian Phillips curve, in conformity with the ECB's economic analysis (which applies to a short- to medium-term horizon), while in the long run, the price level is exclusively determined by the money demand equation, along the lines of the ECB's monetary analysis (which applies to a medium- to long-term horizon).

4. Estimation and dynamics of the New Keynesian models

4.1. Overview of the estimated models and the empirical methodology

Following the previous section's theoretical discussion, we proceed to formulate and estimate two models. The first, our modified model, comprises the New-Keynesian Phillips curve, the aggregate demand equation and the money demand equation. The second, the benchmark model, differs in that it uses the Taylor rule instead of the money demand equation. The two models are estimated using quarterly US data for the period 1982.Q2 – 2009.Q3 and their dynamics are subsequently examined by impulse response analysis.

All four equations have already been presented, in basic form, in Section 2 as equations (1) to (4). The specifications actually estimated extend this basic framework in several ways by introducing: (i) deviations from rationality in the formation of inflation expectations, (ii) habit behavior in spending (iii) short-run adjustment dynamics in the money demand equation and (iv) interest rate smoothing in the central bank rule. These steps add to the realism of the two models, i.e. they enable the respective equations to match the dynamics of the actual data reasonably well, without impairing the models' long-run properties. The empirical form of equations (1) to (4), respectively, is:

$$\Delta p_t = \mu_1 \Delta p_{t+1} + \mu_2 \Delta p_{t-1} + a_2 (y_t - \bar{y}_t) + e'_{\pi t} \quad (8)$$

$$y_t = b_0 + b_1 (i_t - w \Delta p_{t+1} - (1-w) \Delta p_{t-1}) + \varphi y_{t+1} + (1-\varphi) y_{t-1} + e'_{y t} \quad (9)$$

¹¹ An early attempt to address the issue of price level determination both in the short run and the long run in a monetary model can be found in Brissimis and Leventakis (1984). In their study, whose main orientation was to examine the monetary approach to the balance of payments and the exchange rate, the price level is determined in the short run primarily by demand and supply in the output market and in the long run exclusively by the money demand equation.

$$\Delta(m-p)_t = \lambda_1(m_{t-1} - p_{t-1} - d_0 - d_1 y_{t-1}) + \lambda_2 i_t + \lambda_3(w\Delta p_{t+1} + (1-w)\Delta p_{t-1}) + e'_{mt} \quad (10)$$

$$i_t = \kappa_0 + \kappa_1 \pi_t + \kappa_2 (y_t - \bar{y}_t) + \kappa_3 i_{t-1} + e'_{it} \quad (11)$$

In equation (8), $\lambda_1 = a_I w$, $\lambda_2 = a_I(1-w)$, and w and $1-w$ are the weights of the inflation rate with a lead and a lag respectively in the expected inflation term of equation (1). In equation (9), φ and $1-\varphi$ are the weights of future and lagged output respectively in the expected future output term of equation (2).

Each of the four equations is estimated individually; however, the cross-equation restriction referring to the expected inflation variable is imposed on all equations where this variable enters. Estimation proved a challenging task in view of the difficulties encountered in the empirical literature to obtain robust estimates of the parameters of New-Keynesian models. Subsequently, we proceed to solve the stochastic models comprising the estimated equations (8), (9) and (10) on the one hand and (8), (9) and (11) on the other, in order to consider the systems' dynamic properties.

4.2. Presentation and analysis of the equation specifications

The first equation is the NKPC equation, which, in addition to the forward-looking inflation term, includes one lag of the inflation variable. As already outlined, the theoretical appeal of the NKPC stems from the fact that in its purely forward-looking specification it is based on the optimal pricing behavior of agents with rational expectations. However, it has repeatedly been noted in related empirical research that this theoretically appealing specification does not, in practice, adequately capture observed inflation persistence. This feature of inflation is often introduced in inflation models by adopting a specification of the NKPC, which, deviating from rationality, has both forward and backward inflation dynamics. More specifically, following Gali and Gertler (1999) and Gali et al. (2001, 2005), a departure can be made from the basic Calvo model by allowing for the co-existence of two types of firms. Firms of the first type have a purely forward-looking price-setting behavior, as in the basic specification. Firms of the second type set their prices using a backward-looking rule of thumb based on the recent history of aggregate price inflation. This assumption leads to an extension of the NKPC by including a lag of inflation (hybrid NKPC). Alternatively, inflation inertia is often introduced through “dynamic price indexing”, i.e. the assumption that a subset of firms set their

prices by indexing price changes to past inflation (Smets and Wouters, 2003, 2004) or through learning processes on the part of private agents that may be converging to the rational expectations outcome in the long run (Brissimis and Magginas, 2008; Brissimis and Migiakis, 2011).

The real driving variable included in our specification of the NKPC is the output gap, in line with the practice adopted in the majority of the related empirical literature. A strand of recent empirical work uses either measures of the marginal cost (see Gali and Gertler, 1999) in an effort to be more faithful to the original Calvo setup or measures of unemployment (Beyer and Farmer, 2003) that draw on Okun's law. Dupuis (2004) estimates a number of structural models of U.S. inflation that incorporate lags of inflation in the forward-looking New Keynesian Phillips curve and finds that the hybrid NKPC with the output gap as an explanatory variable performs marginally better than the alternative specifications.

The second equation in our framework (equation 9) is the AD relation. The specification to be estimated allows for effects of both future and lagged output. The backward dynamics are theoretically motivated in the literature by the need to capture habit persistence. Habits can be conceived as either internal to households (where a household's marginal utility of consumption depends on the history of its own consumption) or external to households (where it depends on the history of other households' consumption). Here the AD equation is based on representative agent intertemporal utility maximization with external habit persistence as proposed by Fuhrer (2000).

In the AD equation the level of output depends, as in the traditional IS equation, on the real interest rate. To ensure internal consistency of our model, the relevant cross-equation restriction on the expected inflation variable is imposed in estimation, implying that the weights on the forward- and backward-looking inflation terms are constrained to be identical to those obtained from the estimation of the NKPC. Additionally, a linear time trend has been included in the aggregate demand equation with the aim of capturing the decline in the equilibrium

(natural) real interest rate, which has been documented in the literature (see e.g. Benati and Vitale, 2007).¹²

The modified model is completed with the specification of the money demand equation. We shall estimate a short-run dynamic adjustment equation, which typically features in any empirical approach to money demand. In this equation, which is of the error correction type, real money balances adjust in response to the deviation in the previous period of real money balances from their equilibrium value (error correction term). In our specification the equilibrium money demand (co-integrating equation) is a function of real output only. Two assumptions underlie this specification. First, there is no rate of return homogeneity in financial asset demand. This justifies the inclusion in our empirical money demand equation of both the own rate of return on money in real terms and the real opportunity cost of holding money, instead of solely the nominal interest rate that appears in equation (7). Second, the two real rate-of-return variables mentioned previously display stationary behavior and thus are not included in the equilibrium relation but are included in the error correction model.¹³ Moreover, as these variables are endogenous, their current level is used in the estimating equation.

Finally, equation (11) summarizes the behavior of the central bank using a Taylor rule with interest rate smoothing. The main notable aspect of this specification is that, here too, a linear trend has been included to capture the declining equilibrium real interest rate, by analogy to the one included in the aggregate demand equation.

4.3. Estimation, inference and dynamics

We use quarterly data for the US economy spanning the period from 1982.Q2 to 2009.Q3, which excludes the period of non-borrowed reserves targeting in the early 1980s. This yields a total of 111 observations. All variables except for the interest rate are in natural logarithms and seasonally adjusted. Money supply is M1. The inflation rate is defined as the

¹² We note that the estimation of equation (9) without the inclusion of a time trend yields a negative value for the constant term b_0 and, therefore, a negative equilibrium real interest rate (calculated as $-b_0/b_1$), precisely because this coefficient is picking up the above negative trend.

¹³ The real rate of return on money is given by $0 - E_t p_{t+1}$ and the real opportunity cost by $i - E_t p_{t+1}$. By rearranging terms in these two rate-of-return variables, we arrive at a specification which includes the nominal interest rate and expected inflation. We do not know a priori the sign of the coefficient on the latter variable. Note that in equation (10) we also impose the cross-equation restriction on the expected inflation variable.

quarter-to-quarter logarithmic change in the price level. The definition of the variables and sources of data are given in Table 2, while summary statistics for all variables included in our estimation are provided in Table 3.

In line with the majority of the empirical studies estimating the benchmark model, the parameters of the two models are estimated consistently using single-equation GMM (generalized method of moments) subject to the theory restrictions referred to above.¹⁴ The errors are assumed to be independently and identically distributed following the normal distribution. We use the heteroskedasticity- and autocorrelation-consistent (HAC) weight matrix of Newey and West (1987), which is suitable for the correction of the effects of correlation in the error terms in regressions estimated with time series data. The number of autocovariances used in computing the HAC weight matrix is selected using Newey and West's (1994) optimal lag-selection algorithm. Moreover, we employ the quadratic spectral (Andrews) kernel and verify that our results are approximately the same when using the Bartlett kernel. Instrumental variables are selected using as criterion the J-statistic. For the NKPC we use as instruments (given the J statistic) the first two lags of p and y and the first three lags of i . The set of instrumental variables used in the Euler equation includes the third lag of p , the first two lags of y and the first lag of i . Further, for the estimation of the money demand the second lags of p , m and i are the instruments of choice. Lastly, the Taylor rule is estimated using as instruments the second to fourth lags of i and π , as well as the second and third lags of the output gap.

All estimates of equations (8) to (11) are presented in Table 4. Our results are broadly in line with those in the literature, especially as far as the NKPC and the aggregate demand equation is concerned. We highlight the most noteworthy aspects of our estimates.

Turning first to the NKPC, a positive and significant coefficient of about 0.004 is obtained for the output gap. This estimate is somewhat larger than in Cho and Moreno (2006), where this coefficient is insignificant, higher compared to Gali and Gertler's (1999) estimates, who find a negative coefficient and similar to those of Shapiro (2008) and Bekaert et al. (2010). More interesting is the fact that we obtain a much larger coefficient on the forward-looking

¹⁴ Several other econometric techniques have been used in comparable research, mainly maximum likelihood approaches such as FIML. Galí et al. (2005) critically present the alternative approaches in the context of the New Keynesian Phillips curve and convincingly argue that GMM performs at least as well if not better than competing techniques.

inflation term than we do on the backward-looking one (the coefficient β_1 is estimated at 0.809, while β_2 is estimated at 0.109). Both coefficients are statistically significant at the 1% level and imply a weight of 0.88 for firms with forward-looking behavior in relation to inflation and a discount factor of 0.92, which is lower than the value of 0.99 that is widely used in calibrations of the New-Keynesian model. Clearly, our results suggest that the influence of backward-looking behavior with respect to inflation is quantitatively minor. In other words, the fraction of firms that are backward-looking in their price-setting behavior is quite small compared to the forward-looking ones.

Our estimates corroborate those of Gali and Gertler (1999) who, using GMM to estimate their hybrid variant of the NKPC, find that forward-looking behavior is dominant, i.e. their coefficient on expected future inflation substantially exceeds the coefficient on lagged inflation. We quote Gali et al., (2001) who state that “while the pure forward-looking version of the New-Keynesian Phillips curve is rejected by the data, the hybrid variant with a dominant role for forward-looking behavior does reasonably well”.

As far as the estimates of the aggregate demand equation are concerned, the constant term is positive and significant, though only at the 10% level. Notably, the estimated coefficient b_1 is negative, as expected, and highly significant, its magnitude comparable to analogous estimates in the literature that consider robust estimation of the AD equation (e.g., Bekaert et al., 2010). In contrast to much of the literature on the output equation (see e.g. Fuhrer and Rudebusch, 2004), we do not find evidence of a habit formation process as the coefficient of lagged output turns out to be highly insignificant. Thus inertial dynamics are not incorporated and we set $\varphi=1$ in estimation. We also find a very small but clearly significant coefficient on the linear time trend of the real interest rate, confirming the necessity of its inclusion in our specification.¹⁵ Notably, the AD estimation yields a value for the real interest rate (calculated as $-b_0/b_1$) equal to 2.5%. This is indeed very close to our priors (cf. Dennis, 2005).

Estimation of the MD equation yields statistically significant estimates at the 1% level for the coefficients on the error-correction term, the nominal interest rate and inflation expectations. The results are intuitive and in line with the broad literature on money demand

¹⁵ In fact, exclusion of this time trend renders the constant term negative, which implies that it captures a negative trend in the data. Of course a negative constant term is at odds with the theoretical predictions for the real interest rate. Therefore, inclusion of the trend seems highly intuitive.

estimation, suggesting that higher nominal rates are negatively associated with real money balances. The long-run income elasticity of M1 demand is 0.5, similar to Ball's (2001) estimates which like our study are based on relatively recent data.

The estimation results from the Taylor equation are also in line with the literature (see e.g., Orphanides, 2003). Here we identify a somewhat higher relative importance of the output gap compared to inflation. This finding seems to suggest that, given the developments in 2001 and the financial crisis of 2007, the central bank places a higher emphasis on output in the last decade. In fact, evidence from the earlier period suggests coefficients very close to those of Orphanides (2003). It is also comforting that the estimate of the equilibrium real interest rate obtained from the Taylor rule once the trend decline has been accounted for is comparable to the one obtained from the aggregate demand equation (2.3%). A final interesting finding is that monetary policy gradualism is not confirmed by our estimates since the coefficient of the lagged interest rate was highly insignificant and thus this variable was omitted in estimation. This result accords well with the criticism that large lag coefficients in estimated policy rules may reflect serially correlated or persistent special factors or shocks that cause the central bank to deviate from the policy rate (see Rudebusch, 2002); the decline in the equilibrium real interest rate evidenced in our sample may well account for the lack of interest rate smoothing that was found.

Using the estimates obtained, we proceed to solve both models with the help of Dynare and consider their dynamic properties. We first solve the modified model¹⁶ and introduce a permanent shock of 10 percent to the money supply variable. Since our model is stochastic, the permanent shock is introduced through the stochastic term of a first-order autoregressive function of the form $m_t = 0.999999 * m_{t-1} + u_t$. Initial values of the parameters of the model come from the estimates obtained above.¹⁷ For the stochastic simulation procedure we use a standard Taylor approximation of the decision and transition functions for the model. Subsequently, we generate structural impulse responses for the variables p , y , i and m to this shock and present them in Figure 1. It is notable that all variables converge to their theory-

¹⁶ Dynare uses the Klein (2000) and Sims (2002) algorithm for solving the model.

¹⁷ As a sensitivity analysis, we examined whether our results change when using parameter estimates obtained directly from the theoretical literature on New-Keynesian monetary models. The pattern of the impulse responses remained practically unaffected.

implied long-run attractors. Following the expansionary monetary policy shock, the effect on output is, as expected, a jump in the short run, followed by a return (albeit gradual) to its long-run level. Thus, in the long run, output remains unaffected by the monetary policy shock, implying monetary neutrality. Similarly, the interest rate declines instantaneously, but remains unaffected in the long run, while the effect on the price level is a proportional one. In other words, all three fundamental monetarist properties outlined in section 3 are present in our proposed system of equations.

For the benchmark model, the one including the Taylor rule, convergence problems were encountered when we introduce a one-period shock to e'_{ii} . Clearly, the convergence problems are due to the fact that the price level in the benchmark model is left undetermined. In particular, as is evident from column 3 of Table 1 and the theoretical discussion of section 3, the long-run static equilibrium value of output is determined from the NKPC, and the nominal interest rate from both the AD equation and the Taylor rule. In contrast, the modified model allows determination of the price level through the MD equation and, therefore, it also allows obtaining long-run equilibrium values. Notably, the convergence problems persist when using different specifications of the benchmark model with the price level as the variable of interest, or when calibrating the model with parameter estimates obtained directly from the theoretical literature on New-Keynesian monetary models. A plausible interpretation for this failure may be that the Taylor rule does not contribute any new elements capable of rendering the benchmark model a consistent system. The Taylor rule only reflects the preferences of the monetary authorities as expressed in their loss function (plus the structural parameters of the underlying model which however do not constitute new elements).

5. Conclusions

In this paper we examined the properties of the static long-run equilibrium corresponding to the three-equation New-Keynesian model, which has been advocated by Woodford (2003) as a self-contained system on which to base monetary policy analysis. This model – consisting of a New-Keynesian Phillips curve, an aggregate demand equation and a Taylor rule – provides the basis for most DSGE models, which are being increasingly used by central banks nowadays. However, the static counterpart of the New-Keynesian model appears

to be overidentified in the sense that the interest rate is determined from two separate equations, while the price level is left undetermined. We have remedied this problem by replacing the Taylor rule in the original New-Keynesian model by a money demand equation. The modified model has a corresponding static long-run equilibrium where all three endogenous variables (i.e. real output, real interest rate and price level) are consistently determined, while all the theoretical features of the original model are maintained. Solution of the modified model and impulse response analysis show that – in conformity with its static version – the modified model exhibits the key long-run monetarist properties, namely monetary neutrality with respect to real output, proportionality between money and prices and no lasting effect of money on the real interest rate.

Our analysis then re-establishes the role of monetary aggregates in the New-Keynesian framework, a role that has recently declined in importance primarily owing to empirical problems with the money demand function. In other words, we suggest here that these problems do not invalidate the importance of monetary aggregates in the analysis of monetary policy. Therefore, we provide a theoretical argument in favor of the ECB's monetary policy strategy that recognizes linkages between money and prices. In particular, in the short run the price dynamics of our model are primarily determined by the New-Keynesian Phillips curve and the aggregate demand equation, while money demand alone determines the path of the price level in the long run. Admittedly, the empirical model analyzed in this paper would need to be enhanced along the lines of the DSGE models currently appearing in the literature. This would yield a richer policy-oriented analysis and a framework that could further the empirics of monetary-policy implementation.

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Table 1
Monetary policy framework

Benchmark model with an “add-on” money demand relationship (1)	Equilibrium solution of benchmark model (2)	Long-run static equilibrium of benchmark model (3)	Long-run static equilibrium of modified model (4)
$\Delta p_t = a_1 E_t \Delta p_{t+1} + a_2 (y_t - \bar{y}_t) + e_{\pi t}$ $y_t = b_0 + b_1 (i_t - E_t \Delta p_{t+1}) + E_t y_{t+1} + e_{yt}$ $i_t = i_t^* + c_1 (\Delta p_t - \pi^*) + c_2 (y_t - \bar{y}_t) + e_i$ $m_t - p_t = d_0 + d_1 y_t - d_2 i_t + e_{mt}$	$y = \bar{y}$ $i = -b_0 / b_1 + \pi$ $\pi = \Delta p = \pi^*$	$y = \bar{y}$ $i = -b_0 / b_1$ $i = r^*$	$y = \bar{y}$ $i = -b_0 / b_1$ $p = m - c_0 - c_1 y + c_2 i$

Table 2
Variables used in the empirical analysis

Variable	Notation	Measure	Data source
Price level	p	$\ln(\text{GDP deflator})$	US Department of Commerce: Bureau of Economic Analysis
Output	y	$\ln(\text{real GDP})$	US Department of Commerce: Bureau of Economic Analysis
Potential output	\bar{y}	$\ln(\text{natural level of real GDP})$	US Congress: Congressional Budget Office
Nominal interest rate	i	3-month T-bill	Board of Governors of the Federal Reserve System
Money supply	m	$\ln(M1)$	Board of Governors of the Federal Reserve System

Notes: The table reports the variables used in the empirical analysis, their notation, the way these variables are measured and data sources. Data were downloaded from FRED.

Table 3
Summary statistics

Variable	Mean	Std. dev.	Min.	Max.
p	4.38	0.20	4.00	4.70
y	9.14	0.25	8.68	9.50
y	9.02	0.24	8.61	9.41
i	0.05	0.03	0.00	0.14
m	6.90	0.34	6.09	7.41

Notes: The table reports summary statistics (mean, standard deviation, minimum and maximum) for the variables used in the empirical analysis. The sample covers the period 1982.Q1-2009.Q3 (111 observations). The variables are defined in Table 1.

Table 4
GMM parameter estimates of the equations of the New-Keynesian models

Equation	Parameter	Coefficient	Std. Err.
NKPC	1	0.809***	0.035
	2	0.109***	0.025
	a_2	0.004**	0.002
J-stat = 3.26 (p-val. = 0.66)			
AD	b_0	0.003*	0.002
	b_1	-0.119***	0.028
J-stat = 2.72 (p-val. = 0.23)			
MD	d_0	1.996***	0.338
	d_1	0.491***	0.037
	λ_1	-0.062***	0.004
	λ_2	-0.084***	0.020
	λ_3	1.989***	0.420
J-stat = 1.22 (p-val. = 0.27)			
Taylor rule	κ_0	0.023***	0.004
	κ_1	0.038***	0.002
	κ_2	0.326***	0.034
J-stat = 4.65 (p-val. = 0.59)			

Notes: The table reports parameter estimates and standard errors from the estimation of Eqs. (8)-(11). The number of observations equals 107. ***, ** and * denote statistical significance at the 1, 5 and 10% level, respectively.

Figure 1
Response of variables to a permanent 10% shock in money supply

