CESifo Economic Studies Advance Access published November 28, 2006

CESifo Economic Studies, 2006 doi:10.1093/cesifo/ifl014

Dynamic Stochastic General Equilibrium Models as a Tool for Policy Analysis

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Abstract

This article discusses the evolution of dynamic macroeconomic models from calibrated Real Business Cycle models to estimated dynamic stochastic general equilibrium models. The purpose is to suggest the usefulness of these models as a tool for policy analysis, with a particular emphasis on aspects of monetary policy. (JEL classification: D58, E50)

1 Introduction

This article gives an overview of the literature that has led to the emergence of dynamic stochastic general equilibrium (DSGE) models. This approach to macroeconomic modelling has gained widespread support among researchers and has recently started to be taken seriously by policy-making institutions as a modelling framework which is useful for policy analysis and the conceptual support of decision making.

Modern macroeconomics is the result of an intense, and at times passionate, scientific debate that has taken place over the last decades. In the early 1980s, a new approach to the business cycle analysis was introduced by Kydland and Prescott (1982). The main tenet of their approach was that a small model of a frictionless and perfectly competitive market economy, inhabited by utility-maximising rational agents which operate subject to budget constraints and technological restrictions, could replicate a number of stylised business cycle facts when hit by random productivity shocks. This so-called real business cycle (RBC) approach to macroeconomic modelling was early on criticised on various aspects. Nevertheless, as it is now widely acknowledged, the RBC agenda has made a lasting methodological contribution. Most of today's DSGE models

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The views expressed in this paper are those of the authors and do not necessarily reflect the views of the Deutsche Bundesbank and the European Central Bank.

adopt the general structure of a RBC model, i.e. they feature an impulse–response structure built around optimising agents in a general equilibrium setting. However, the way these models rationalise the business cycle differs substantially from the original contribution and is everything but unique. Various types of imperfections and rigidities in the markets for goods, for factors of production and for financial assets have been introduced alongside a broader set of random disturbances. The current generation of DSGE models has also been successfully used to address normative issues concerning optimal policy-making in a relatively simple and fully transparent way.

Compared with the traditional macro models, the current DSGE models have the advantage of stating explicitly the microeconomic decision problems that give rise to the macroeconomic dynamics. This makes it easier to link the development in macroeconomic theory to the advances in microeconomics. Incentive constraints, imperfect information and strategic interactions among agents are but some of the microeconomic concepts that feature in modern dynamic general equilibrium models. This fact increases the consistency of these models considerably, both internally (i.e. in relation to the underlying assumption of the rational decision-making of agents) and externally (i.e. in relation to other subfields of economics).

The main reason of dissatisfaction with traditional macro modelling has, nevertheless, been empirical. The models typically used for macroeconomic policy analysis often performed not satisfactorily in terms of forecasting and, over time, loosened their grip on econometric principles. For example, the typical model used at central banks derived from the so-called Cowles Commission Approach and featured a rich set of equations describing the behaviour of key macroeconomic variables, typically estimated by simultaneous equations techniques. Owing to flaws in the original approach as well as to developments in macroeconomic and econometric research, these models were partially amended and enriched with the consequence that they departed from the original without getting sufficiently close to the more theory-based models developed in the academic circle. A pointed criticism of this development offers the following quote by Sims (2002): “The primary models in use as part of the policy process in central banks are deeply flawed . . . In giving up on the [simultaneous equations] statistical theory that seemed to be providing no guidance to models of the scale actually in use, central bank modelers have ended up back at the level of the original Tinbergen model or worse.” In historical perspective, however, one should not forget the important role played by large-scale simultaneous equation models for policy analysis. At the end they *were* the state of the art in macro modelling. Moreover, these traditional models still play an important role in many policy-making institutions. Therefore, it seems more appropriate to see the rapid development of DSGE models for policy analysis in parallel to the improvement of the existing econometric tools.

Current research in DSGE models has made big progress on the empirical front. As we discuss in this article, there are now various techniques to take these models to the data. This helps selecting the appropriate modelling assumptions and makes the model more suited to answer policy-related questions. With these models we are today able to give model-consistent answers to questions like (i) "which of the assumed disturbances contributes most to the fluctuations of the economy?"; or (ii) "what are the consequences of a particular shock for the likely future path of a given variable or set of variables?" or; finally, like (iii) "how should policy-makers set their instruments in response to a given disturbance?" Evidently, DSGE models are subject to ongoing and very intensive research. Yet, the most recent vintages of these models have already reached a degree of sophistication which makes them a very valuable tool for policy analysis, and their increased use in policy-making institutions brings the latter closer to academic research and knowledge.

The remainder of this survey is structured as follows. Section 2 broadly discusses the evolution from RBC models to state-of-the-art DSGE models. Section 3 summarises the basic steps of constructing and solving a DSGE model. Section 4 describes how DSGE models are brought to the data. Section 5 shows how recent vintages of DSGE models account for the main sources of business cycle dynamics. Section 6 discusses from two perspectives how DSGE models are used for policy analysis. The first subsection focuses on aspects of monetary and fiscal policy and the second subsection sketches how DSGE models have recently been used to address issues in asset pricing and monetary policy. Given the very large number of contributions to the DSGE literature this survey is certainly not exhaustive and, in line with our personal background, most of the examples are related to aspects of monetary policy-making.

2 The state of modern macroeconomic modelling: from RBC to DSGE models

In their influential paper of 1982, Kydland and Prescott proposed a model of the business cycle in sharp contrast with both the Keynesian tradition and the Monetarist school. Following Frisch's view of the business cycle (Frisch, 1933) they augmented the neoclassical Ramsey–Cass–Koopmans growth model by introducing stochastic productivity shocks.[1] They, and many others after them, showed that such a model is capable of reproducing a number of stylised facts of the business cycle. These models, known today as Real Business Cycle (RBC) models, are based on the assumption that the economy is populated by rational agents that optimise their welfare subject to various restrictions, like budget constraints, technological constraints summarised in the production function and incentive constraints. The typical version of these models would feature an infinitely lived representative household, whose objective would be to maximise its utility by choosing an optimal path for consumption and leisure, alongside a representative firm whose objective would be to maximise profits.[2] Even in the more sophisticated versions of the RBC models there is very little role (if any) for monetary or fiscal policy which has often been seen as a strong shortcoming from the viewpoint of economic policy analysis. This is only one of the reasons for disagreement among economists about the usefulness of RBC models. The ability of these models to match the empirical evidence has also been questioned. On the one hand, many empirical regularities could not be reproduced by these models, or at least not under reasonable parametrisations. Examples of such regularities include the liquidity effect, the comovement of productivity and employment or the comovement of real wages and output. On the other hand, the way in which the empirical fit of these models was measured came under strong criticism.

A vast literature has therefore been dedicated to the improvement of RBC models on the theoretical as well as the empirical front.[3] Many researchers soon realised that there was more in RBC modelling than the explanation of the business cycle. Its main contribution was soon acknowledged to be methodological, namely to offer a consistent way to describe and solve a rational expectation stochastic dynamic general equilibrium model. Meanwhile, a new school of thought was gaining ground in economics, the so-called New-Keynesian Macroeconomics (NKM). The NKM school shared with the RBC approach the belief that macroeconomics needed more rigorous microfoundations.[4] In contrast to the RBC approach, however, the NKM researchers considered market

[1] More precisely, Kydland and Prescott (1982) attributed an important role in business cycle dynamics to the "time to build" of investment goods. Their paper is nevertheless mainly referred to for the use of a neoclassical stochastic growth model rather than for the assumptions regarding investment.

[2] An alternative modelling strategy is to have overlapping generations of agents (Diamond 1965). Because of timing assumptions which typically favour long-run (i.e. intergenerational) considerations, they are generally deemed inferior for business cycle analysis.

[3] For more details on the origins and the evolution of the RBC literature, see Stadler (1994).

[4] For a discussion of the NKM approach see Gordon (1990).

imperfections as the key element to understanding the real world. Part of the NKM school delved into the implications of firm-level price and wage rigidities for macroeconomic variables. Seminal papers by Taylor (1980), Calvo (1983), Akerlof and Yellen (1985) and Mankiw (1985), *inter alia*, suggested ways to derive aggregate price inertia from the price setting behaviour of firms.[5] The inclusion of New-Keynesian ideas into an otherwise RBC model proved to be extremely successful, in terms of reception by the economic profession as well as in terms of explanatory power of the empirical evidence. In particular, the introduction of sticky prices was sufficient to break the neutrality of money typical of RBC models, and hence it opened a new avenue for monetary policy analysis. So much so, that many economists saw in this "marriage" the birth of a "new synthesis" (Goodfriend and King 1997). Similarly, modelling assumptions regarding the real side of the economy have become more diversified. Concentrating on the microstructure of the labour market specification, Merz (1995) and Andolfatto (1996), for example, have shown how to marry search and matching considerations with the RBC agenda.

As time went by, researchers realised that a wide set of possible assumptions could be introduced into DSGE models in a tractable way. Today in most branches of macroeconomics the DSGE modelling strategy dominates. Particularly important are the contributions made in international macroeconomics by Obstfeld and Rogoff (1995), in monetary economics by Rotemberg and Woodford (1997) and in fiscal policy analysis by Baxter and King (1993) or Chari, Christiano and Kehoe (1994).

3 The basic steps of constructing and solving a DSGE model

The purpose of this self-contained section is to sketch the main steps necessary for constructing and solving a DSGE model. The main point of this section is to show that it is possible to reduce a microfounded forward-looking model to a vector autoregression (VAR) representation that has well-defined empirical implications.

For the sake of concreteness we describe these steps with reference to the basic New-Keynesian model in the spirit of Woodford (2003a). The model consists of a large number of consumer–producers who choose consumption (C_i), labour (L_i), nominal bonds (B_i), individual output (Y_i) and individual output prices (P_i) in order to maximize their utility given an

[5] See Taylor (1999) for a survey of staggered price-setting models.

elastic demand for individual output and quadratic costs of adjusting individual prices in line with Rotemberg (1982).

3.1 Specification of the model in mathematical form

The first step requires choosing the set of economic assumptions that is appropriate given the normative or positive question of interest. These assumptions need then to be translated into a mathematical model, as done in the following equations.

The representative consumer-producer chooses a plan for consumption, labour (output), prices and bond holdings in order to maximize her utility (profits) subject to her budget constraint, technology (the production function) and the demand for her products.

For example, the *i*-th consumer-producer solves the following problem:

$$\max_{C_{i,t},\, Y_{i,t},\, B_{i,t},\, P_{i,t}} E_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{C_{i,t}^{1-\gamma}}{1-\gamma} - L_{i,t} \right) \qquad \text{(Objective)}$$

subject to the set of constraints:

$$B_{i,t} + P_t C_{i,t} = P_{i,t} Y_{i,t} - \frac{\phi}{2} \left(\frac{P_{i,t}}{P_t} - \pi_t^* \right)^2 P_t C_t + (1 + R_{t-1}) B_{i,t-1} \qquad \text{(Individual budget constraint)}$$

$$C_t \equiv \sum_{i=1}^{I} C_{i,t} = \sum_{i=1}^{I} Y_{i,t} \qquad \text{(Aggregate resource constraint)}$$

$$Y_{i,t} = z_t L_{i,t} \qquad \text{(Technology)}$$

$$Y_{i,t} = \left(\frac{P_{i,t}}{P_t} \right)^{-\theta} C_t \qquad \text{(Demand)}$$

where C_t denotes aggregate output, P_t is the aggregate price level, β is the subjective discount factor, θ is the elasticity of demand, γ^{-1} measures the elasticity of intertemporal substitution of consumption, ϕ measures the cost of setting the relative price different from π_t^* (e.g. the central bank's inflation target), R_t is the nominal interest rate, z_t denotes the productivity of labour and E_0 is the mathematical expectation operator.

The central bank sets the interest rate following a so-called Taylor-type rule

$$R_t = \delta \left(\frac{\pi_t}{\pi_t^*} \right)^{\lambda_\pi} \left(\frac{C_t}{C_t^*} \right)^{\lambda_y} e^{\nu_t} \qquad \text{(Interest rate rule)}$$

where δ is a constant, λ_π and λ_y are policy response parameters, π_t^* and C_t^* are the target levels of inflation and output, respectively, and ν_t is a stochastic policy stock. Notice that in long-run equilibrium and in the absence of shocks, consumption and inflation will be identical to their target levels, implying that the nominal interest rate reaches the (constant) equilibrium level δ, which can be seen as the neutral level of the interest rate. The stochastic shocks are assumed to follow the following linear processes:

$$z_t = \rho z_{t-1} + \varepsilon_t;\ \ \varepsilon_t \sim i.i.d.\,(0, \sigma_\varepsilon) \qquad \text{(Exogenouos forcing process)}$$
$$\nu_t \sim i.i.d\,(0, \sigma_\nu)$$

3.2 Derivation and approximation of the equilibrium conditions

The second step involves deriving the first-order conditions of the optimisation problems implied by our model. As these conditions are typically nonlinear, the researcher needs to derive a tractable approximation. This generally amounts to obtaining the first-order Taylor-approximation of the non-linear functions around a stable steady state, making the analysis locally valid.[6] It is important to notice that the current literature has made important leaps forward in the solution of DSGE models at higher order of approximation [see for example Schmitt-Grohé and Uribe (2004b) and Lombardo and Sutherland (2006)]. One of the most important reasons for resorting to higher orders of approximation is that certainty equivalence holds in a linear expectational system—so that the effect of risk on the equilibrium dynamics of the system is absent—, while in more general systems this is no longer the case.

In this model, all consumer-producers make the same choices in equilibrium so that we can eliminate the index i in the following set of aggregate equilibrium conditions

$$E_t\hat{C}_{t+1} = \hat{C}_t + \gamma^{-1}\left(\hat{R}_t - \hat{E}_t\hat{\pi}_{t+1}\right) \qquad \text{(Consumption Euler equation)}$$
$$\hat{\pi}_t = \beta E_t\hat{\pi}_{t+1} + \frac{\theta - 1}{\phi}\left(\gamma\hat{C}_t - z_t\right) \qquad \text{(Phillips curve)}$$
$$\hat{R}_t = \lambda_\pi\hat{\pi}_t + \lambda_y\hat{C}_t + \nu_t \qquad \text{(Policy rule)}$$

where a caret on a variable denotes the difference, in logs, of that variable from its steady state and where, for simplicity, the target rate of inflation and output have been assumed constant. Taking as given a realisation of the shock ν_t, these equations specify how the three endogenous variables inflation, consumption and the nominal interest rate evolve over time.

[6] The software Dynare (freely available at http://www.cepremap.cnrs.fr/dynare/) is able to carry out automatically all the remaining steps starting from the first-order conditions of the model: i.e. from the approximation to the solution, simulation and estimation of the model.

3.3 Solution of the linear system

The third step involves finding the solution to the approximated dynamic system. In general, this type of forward-looking recursive systems can be solved with numeric computer algorithms.[7] The solution takes the vector autoregressive form

$$X_t = A\,X_{t-1} + B\,Z_t$$

where A and B are matrices of coefficients that depend on the deep behavioural and policy parameters of the model, and where X_t is a vector of endogenous variables, e.g. $X_t = [\hat{C}_t, \hat{\pi}, \hat{R}_t]'$ and Z_t is a vector of exogenous stochastic forcing processes, e.g. $Z_t = [z_t, \nu_t]'$. It is worth pointing out that this representation of the DSGE model has the same form like a VAR model used in econometrics. The crucial difference is that the DSGE model imposes restrictions on the coefficient matrices A and B which relate directly to the economic structure of the model. By contrast, the VAR literature would impose identifying restrictions which do not come directly from an explicit model.

3.4 Assignments of values to the parameters of the model and policy analysis

A fourth step requires the researcher to assign numerical values to the parameters of the model. There are a number of alternative ways in which parameter values can be chosen. Most of the current debate around DSGE models concerns this crucial step and we postpone the discussion to Section 4.

Finally, the DSGE model can be used for ‘‘computational experiments’’ (Plosser 1989). A short survey of recent applications of DSGE analysis is offered further below. Ideally, by having satisfactorily specified the model and estimated its parameters the researcher has succeeded in approximating the true data-generating process (DGP). She can then subject the model economy to particular innovations (e.g. productivity shocks) and study the response of the endogenous variables (e.g. by plotting impulse response graphs, computing simulation moments, etc.).

The researcher, in principle, should also be able to conduct policy analysis concerning the optimal response of policy instruments like the short-run interest rate, taxes or the level of government spending to exogenous perturbations. Traditionally, this type of policy experiments used to be conducted with models that lacked a consistent choice-theoretic foundation. These exercises received a fatal blow by the Lucas Critique

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[7] Forward-looking dynamic systems do not necessarily have a unique stable solution. When multiple stable solutions exist (i.e. the so-called case of indeterminacy) it is possible that the economy settles on non-fundamental or sunspot equilibria.

(Lucas 1976) which says that experimenting with policy-regime changes must take into account the fact that economic behaviour is not independent of the policy regime.[8] In other words, such experiments would be correct only if the behavioural parameters of the model are sufficiently deep with respect to policy. Whether DSGE models can claim to be immune from the Lucas Critique or not is still an open debate. Leeper, Sims and Zha (1996), for example, reject the claim that DSGE modelling is not subject to the critique. These authors argue that the only way a DSGE model would be immune from the critique would be to use it in simulations where the policy rule is changed unexpectedly in an unprecedented and permanent way. But this, the authors suggest, is like experimenting on something that has zero probability to happen.[9] More recently, Leeper and Zha (2003) have offered a metric that can be used to judge the validity of the policy experiment. Their idea applies primarily to VAR-based experiments but can be easily extended to DSGE models. In essence, these authors suggest that a policy change that falls in the tails of the estimated distribution of the policy instrument would be perceived by the private agents as a change in regime and could therefore trigger changes in economic behaviour. Therefore, for a given set of private sector decision rules, only moderate exogenous policy changes should be considered as valid experiments.

4 Taking the model to the data

A DSGE model, as represented by the vector autoregressive solution form established in Section 3.3, has stochastic implications that can be compared with empirical counterparts. In this section, we briefly describe alternative techniques that can serve this purpose. It should be noticed, nevertheless, that the borderline between these techniques is very blurred as elements of calibration appear in estimation exercises and vice-versa. Our exposition is intended to provide only a very superficial overview of the techniques. For a thorough survey of the empirical methods in DSGE modelling see Canova (2005).

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8 See Sims (1987) and Cooley, LeRoy and Raymond (1984) for an earlier critique of the Lucas Critique. A standard interpretation of the Lucas Critique is provided by Walsh (1998, p. 20). The standard (or literal) interpretation of the Lucas Critique argues that reduced form econometric relationships cannot be used to predict the implications of alternative policy regimes, as the estimates of the reduced form coefficients are conditional on fixed policy parameters.

9 In other words, if the researcher believes that the policy parameter can be varied by the policy maker, she should model it as a variable or a stochastic process and not as a constant parameter.

4.1 Calibration

Calibration means that most of the values of the parameters of the model are chosen from "findings in other applied areas of economics..." (Kydland and Prescott 1996). The few remaining parameters are chosen in order to "yield, as close as possible, a correspondence between the moments predicted by the model and those in the sample data" (Plosser 1989). Moment-matching (the most crucial of the two steps) consists in informal judgement of the proximity of the second moments implied by the calibrated model to the analogous sample moments. No formal probability-based metric is used in this evaluation. The rationale behind this approach, which Geweke (1999) calls the weak econometric interpretation, rests on the fact that any model is likely to be rejected by formal statistical inference, given a sufficient amount of data.[10] According to Kydland and Prescott a macroeconomic model should be expected to "... [mimic] the world as closely as possible along a limited, but clearly specified, number of dimensions" (Kydland and Prescott, 1996, p. 74). Yet, the problem remains of how one should distinguish among models that seem to score equally well in "mimicking" the world. In carrying out such an exercise, researchers soon found it necessary to resort to formal, and widely accepted, criteria.[11]

A more sophisticated type of calibration is based on Bayesian Monte Carlo techniques, which take into account the uncertainty surrounding the parameter values (e.g. when the empirical literature is not unanimous about these values or in order to reflect the statistical uncertainty implicit in the empirical estimates). When this type of uncertainty is taken into account it is possible to attach a measure of uncertainty (e.g. confidence bands) to the model-based simulated moments as well as to the policy exercises [see Canova (1994, 1995) for details].

4.2 Classical estimation

Estimation of the parameters of the DSGE model implies deriving the values of the parameters as the result of the minimisation of a given objective function involving some sample statistics as well as model-based statistics (Schorfheide, 2000). Estimation, as compared to simple calibration, allows the researcher to base her inference on well-defined statistical measures. The technique currently most widely used to estimate DSGE

[10] Related to this argument, see also Sims (1996).

[11] Geweke (1999) argues that in fact also the weak econometric interpretation must be taken as a measure of fit of the model under all the dimensions of the data. He points out, for example, that first sample moments are related to second moments of the sample so that a model that matches first moments but not second moments of the sample would be inconsistent and should be rejected.

models is a full information maximum likelihood estimation (MLE). The advantage of MLE is well summarised in the following quote:

> "...[The MLE of a DSGE model] allows us to bring all aspects of the data to bear in generating estimates. ...[Otherwise] important aspects of [the model's] dynamic structure may never have been confronted with the data and its policy implications may be correspondingly unreliable" (Leeper and Sims, 1994).

The MLE amounts to maximising the likelihood of the observed data given the DSGE model by appropriately choosing the model's parameters.

A major problem with classic MLE is that for the inference to be valid we should assume that the DSGE is the true DGP. This is clearly a strong assumption and is clearly in contrast with the RBC view of the model being a false representation of reality, although potentially being a good approximation of some specific aspects of the data. The implausibility of the assumption that the DSGE is the DGP implies, in practice, that the model is easily rejected by the data.

4.3 Bayesian estimation

A promising alternative to MLE techniques is offered by the Bayesian approach. This approach can be seen as taking together some aspects of the calibration tradition with more rigorous estimation techniques. The Bayesian programme entails specifying some priors for the parameters to be estimated. Such a prior could, for example, come from the same sources used in calibration exercises. The degree of confidence in the prior is measured by a statistical distribution for the parameter in question. This prior is then weighted against the likelihood of the sample evidence, given the DSGE model. In other words, the researcher gives the data a chance to tilt her prior beliefs in one direction or the other. Furthermore, from a Bayesian decision theory point of view, the idea that the model is not the true DGP should not stop us from using it, as long as no better alternative is available. It should be stressed that the other side of this argument is that model comparison is a crucial step in Bayesian estimation.

Two important caveats are in order. First, computational power, though enormously increased since the birth of RBC models, is still limited and often requires questionable compromises. One of these is the need to adopt time-consuming numerical algorithms in order to find the steady state of the nonlinear model for the given set of parameter values. This, in practice, implies that for medium-to large-scale models the researcher has to choose between matching long-run features of the data (e.g. the consumption share in output, etc.) or somehow circumvent the latter in order to confront more aspects of the model with high-frequency aspects of the data. Second, very often DSGE models suffer from poor identifiability of the underlying parameters. In simple words, this means that the loss function used for estimation (e.g. the likelihood function of the data) is insensitive to variation in the value of some of the parameters (or combinations of parameters).

This lack of identifiability is often circumvented by imposing priors on the parameters of the model. It is important to notice, though, that the curvature introduced by the prior, in this case, can only conceal the fact that the data is silent on some of the parameters. It remains true, nevertheless, that imposing a true prior (i.e. reflecting beliefs and not dictated by numerical concerns) is fully legitimate from a Bayesian perspective even in this case.

5 DSGE and the business cycle: identifying the shocks

As we have seen, the RBC research agenda was concerned with purely methodological aspects as much as it was concerned with identifying in productivity (i.e. real) shocks the main source of economic fluctuations. This was particularly in contrast with the monetarist view, which tended to interpret economic fluctuations as mainly caused by "money mischiefs" (Friedman, 1992).[12] The RBC theory had, potentially, a very strong ideological implication: public economic institutions (i.e. fiscal and monetary authorities) had little or no role in the business cycle.

However, whether the business cycle is mainly caused by real or nominal shocks is clearly an empirical issue.[13] As discussed further below, DSGE models are often taken to the data directly. Nevertheless, in order to take the "correct" model to the data, economists have often resorted to econometric evidence on the nature and properties of the business cycle. In particular, VAR analysis has greatly contributed to shed light on these issues.[14]

The identification of the shocks driving the economy is a daunting task so that the inconclusiveness of the literature, up to now, is not surprising. Nevertheless, there is by now wide consensus in the VAR-based literature that technology (productivity) shocks are not the only source of the business cycle (as maintained early on by the RBC school) nor the

12 This view is strongly maintained in the classical work by Friedman and Schwartz (1963).

13 The structure of DSGE models allows, in principle, also for the possibility of non-fundamental (or animal spirit-type) shocks which are associated with indeterminate rational expectations equilibria. This feature can be actively used as a source of business fluctuations in Keynesian spirit, as discussed in detail in Farmer (1999).

14 For a recent discussion of the VAR methodology see Stock and Watson (2001).

major one. As far back as the late 1980s, Shapiro and Watson (1988) showed for the US that "technological shocks account for about one-quarter of cyclical fluctuations". Shocks to aggregate demand and labour supply shared an equally large portion of the overall aggregate fluctuations. To what extent monetary shocks contribute to aggregate fluctuations is less clear. A tiny role for monetary shocks (the most typical result) is documented, among others, by Sims and Zha Leeper (1996), Galí (1992) and Uhlig (2005). Faust (1998) and Canova and Nicoló (2002) offer the opposite evidence.[15] All these papers stress that the results crucially depend on the identification scheme adopted.[16]

In a sense, the identification problem is therefore simpler in a DSGE model. In such a model, the policy shock would be modelled explicitly and as orthogonal with respect to other disturbances. The interpretation of the shocks is therefore made clear from the start. Today, there are various examples of estimated DSGE models. The major differences among these examples concern the number and type of shocks on the one hand and the estimation technique on the other hand. Leeper and Sims (1994) offer probably one of the first attempts to estimate a DSGE model by maximum likelihood. In their seminal paper, the authors stress the importance of explicitly introducing a wide set of interpretable shocks in the model (they have 13 structural shocks). Other approaches would introduce *ad hoc* measurement errors in order to have sufficient variability for the estimation.[17] An example of the latter strategy is provided by McGrattan, Rogerson and Wright (1997), who estimate a DSGE model where the randomness derives from government expenditures, taxes, and the split between home production and the production in firms. They estimate the model by imposing that variables are measured with errors so that a Kalman–Filter MLE can be applied. Kim (2000) estimates a model with two technology shocks, a money demand shock and a monetary policy shock. His estimation technique uses the fact that with four shocks only the time series of four variables should be used in order to avoid singularity. Ireland (2004b) re-addresses the original RBC question of the relevance of technology shocks within a New-Keynesian DSGE model.

15 Concerning the demanding identification of fiscal shocks in (structural) VARs, see, e.g. Blanchard and Perotti (2002) and Fatas and Mihov (2001).

16 Uhlig (2005), in particular, emphasises the fact that structural identification schemes are implicitly or explicitly derived from theory. This implies that often the "evidence" is just a reflection of our prior beliefs. Uhlig (2005) as well as Faust (1998) and Canova and Nicoló (2002) explore identification schemes that aim to minimise the reliance on prior beliefs.

17 A number of shocks smaller than the number of variables in the model would generate the type of singularity (of the variance–covariance matrix) as that implied by perfect multicollinearity in a standard regression. See Fisher Ingram, Kocherlakota and Savin (1994) on the problem of singularity.

He shows that technology shocks play a minor role in a sticky price model and he takes these results as further evidence of the distinction between RBC models and current generation DSGE models.[18] Bergin (2003) offers a first example of MLE of an open-economy model (semi-small economy). He studies seven different shocks (nominal and real) and estimates the model for Australia, UK and Canada. Money supply shocks play almost no role in determining the variability of output, which is mainly due to technology shocks. Money supply shocks also have a minor role in determining the current-account volatility, whereas they are the major force driving the nominal exchange rate as well as the real exchange rate (also in the long run, although to a lesser extent).

Christiano, Eichenbaum and Evans (2005) develop an estimated DSGE model which they use to assess the role and implications of monetary policy shocks. The paper is an important contribution since it uses an estimation method (also used by Rotemberg and Woodford 1997) based on a VAR so that the complementarity of DSGE models and VAR is exploited. Moreover, they impose a rich set of assumptions on the economic structure and evaluate their relative contribution to the business cycle in terms of statistical significance.

Smets and Wouters (2003) carry out an exercise similar to that of Christiano, Eichenbaum and Evans (2005) as they use the same model but a different data set and estimation technique. Their paper is a good and widely cited example of a DSGE estimation based on Bayesian econometrics. Furthermore the results of Smets and Wouters are among the best in terms of model fit. Based on Bayesian criteria, they show that their estimated DSGE model fits the data better than an unrestricted VAR and better than a Bayesian VAR. Contrary to Christiano, Eichenbaum and Evans (2005), Smets and Wouters introduce a large number of shocks so that alternative sources of stochastic volatility are able to explain different historical episodes.[19]

Finally, it is worth pointing out that DSGE models can also be used in support of VAR analysis. In this spirit, Del Negro and Schorfheide (2004)

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18 Ireland (2004a) discusses more generally a (maximum-likelihood) method to take DSGE models to the data. His method is based on the idea that measurement errors can be conveniently introduced in the model in order to study a limited set of structural shocks [similarly, see McGrattan, Rogerson and Wright (1997)].

19 However, a potential problem with this approach is that we know very little about the deep nature of the shocks and how they enter structural relationships. What we end up calling a demand shock could simply be a reflection of the mis-specification of the model: the more so the more the shocks display some structure themselves (e.g. they are estimated to be some version of ARIMA processes).

have shown in a recent paper that a DSGE model can be used as a prior in a Bayesian VAR.[20]

6 Using DSGE models for policy analysis

This section indicates how estimated DSGE models are used for policy analysis, both from a positive and a normative perspective. We start out with some illustrative examples from the analysis of monetary and fiscal policy, before we turn to aspects of asset pricing and monetary policy.

6.1 Monetary and fiscal policy aspects

Concerning *positive* policy analysis, estimated DSGE models can be used to infer which of the assumed nominal and real frictions are the most important ones in order to replicate the identified impulse response patterns. A particularly rich example of this approach is the analysis by Christiano, Eichenbaum and Evans (2005) who allow at the outset for a large number of nominal and real frictions, including nominal rigidities in wage and price setting, in order to explain the inertial behaviour of inflation and the persistent reaction of output in response to a monetary policy shock. The paper shows that a version of the model with only nominal wage rigidities does almost as well as the full model. In contrast, if one allows only for nominal price rigidities the model performs very poorly. This comparative analysis indicates that the critical nominal friction is wage contracts, not price contracts. Evidently, exercises of this type help to improve our understanding how private sector behaviour and responses of policy-makers jointly shape aggregate outcomes over the business cycle.

Importantly, estimated DSGE models can also be used to tackle *normative* issues concerning monetary policy since these models provide an integrated approach to the study of the business cycle and the study of the optimal response of policy-makers to shocks. Unlike the traditional IS-LM approach to optimal policy analysis (Poole 1970) normative DSGE analysis is based on the idea that, as long as the behavioural equations on which a model is constructed derive from optimisation problems, a consistent welfare analysis should be based on the same optimality criteria. In particular, if a business cycle model is based on the optimal intertemporal allocation of consumption and leisure by households, a benevolent policy-maker should also try to maximise the household's objective. Key references in this context are

[20] Bayesian techniques are also used by Lubik and Schorfheide (2003) to estimate a DSGE open economy model.

Rotemberg and Woodford (1997, 1998). Essentially, the normative analysis compares the welfare consequences of different, counterfactual policy rules in terms of the welfare of the representative household, taking as given the shock processes of the structural equations of the model that were obtained in the estimation process.[21] The structure of Rotemberg and Woodford (1997) is similar to the model sketched in Section 3.2, exhibiting two structural equations and one nominal friction. Reflecting this relatively simple structure the normative analysis reveals that the welfare of the representative household would have been substantially improved if US monetary policy, counterfactually, had followed over the estimation period 1980–95 a more aggressive policy of stabilising inflation rates around a lower average inflation rate.[22]

However, the fully optimal policy prescription is often not easily implementable in practice. For example, this would be the case if the optimal rule requires to link the policy instrument to unobservable variables. Therefore, it is attractive to look into the welfare properties of operational policy rules which set the policy instrument as a function of readily observable macroeconomic variables, like the Taylor-rule established in Section 3.2. which links the interest rate to inflation and output.[23] In terms of such a simple Taylor rule, the strong case for inflation stabilisation discussed in Rotemberg and Woodford (1997) translates into a strongly positive response of the nominal interest rate to inflation (λ_π), while the response to output (λ_y) is at best very small.[24]

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21 Using a second-order approximation of the utility function combined with first-order approximations of the equilibrium conditions of the economy, Rotemberg and Woodford (1997) have provided a simple solution to this problem which is valid if the non-stochastic steady state is efficient. More recently, developments in the solution of second-order approximations by Sims (2000), Schmitt-Grohé and Uribe (2004b) and Lombardo and Sutherland (2006) have opened up the possibility of performing welfare analysis also in more general settings in which the underlying non-stochastic steady state is inefficient.

22 However, a complete stabilisation of inflation around a zero inflation rate (i.e. price stability) is likely to be impossible because of the implied strong volatility of the interest rate which may violate the zero bound restriction. Nevertheless, this broad result is evidently of relevance for "inflation targeting" central banks, since it suggests that a strong focus on price stability is the best a central bank can do to improve households' welfare. Here we use the inflation targeting concept in a broad sense (i.e. central banks whose main or primary concern is price stability) and not in a narrow sense (which would require a detailed comparison of implementation procedures of monetary policy across central banks). In similar spirit, see the analysis in Goodfriend and King (2001) and Clarida, Gali and Gertler (1999), as well as the comprehensive treatment in Woodford (2003a).

23 For a careful discussion of operational monetary rules, see Schmitt-Grohé and Uribe (2005a). As additional features, operational rules typically ensure that the interest rate respects the zero lower bound and that the induced rational expectations equilibrium is unique.

24 Notice, however, the local character of this policy recommendation. Drawbacks from a global perspective are discussed in Benhabib, Schmitt-Grohe and Uribe (2002).

More recent richer model specifications have lead to some modifications of the features of optimal policy, without overturning so far the general thrust of the small scale New-Keynesian paradigm. For concreteness, we mention briefly two such modifications. First, optimal generalised Taylor-rules which also allow for a lagged response of the interest rate to its own past value typically call for gradual adjustments of the interest rate to new information. Since aggregate demand depends not only on current interest rates but also on expected future rates, a policy of gradual interest rate adjustments has substantial leverage over aggregate demand, without requiring large swings in short-term interest rates, as shown in Woodford (2003b). Second, models which allow for a larger set of frictions and trade-offs typically report optimal Taylor coefficients on inflation which are lower, while still in line with the Taylor-principle that (expected) real rates should optimally rise in response to increases in inflation above the target. In this spirit, Schmitt-Grohé and Uribe (2005a) study the optimal operational monetary policy in the rich framework of Christiano, Eichenbaum and Evans (2005) and derive an inflation coefficient of the Taylor-rule close to unity, implying essentially a monetary reaction which amounts to a real interest rate targeting rule. Moreover, depending on the assumed indexation schemes of wage and price contracts complete inflation stabilisations may no longer be optimal.

Moreover, a number of DSGE-contributions acknowledge that optimal features of monetary policy should be established in a comprehensive framework which simultaneously allows for non-trivial features of fiscal policy. Going back to the research agenda set out by Lucas and Stokey (1983), this public finance or Ramsey approach to optimal monetary and fiscal policy-making has spurred a large literature which today has become fully integrated into DSGE models, as discussed, for example, by Benigno and Woodford (2003), Schmitt-Grohé and Uribe (2004a, 2005b) and Siu (2004). In particular, if fiscal policy is restricted to distortionary tax instruments this challenges *a priori* the afore discussed recommendation of a strong stabilisation of inflation rates around a low target rate. Intuitively, in the absence of government debt with explicit state-contingent pay-offs, volatile inflation rates may optimally absorb fiscal shocks by making the pay-offs of nominal government debt state-contingent, i.e. inflation surprises make government debt state-contingent in real terms even if it is not in nominal terms. The associated gains from a more volatile inflation process need to be balanced, however, against the costs which depend in particular on the assumed degree of price and wage stickiness. Under fully flexible prices the optimal inflation volatility under distortionary taxes is substantially higher than in models without a meaningful role of fiscal policy. However, plausible estimates of nominal rigidities suffice to reduce the optimal inflation volatility near to zero.

Similarly, richer models can be used to derive endogenously the optimal average rate of inflation. The answer to this question depends, again, on the estimated magnitudes of the assumed frictions. In particular, the famous benchmark result of choosing optimally a negative inflation objective under flexible prices and wages (in line with the so-called Friedman rule) is no longer robust under reasonable degrees of nominal rigidities. Instead, an inflation objective close to genuine price stability seems preferable. In sum, these richer models which jointly assign monetary and fiscal policy non-trivial roles do not overturn the insight that low and stable inflation rates appear to be a central goal of optimal policy-making.

Finally, to conclude this subsection, it is worth pointing out that the case for consumer price stability is much weaker in an open economy context, as shown by Benigno and Benigno (2003). Their approach highlights the presence of inflationary and deflationary incentives for central banks of imperfectly competitive open economies. A similar analysis is carried out by Corsetti and Pesenti (2005), Devereux and Engel (2003) and Obstfelf and Rogoff (2002). These authors show that the optimal monetary policy rule depends, among other things, on the degree of the international integration of goods and financial markets. The fact that under sticky prices national monetary policies affect the terms of trade produces international spillovers reminiscent of the optimal tariff literature. A natural implication of these models is then that, in principle, there is room for coordination among independent central banks. The empirically relevant issue, though, is the size of the gains from coordination. Obstfeld and Rogoff (2002) claim that the gains are small so that self-interested central banks are likely to produce higher welfare also at a global level. Some papers dispute the generality of these results [e.g. Benigno and Benigno (2003) and Sutherland (2002)]. Overall, the literature on open-economy aspects of optimal monetary policy is still inconclusive. The methodology, though, is gaining ground and its relevance for policy analysis looks promising.

6.2 Asset pricing and monetary policy

Traditionally, in most parts of modern finance a partial equilibrium approach is used. For example, the famous capital asset pricing model (CAPM) values an individual stock relative to the market portfolio, while the value of the market portfolio itself is left unexplained. Another important example is the pricing of derivatives. Usually derivatives are priced relative to the price of the underlying. One of the most important achievements of modern finance is the development of the stochastic discount factor (SDF) approach as the general principle for asset pricing.[25] The basic idea of this approach is to price any asset by the expected value of the cash-flow times the SDF. When applied to derivative pricing, the SDF is extracted from the price process of the underlying (e.g. the stock market index) and then used to price the derivative. The shortcoming of this partial equilibrium approach, however, is the inability to price the underlying. Related to this, to understand the so-called equity premium, i.e. the higher returns of equities in relation to government bonds, it is important to model the price of the aggregated stock market.[26] Since stock prices are strongly influenced by macroeconomic factors, this leads to a natural role for DSGE-based analysis in this context.[27] In this spirit, DSGE models along the lines of Christiano and Fisher (2003) offer promising explanations of stock price movements in relation to business cycle dynamics. The strong connection of asset pricing and DSGE models is also obvious in the case of a consumption-based asset pricing model. In this type of asset price models, the SDF is proportional to the intertemporal marginal rate of substitution of the representative household. A natural exercise of using DSGE models is to analyse the reaction of the intertemporal marginal rate of substitution to exogenous shocks. Using the aforementioned SDF methodology we can then analyse also the reaction of any asset price to such a shock.

Apart from asset pricing, DSGE models are useful to analyse the relation between stock prices and monetary policy. In a recent paper, Neri (2004) finds a small negative and transitory effect of a contractionary monetary policy shock on the stock market for the G7 countries, using a structural VAR. He is also able to replicate this result with a limited participation DSGE model which allows households to trade in stocks. From a normative perspective, the key question is whether monetary policy should react to the stock market. In this spirit, Bullard and Schaling (2002) find a negative effect for the overall performance of the economy if stock prices are included in the monetary policy rule. This finding is driven by the arbitrage relation between the interest rate and the overall stock price. If the central bank puts low weight on stock prices then the results are identical to inflation targeting. If it puts, however, a large weight on stock prices the interest rate policy becomes more and more like an interest rate peg and the economy suffers from an

[25] This approach is forcefully described in the recent book by Cochrane (2001).

[26] Due to lack of space, this survey cannot review the large literature on the equity premium puzzle. A very readable survey summarising this debate is provided by Mehra and Prescott (2003).

[27] For recent empirical results on this relationship, see, for example, Flennery and Protopapadakis (2002).

indeterminacy problem. Hence, putting weight on the stock market is actually destabilising in this environment. A key problem of Bullard and Schaling (2002) is that the investment process is not modelled. Dupor (2005) shows that in a DSGE model with a q-type of investment behaviour the central bank should react (strongly) to stock prices if these deviate from their fundamental values. In sum, while the analysis of the relation between asset prices and monetary policy is still in its infancy, it is clear that a DSGE-based approach has a strong appeal.

The final example of DSGE modelling in the context of asset pricing we want to present relates to the term structure of interest rates. Interestingly, the term structure literature is divided into two separated parts. The first part is the arbitrage-free modelling of the term structure with unobservable factors as the driving force. This type of modelling is mostly done in finance and has led to the identification of factors which are called "level", "slope" and "curvature". These factors are unobservable and related only to the effect on the shape of the yield curve. It is not easy to give these factors an economic interpretation. The other part of the literature analyses the relation of the term structure to macroeconomic variables in the framework of unrestricted VAR models. In such models, one can interpret the movements of the yield curve in an economically meaningful sense but this comes at the cost of a number of inconsistencies. The unrestricted VAR models do not generate arbitrage-free term structures and are therefore problematic. General equilibrium models are an excellent framework to match these two parts of term structure modelling. Since the concept of an equilibrium is more general than the concept of no-arbitrage and since DSGE models are constructed for the analysis of structural macroeconomic shocks they combine the advantages of both parts. At this stage, very little work in this direction has been done yet, but the paper by Wu (2005) is a promising first step. He constructs a DSGE model that can associate the driving forces of the term structure with macroeconomic shocks. Another important contribution is given by Evans and Marshall (2001). They show that the price of risk responds differently to different sources of the business cycle shock.[28] In sum, to incorporate the term structure analysis in DSGE frameworks seems to be very promising because this approach may make it possible to model the macroeconomic aspects of the risk premium in a satisfactory manner.

[28] Related to this, Kozicki and Tinsley (2002), although not directly focusing on term structure modelling, use the yield curve implications of their model to assess its empirical performance. Further recent papers linking DSGE modelling with term structure analysis are, for example, Dewachter and Lyrio (2004) and Hördahl, Tristani and Vestin (2006).

7 Conclusion

This article surveys key developments of dynamic macroeconomic modelling over the past decades that have led to the by now widespread use of DSGE models. The survey highlights that this type of modelling is the heir of the real business cycle research. In their current form, however, DSGE models embed a large variety of assumptions stemming from rather diverse schools of thought like the New Classical or the New-Keynesisan paradigm. The most recent vintages of DSGE models offer versatile, consistent and relatively small macromodels which can be directly estimated and which have proved to perform quite well in matching the empirical evidence. Many policy-making institutions worldwide, with central banks playing a prominent role among them, have embarked on projects for the further development of such models with the aim of using them as tools for policy analysis and possibly forecasting. This process should be welcome since it helps to close gaps between policy analysis and academic research. Moreover, it improves the internal communication among policy analysts who will increasingly share a common and up-to-date analytical framework.

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