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A Structural Cointegrating VAR Approach to Macroeconometric Modelling *

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Abstract

In this paper we discuss the 'structural cointegrating VAR' approach to macroeconometric modelling and compare it to other approaches currently followed in the literature, namely the large-scale simultaneous equation macroeconommetric models, the structural VARs, and the dynamic stochastic general equilibrium models. The structural cointegrating VAR approach has the attractive features that the estimated long-run relationships embedded in the model are theory consistent, and have a clear economic interpretation, and yet the short-run dynamics are flexibly estimated within a VAR framework. The approach is illustrated using a small quarterly macroeconometric model of the U.K.. The uses of the model in impulse response analysis and probability forecasting is also discussed.

Keywords: Structural Cointegrating VAR, Macroeconomic Modelling, Generalised Impulse Responses, Persistence Profiles, Probability Forecasts.
JEL Classifications: C5, C32, E17

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1 Introduction

Macroeconometric modelling in the U.K. and elsewhere has undergone a number of important changes during the past two decades, largely in response to developments in economic and econometric theory as well as to changing economic circumstances. One important impetus in this process was Lucas' (1976) critique of macroeconometric policy evaluation, which resulted in widespread adoption of the rational expectations methodology in macroeconomic models. It also provoked considerable scepticism concerning the use of large-scale macroeconometric models in policy analysis and initiated the emergence of a new generation of econometric models explicitly based on dynamic intertemporal optimisation decisions by firms and households. In contrast, Sims' (1980) critique raised serious doubts about the traditional, Cowles Commission approach to identification of behavioural relations, which had been based on what Sims termed 'incredible' restrictions on the short run dynamics of the model. This critique generated considerable interest in the use of vector autoregressive (VAR) models in macroeconometric analysis.[1] A third impetus for change in the way in which macroeconometric modelling has been undertaken came from the increased attention paid to the treatment of non-stationarity in macroeconomic variables. The classic study was that by Nelson and Plosser (1982), who showed that the null hypothesis of a unit root could not be rejected in a wide range of macroeconomic time series in the U.S.. This resurrected the spectre of spurious regression noted originally by Yule (1926), Champernowne (1960), and more recently by Granger and Newbold (1974). Subsequently, the work of Engle and Granger (1987), Johansen (1991) and Phillips (1991) on cointegration showed possible ways of dealing with the spurious regression problem in the presence of unit root variables, with important consequences for macroeconometric modelling in particular.

Following these developments, the alternative approaches to macroeconometric modelling in the U.K. and elsewhere can be grouped under four broad categories. *First*, there are large-scale macroeconometric models such as the HM Treasury's model of the U.K. economy, and the Federal Reserve Boards model of the U.S. economy. Although these models have made many important innovations, by their very nature they have been slow to evolve and essentially follow the tradition of the Cowles Commission, making a distinction between exogenous and endogenous variables and imposing restrictions, often on the short-run dynamic properties of the model, in order to achieve identification. The parameters are typically estimated by least squares or by instrumental variables methods, and full information estimation of the model parameters is rarely attempted.

Secondly, following the methodology developed by Doan, Litterman and Sims (1984) and Litterman (1986), there are unrestricted, Bayesian, and structural VARs. These are frequently employed for forecasting but are of limited use in policy evaluation.[2] The structural VAR approach aims to provide the VAR framework with structural content through the imposition of restrictions on the covariance structure of various shocks.[3] However, this approach is typically employed to carry out impulse response analysis in a "structurally" meaningful manner, and does not attempt to model the structure of the economy in the

[1] Sims' critique also extends to the identification of rational expectations models.
[2] See, for example, Cooley and LeRoy (1985).
[3] This approach has been used, for example, by Blanchard and Quah (1989).

form of specific behavioural relationships.

The *third* approach is closely associated with the Dynamic Stochastic General Equilibrium (DSGE) methodology employed in the Real Business Cycle literature. This approach developed following the seminal work of Kydland and Prescott (1982) and Long and Plosser (1983) provides an explicit intertemporal general equilibrium model of the economy based on optimising decisions of households and firms. Originally, the emphasis of these models was on real factors (e.g. productivity shocks), but more recently the DGSE models have been extended in a number of directions aimed at allowing for nominal effects, adjustment costs, heterogeneity, and endogenous technological progress, for example.[4] In consequence, the differences between the DGSE and the traditional macroeconometric models have become less pronounced. Also many of the DGSE models can be approximated by restricted VAR models, which brings them more in line with other modelling approaches.[5]

The *fourth* approach, and the one which we aim to promote in this paper, is the 'structural cointegrating VAR' approach. This approach is based on the desire to develop a macroeconometric model which has transparent theoretical foundations, providing insights on the behavioural relationships which underlie the functioning of the macroeconomy, and which has flexible dynamics that fit the historical time series data well. The modelling approach advocated here is based on a log-linear VAR model estimated subject to *long-run* relationships obtained from economic theory. On the assumption that the individual macroeconomic series have a unit root, each of the long-run relationships derived from theory is associated with a cointegrating relationship between the variables, and the existence of these cointegrating relationships imposes restrictions on a VAR model of the variables. Hence, the approach provides an estimated structural model of the macroeconomy, in which the only restrictions on the short-run dynamics of the model are those which are imposed through the decision to limit attention to log-linear VAR models with a specified maximum lag length. The work of King *et al.* (1991) and Mellander *et al.* (1992) is in this vein, but is limited in scope. The six-variable model of King *et al.* is a closed economy model not suitable for modelling a small open economy such as the U.K.. The four-variable model by Mellander *et al.* attempts to capture the open nature of the Swedish economy only by adding a terms of trade variable to the familiar consumption-investment-income model also analysed by King *et al.* In this paper we use the recently developed core U.K. model by Garratt *et al.* (1998a,b) to illustrate the practical advantages of the structural cointegrating VAR approach to macroeconometric modelling of small open economies.

The structure of the remainder of the paper is as follows. Section 2 gives a brief overview of the alternative macroeconometric modelling approaches. Section 3 provides a more detailed description of the structural cointegrating VAR approach. Section 4 illustrates the uses of the approach in impulse response analysis and probability forecasting. Section 5 concludes.

[4]See Section 2.3 for details.

[5]See, for example, Kim and Pagan (1995) and Christiano, Eichenbaum and Evans (1998).

2 Alternative Approaches to Macroeconometric Modelling

In this section, we elaborate on three of the broad approaches to macroeconometric modelling raised in the Introduction, focusing in particular on the implications of the different approaches for modelling the long-run. The discussion considers the different ways that the long-run relations are modelled (whether explicitly or not) in large-scale simultaneous equation macroeconometric models, in unrestricted and structural VAR models and in Dynamic Stochastic General Equilibrium models.

2.1 Large-Scale Simultaneous Equation Models

Recent Developments

Large-scale simultaneous equation macroeconometric models (SEMs) can be traced back to the modelling approach of Tinbergen and Klein and its subsequent developments at the Cowles Commission. Prominent examples of such large-scale models include the first and second generation models developed at the Federal Reserve Board (see, for example, Ando and Modigliani, 1969, Brayton and Mauskopf, 1985, and Brayton and Tinsley, 1996) Fair's (1994) model of the U.S. economy, Murphy's (1988,1992) model for Australia, and the models constructed for the U.K. at the London Business School (LBS), the National Institute of Economic and Social Research (NIESR), HM Treasury (HMT), and up until recently at the Bank of England (BE).[6]

The relatively poor forecasting performance of the large-scale models in the face of the stagflation of the 1970's, in conjunction with the advent of rational expectations and the critiques of Lucas (1976) on policy evaluation and Sims (1980) on identification, brought about a number of important changes in the development and the use of large-scale SEMs throughout the 1980's and 1990's. Important developments have taken place in three major areas:[7] *First*, in response to Sims' criticism of the use of 'incredible' identifying restrictions involving short-run dynamics, and under the influence of recent developments in cointegration analysis (*e.g.* Engel and Granger, 1987), a consensus has formed that the important aspect of a structural model is its long-run relationships, which must be identified without having to restrict the model's short-run dynamics. *Second*, in response to the criticism that large-scale models paid insufficient attention to the micro foundations of the underlying relationships and the properties of the macroeconomic system considered as a whole, there is now a greater use made of economic theory in the specification of large-scale models. And *third*, in response to the criticisms of Lucas, considerable work has been undertaken to incorporate rational expectations (RE), or model consistent expectations, into large-scale models.

[6]Bodkin *et al.* (1991) provide a comprehensive survey of the history of macroeconometric model building. The evolution and the development of macroeconometric modelling at the Federal Reserve Board is reviewed by Brayton *et al.* (1997). For the U.K. these developments have been documented in a series of volumes produced by the ESRC Macroeconomic Modelling Bureau (see, for example, Wallis *et al.*, 1987). Further reviews of the modelling in the U.K. and elsewhere can be found in Smith (1994), Wallis (1995) and Hall (1995).

[7]A detailed discussion of these developments in the case of the U.K. practice can be found in Hall (1995). Similar arguments have also been advanced by Brayton *et al.* (1997) in the case of the U.S. experience.

Under the influence of these recent developments, the new generation large-scale models share a number of important features. Invariably they comprise of three basic building blocks: equilibrium conditions, expectations formation, and dynamic adjustments. The equilibrium conditions are typically derived from the steady state properties of a Walrasian general equilibrium model, and there seems to be clear evidence of a developing consensus on what constitutes the appropriate general equilibrium model for characterising the long-run relations. This consensus side-steps the Sims critique by focusing on the long-run and remaining agnostic on short-run dynamics. Britton and Westaway (1998) provide a good example of the nature of the consensus in the U.K..[8] These authors use standard simulation methods to show that, broadly speaking, the NIESR model has the characteristics of a Walrasian general equilibrium system in the long-run. The steady state values of the key aggregates in the NIESR model (namely output, net investment overseas, domestic investment, and employment) are determined as outcomes of utility maximisation by households and profit maximisation by firms subject to appropriate budget and technological constraints. The relative prices (namely the real wage, the relative price of domestic to foreign outputs, and the differential between domestic and foreign interest rates) are then determined to ensure market clearing and the neutrality of nominal magnitudes in the long-run.

In a similar vein, Allen *et al* (1994) describe the role of the supply side in determining the LBS model's long-run properties. The relations characterising the supply side in the LBS model are explicitly based on optimizing models of firm and union behaviour, and consist of a system of factor demand and (relative) price equations (for labour, energy, imported inputs and capital). The relationships are estimated as a single system, imposing all the cross-equation restrictions suggested by cost minimisation on the part of firms. And finally, as a third illustration of the developing consensus, Murphy's macroeconometric model of the Australian economy is described in Murphy (1992) as sharing the main features of the intermediate-run version of the Dornbusch (1976) model, but in addition includes all balance sheet and flow of funds constraints applicable to households, firms, government and foreign sectors, and incorporates full neoclassical optimising behaviour in production in the steady state. Restrictions are also imposed to ensure that there is 'balanced growth' in the long-run, where 'balanced growth' is taken to mean that real growth is driven by technical progress and population growth, the unemployment rate equals the NAIRU, and inflation is the difference between the monetary and the real output growths.

The Need for Transparency

Despite the progress made so far, and the growing consensus on what constitutes best practice in macroeconometric modelling, large-scale models continue to be viewed with some scepticism, in particular in the area of policy analysis.[9] Furthermore it can be argued that it is simply not possible for large-scale models to follow such a best practice approach because of their size and complexity. The complexity of the interactions of different parts of a large dynamic model means that the accumulated response of the macro-economy to a particular shock or change in a given exogenous variable can be very difficult to interpret, particularly as far as their effects on the long-run relations are concerned. It is also difficult to identify

[8] Brayton *et al.* (1997) also make similar observations with respect to the new FRB/US model which was officially adopted by the Federal Reserve Board in 1996.

[9] See, for example,Whitley (1997).

and correct for misspecification in large-scale models, as attempts to fix one part of the model could have far reaching (and often unpredictable) consequences for the properties of the overall model. And as far as estimation is concerned, full information methods are often not even an option given the large size of these models. Generally speaking, large-scale models lack transparency, which often hinders interpretation of model properties and impedes communication on policy debate, and this might explain why both academics and policy makers have, on occasions, by passed large models in certain areas of policy debates.

The lack of transparency of large-scale models has resulted in the development of a number of innovative methods for characterising and summarising their short-run and long-run properties. The standard approach is through (stochastic) simulations. Sensitivity analysis is then undertaken, and dynamic multipliers derived, by simulating the model under alternative scenarios for the exogenous variables and/or parameters of interest.[10] However, such a numerical solution procedure for identification of the model's long-run properties, besides being computationally expensive, remains difficult to interpret. Further, it could be sensitive to particular realisations of the forcing variables used in the simulation analysis, especially when there are strong non-linear effects in the relationships between the endogenous and the forcing variables of the model.[11] But the fact that such methods are necessary is in itself an important indicator of the general lack of transparency of large-scale models with respect to their long-run properties.

Because of their size, theory restrictions are imposed in different parts of the large-scale models often in a piece-meal fashion. For example, restrictions might be imposed in one part of a model to ensure long-run consistency with economic theory, but there may be complicated feedbacks in another part of the model which are not fully taken into account and may result in the model as a whole being at variance with the theory in the long-run. Such a possibility is clearly illustrated in the empirical exercise of Fisher *et al.* (1992), where attention is drawn to the differences between the models developed by NIESR, LBS, BE and HMT in terms of the reaction of the current account balance to nominal exchange rate changes.

A second illustration of the difficulties associated with the use of theory restrictions in large-scale SEMs relate to the choice of terminal conditions in the case of models involving forward-looking expectations. The long-run solution and the short-run dynamics of large-scale RE models can be very sensitive to the choice of terminal conditions. However, in the past, many large-scale models employed automatic rules to deal with the terminal conditions which were chosen relatively arbitrarily, with little regard to economic theory.[12] While the more recent generation of large-scale models have paid greater attention to the choice of terminal conditions, particularly as far as the long-run properties of these models are concerned, this provides a further example of the difficulties faced when attempts are made to incorporate theory consistent long-run structures in large-scale models.[13]

[10]For illustrations of this approach in the context of the analysis of the U.K. labour market, see, for example, Wallis *et al.* (1987), Turner (1991) and Wallis and Whitley (1987).

[11]Other more effective methods for the analysis of the long-run properties of large macroeconometic models have been developed by Murphy (1992), Fisher *et al.* (1992), and Wren-Lewis *et al.* (1996).

[12]The importance of the choice of terminal conditions in the context of the LBS, NIESR and the Liverpool models is illustrated in Fisher (1992).

[13]Some of these difficulties concerning the choice of the terminal conditions have been addressed. See,

To summarise, while important progress has been made in the construction and use of large-scale SEMs over the past two decades, it can still be argued that these models are subject to a number of limitations that arise primarily because of their large and complex structure. As Brayton *et al.* (1997) conclude: "Large-scale macro models are by their nature slow to evolve." Simultaneous estimation and evaluation of such models is currently computationally prohibitive, and given the available time series data may not be even feasible. A full integration of theory and measurement has proved elusive to large-scale model builders. Despite the imaginative attempts made over the past two decades, construction of a large-scale macroeconometric theory-consistent model which has transparent long-run properties and fits the data reasonably well remains a formidable undertaking.

2.2 Unrestricted and Structural VARs

Unrestricted VARs

The various technical and methodological difficulties associated with the construction of large-scale models, and their highly labour and capital intensive nature has led many researchers to seek modelling strategies that are less demanding and more manageable. The unrestricted VAR approach introduced into macroeconometrics by Sims (1980) stands at the other extreme to large-scale models. It focuses on fitting the model to the data at the expense of theoretical consistency, both from a short-run or a long-run perspective. Sims' objective was to investigate the dynamic response of the system to shocks (through impulse response functions) without having to rely on 'incredible' identifying restrictions, or potentially controversial restrictions from economic theory. This strategy eschews the need to impose long-run relationships on the model's variables, and relies exclusively on time series observations to identify such relationships if they happen to exist.

The statistical basis of the unrestricted VAR modelling approach is the Wold decomposition theorem. According to this theorem, all covariance stationary processes can be written as the sum of a deterministic (perfectly predictable) component and a stationary process possessing an infinite order moving average (MA) representation. Restricting attention to 'invertible' processes,[14] one obtains a unique MA representation, also known as the 'fundamental' representation which fully characterises the sample autocorrelation coefficients. Such a fundamental representation can be approximated by a finite order vector autoregressive-moving average (VARMA) process. However, estimation of VARMA models poses important numerical problems, particularly when the number of variables in the VARMA model is relatively large. For this reason Sims chooses to work with a finite order VAR model which is much simpler to estimate, but involves further approximations. To perform impulse response analysis, Sims' approach then requires the use of a Choleski decomposition of the variance

for example, Minford *et al.* (1979) and more recently Fuhrer and Bleakley (1996) for a certainty equivalent solution method in the case of non-linear dynamic rational expectations models where the terminal conditions for the solution path are derived using the uniqueness and stability conditions of an associated linearized model.

[14] Limiting attention to the fundamental Wold representation is not uncontentious: as shown in Hansen and Sargent (1991), for example, the MA representation that underlies the VAR model can be non-fundamental (in the sense that one or more of the roots of the MA process fall inside the unit circle) and at the same time be economically meaningful.

covariance matrix of the model's innovations/shocks. This enables the MA representation to be written in terms of orthogonalised innovations. It is the response of the macroeconomic variables to these orthogonalised shocks that are described in Sims' orthogonalised impulse responses.

This approach to modelling has been subject to a number of criticisms (see, for example, Pagan, 1987), some of which are worth noting here. First, the approach requires care in the initial stages in the choice of transformation of the data to achieve stationarity. In particular, it is important that economically meaningful, and statistically significant, relations are not excluded from the analysis at this stage by the choice of transformation. For example, a VAR model of the first-differences of I(1) variables is misspecified if there exists a cointegrating relationship between two or more of the I(1) variables. Second, care is needed in the choice of variables to be included in the VAR analysis, and it is difficult to imagine how this choice could be made without reference to some underlying economic theory. And third, since the choice of the Choleski decomposition is not unique, there are a number of alternative sets of orthogonalised impulse responses which can be obtained from any estimated VAR model. A particular choice of orthogonalisation might be suggested by economic theory, and Sims' own approach to choosing an orthogonalisation was to impose a causal ordering on the VAR. However, this requires recourse to economic theory (which defeats the object of this approach) and in general no such restrictions are available or acceptable. In the absence of such restrictions, the orthogonalised impulse responses are difficult to interpret economically, so that the estimated model gives few meaningful insights into the economic system that it represents.

Notwithstanding their weak theoretical underpinnings, due to their flexibility and ease of use, VAR models are used extensively in forecasting and as benchmarks for evaluation of large-scale and DSGE models. In order to increase the precision of forecasts based on VAR models Doan, Litterman and Sims (1984) have also proposed Bayesian VARs (BVARs) which combines unrestricted VARs with Bayesian, or what has come to be known as "Minnesota", priors. Other types of priors have also been considered in the literature. See, for example, DeJong *et al.* (1997) who combine a VAR(1) model with prior probabilities on its parameters derived from a RBC model.

Structural VARs

The structural VAR approach builds on Sims' approach but attempts to identify the impulse responses by imposing *a priori* restrictions on the covariance matrix of the structural errors and/or on long-run impulse responses themselves. This approach is developed by Bernanke (1986), Blanchard and Watson (1986) and Sims (1986) who considered *a priori* restrictions on contemporaneous effects of shocks, and more recently by Blanchard and Quah (1989), Clarida and Gali (1994) and Astley and Garratt (1996) who use restrictions on the long-run impact of shocks to identify the impulse responses. In contrast with the unrestricted VAR approach, structural VARs attempt explicitly to provide some economic rationale behind the covariance restrictions used, and thus aim to avoid the use of arbitrary or implicit identifying restrictions. However, while the use of 'theory based' covariance restrictions in small systems allow the impulse responses to be identified under the structural VAR approach, such restrictions still do not enable identification of the long-run relationships among the variables.[15] Furthermore, even the covariance restrictions are not always easy to interpret or motivate from an economic perspective, particularly in the case of VAR models with more than two or three variables. The number of exactly identifying covariance restrictions required increases rapidly with the number of variables in the VAR. In a system involving m variables, the number of such restrictions is equal to $m(m-1)/2$. For example, in the case of the model presented in this paper the number of covariance restrictions required to exactly identify the impulse responses will be 28. It is not clear how these restrictions could be obtained, let alone motivated from an appropriate economic theory perspective.

There are also inherent difficulties with the interpretation that are given to the impulse responses obtained under the structural VAR approach. For example, in Blanchard and Quah (1989), a bivariate VAR model of unemployment and output growth is investigated by first solving the two variables in terms of two orthogonalized white-noise shocks, and then estimating impulse responses under the identifying assumption that one of the shocks has no long-run effects on output levels. They then duly refer to this shock as the 'demand' shock, and refer to the other shock as the 'supply' shock.[16] However, while it might be an interesting exercise to consider the effects on output and unemployment of the two different types of shock, and while it might be possible to elaborate a model of the macroeconomy in which demand shocks have the property assumed by Blanchard and Quah, there seems little rationale in referring to these innovations as 'demand' and 'supply' shocks in the context of the purely statistical model used by these authors. The different types of shock considered in this analysis are defined with reference to their statistical properties (i.e. whether or not they have a permanent effect on output levels) and not with reference to a model of how consumers and producers behave in a macroeconomy.[17]

2.3 Dynamic Stochastic General Equilibrium Models

Unrestricted VARs, BVARs, or the Structural VARs all make minimal use of economic theory, while the use of theory in large-scale models is modular, in the sense that the theory is used in a coherent manner only in specific modules or parts of the model. In contrast, the Dynamic Stochastic General Equilibrium (DSGE) models develop a general equilibrium approach to modelling using stochastic intertemporal optimisation techniques applied to decision problems of households and firms.[18]

The DSGE model is expressed in terms of 'deep' structural parameters, namely the parameters that enter the preferences, production technologies and the probability distributions of taste and technology shocks. In practice, very simple forms are chosen for these functions (power utility function and Cobb-Douglas production functions, for example). Nevertheless, the resultant optimal decision rules are complicated and typically are approximated around the deterministic steady-state values of the macroeconomic variables. The outcome for standard models typically is a highly restricted VAR(1) model.[19]

[15] In this sense, it is a misnomer to refer to these models as *structural*.

[16] Recall that since $m = 2$, one only needs one covariance restriction to identify the impulse responses.

[17] For a more detailed critical evaluation of the structural VAR approach see Levtchenkova et al. (1998).

[18] For a survey of recent developments in the literature on DSGE models see the contributions in the volume edited by Cooley (1995).

[19] See, for example, Binder and Pesaran (1995), Kim and Pagan (1995) and Wickens (1995).

The proponents of the DSGE approach to macroeconomic modelling argue that this approach takes macroeconomic theory seriously in a way that the large-scale SEMs do not. In particular, it is argued that the use of a general equilibrium framework ensures that the DSGE models display stock equilibria, rather than the flow equilibria which are characteristic of the traditional approach to macroeconometric models. The derivation of the model's relationships as solutions to intertemporal optimization problems of households and firms ensures that the model has an internal consistency and a relationship with economic theory that is lost in traditional large-scale models. However, we have already noted that the proponents of large-scale models have made considerable progress in relating the structure of their models to economic theory, particularly in relation to the long-run properties of the model. Indeed, we noted that there has developed a consensus on the appropriate theory for the characterisation of the long-run, based on Walrasian general equilibrium theory, which has been adopted (at least in principle) in many of the current generation of large-scale models. In this respect, therefore, the differences in the theoretical underpinnings of the DSGE models and the large-scale models are less polarised than is sometimes argued.

However, there are important differences between the two approaches both in content and in emphasis. They differ significantly in their treatment of short-run dynamics. The DSGE models not only provide the form of relationships between economic variables that exist in the long-run, but also provide an explicit statement of the dynamic evolution of the macroeconomy in response to shocks. It is argued (for example, in Plosser, 1989) that the foundations of typical Keynesian models are static in nature, and that the dynamics are introduced arbitrarily through accelerator mechanisms for investment and inventory behaviour, or through nominal rigidities in wage and price setting, or through partial adjustment mechanisms in various forms, for example. The lack of cohesion in the derivation of the long-run and dynamic properties in the large-scale models represents a fundamental short-coming of the approach, according to this argument, encouraging the view that the long-run evolution of the macroeconomy can be considered independently of short- and medium-term fluctuations. In contrast, there are no dichotomies between the determinants of long-run growth and short-run fluctuations in DGSE models, though the long-run is of course often not modelled explicitly in its entirety, in that model and actual data are (arbitrarily) filtered before they are analysed.

While it is true that many DSGE models provide an integrated approach to the study of growth and fluctuations, it is acknowledged that the approach is in its infancy in terms of providing a satisfactory understanding of economic fluctuations. The current generation of DSGE models have extended the original models to incorporate features such as: adjustment costs (e.g. Kydland and Prescott, 1982, Christiano and Eichenbaum, 1992b, and Cogley and Nason, 1995,); signal extraction and learning (e.g. Kydland and Prescott, 1982, and Cooley and Hansen, 1995); aggregation (e.g. Christiano, Eichenbaum and Marshall, 1991, on temporal aggregation and Cooley, Greenwood and Yorukoghu, 1997, and Ríos-Rull, 1995 on cross-sectional aggregation); endogenous technological progress (e.g. Stadler, 1990, and Hercowitz and Sampson, 1991) and information heterogeneities (e.g. Kasa, 1995). However, it remains unclear whether a model could be developed that is capable of simultaneously dealing with all of these factors in a satisfactory manner, and even if it could, whether it would be any more transparent or easy to interpret than the currently available stock of large-scale models.

Three further points are worth making on the comparison of DSGE models and the large-scale SEMs in terms of their treatment of dynamics (elaborated in, for example, McCallum, 1989). First, while the recent literature on endogenous growth theory has begun to develop a theory of how economic fluctuations might influence technical progress, the extent to which technical progress is exogenously determined remains unclear. If it is believed that technical progress is actually taking place independently of the developments in the macroeconomy, then the emphasis on providing a single, internally-consistent model of growth and fluctuations is likely to be misplaced. Secondly, although the DSGE models place more emphasis on the mechanism by which shocks are propagated over time than the more traditional theories underlying the large-scale models, they are by no means incompatible with them. It is widely acknowledged, for example, that shocks generated by the signal extraction problem (and of a type which can be readily accommodated with a standard large-scale model) are likely to trigger the same type of dynamic response as the taste and technology shocks typically considered in DSGE models. Seen in this light, one might argue that the DSGE approach to dynamics is potentially over-restrictive, limiting attention to particular sources of dynamics. Indeed, when the models were confronted with the data, in Christiano and Eichenbaum (1992b) or Kim and Pagan (1995), for example, the evidence suggests that this might be true.

A third important difference between the approaches taken in the construction of the large-scale SEMs and the DSGE models is in the emphasis placed on real (and especially technological) shocks as opposed to nominal shocks. For example, many proponents of the DSGE approach do not deny the potential importance of money in explaining economic fluctuations. Indeed, a considerable literature has developed to incorporate money in DSGE models (see, for example, Cooley and Hansen, 1989, 1995, and Christiano, Eichenbaum and Evans, 1998). However, one of the primary motivating arguments behind the DSGE research agenda was to establish that the dynamic responses of the macroeconomy are consistent with a model in which there are no market failures, in which the outcome is Pareto optimal, and in which intervention by a social planner to force agents to change their actions will be welfare reducing. Consequently, the research agenda behind the development of the DSGE approach to modelling up until recently has downplayed the potential role of monetary policy in generating economic fluctuations and instead has placed considerable emphasis on real shocks. Indeed, many of the calibration exercises undertaken in the DSGE literature have ignored the monetary sector altogether. In fact, in terms of explaining macroeconomic time series, it is unambiguously the case that the use of data on nominal magnitudes, including nominal interest rates and money stock data, improves the explanatory power of models of real magnitudes such as output or employment (see, for example, King *et al.,* 1991, and Litterman and Weiss, 1985). These results, and associated causality tests, do not provide a test of the relevance of the DSGE models versus the large-scale SEMs, but they emphasise the importance of incorporating a monetary sector in a macroeconomic model despite the difficulties perceived by some proponents of the DSGE approach in developing a convincing and coherent explanation of the monetary transmission mechanism.

3 The Structural Cointegrating VAR Approach

The structural cointegrating VAR modelling strategy begins with an explicit statement of the long-run relationships between the variables of the model obtained from macroeconomic theory. These relationships will typically be based on stock-flow and accounting identities, arbitrage conditions, and long-run solvency requirements that ensure stationary asset-income ratios. The long-run relationships are approximated by log-linear equations, with disturbances that characterize the deviations of the long-run relations from their realized, short-run counterparts. These deviations are referred to as the 'long-run structural shocks'. Not all of the variables contained in the long-run relationships suggested by economic theory are observable, however, and in writing the long-run relationships in terms of observable variables, 'long-run reduced form shocks' are derived as functions of the long-run structural shocks. The long-run reduced form shocks are then embedded within an otherwise unrestricted log-linear VAR model of a given order in the variables of interest to obtain a cointegrating VAR model which incorporates the structural long-run relationships as its steady state solution. In this way the cointegrating VAR model will embody the long-run theory restrictions in a transparent manner. The theory also imposes restrictions on the intercepts and/or the trend coefficients in the VAR, which play an important role in testing for cointegration as well as for testing restrictions on the long-run relations.[20]

This approach, however, differs from many applications of cointegration analysis, which start with an unrestricted VAR and then attempt to impose restrictions on the cointegrating relations, without a clear *a priori* view of the economy's structural relations. Such a strategy is likely to work when there exists only one long-run relationship among the macro variables. However, when the number of cointegrating relations are two or more, without a clear and comprehensive theoretical understanding of the long-run relations of the macroeconomy, identification of the cointegrating relations and the appropriate choice of intercepts/trends in the underlying VAR model will become a very difficult, if not an impossible, undertaking.

3.1 Comparisons with the Three Alternative Approaches

Comparison with large-scale SEMs

As the discussion above makes clear, the structural cointegrating VAR approach to macroeconometric modelling begins by describing the relationships which define the long-run structure of the macroeconomy, and embeds these long-run relationships within an otherwise unrestricted VAR model of the macroeconomy. The number of variables chosen to include in the core model is selected to ensure that the system can be estimated simultaneously, taking into account all of the potential feedbacks between the variables captured by the short-run dynamics and suggested by the long-run economic relationships. One of the primary strengths of this approach, therefore, is that the model is developed and estimated in a way that ensures that the estimated model is consistent with, and is based on, a theoretically-coherent view of the long-run properties of the macroeconomy. Furthermore, this is accomplished without compromising empirical adequacy as an important criteria by

[20]For a discussion of the relevant econometric issues involved in the analysis of cointegrating VARs see Johansen (1995), Pesaran, Shin and Richard Smith (1997), and Pesaran and Ron Smith (1998).

which models in the final analysis must be judged. The transparency of the model's long-run properties will also be important for impulse response analysis and forecasting, particularly over the medium term.

Despite its advantages, the cointegrating VAR model is still highly restrictive and, given the available time series data, it can deal with at most 8-10 variables simultaneously. This clearly precludes addressing many important issues, if we were to confine our analysis to a single cointegrating VAR model. Macroeconometric models are used for many different purposes by government, academic and corporate institutions, and no one model will be appropriate for all of these uses (see Whitley, 1997). However, traditional macroeconometric models tend to become large often in response to demands for more disaggregated analysis, and for addressing a wider range of policy questions. For example, a central bank may require a detailed model of the monetary sector, corporate institutions might require forecasts and analysis disaggregated by the main industrial sectors (energy, construction, agriculture, transportation etc.), and government agencies might be required to investigate the effects of a given policy on particular interest groups and/or markets. Our approach to meeting these model-specific requirements is through the development of appropriate *satellite* models. These are constructed using similar econometric techniques to those employed in the estimation of the core model, and are then linked up to the core model, with the core variables (and the associated error correction terms from the core model) influencing sectoral developments, but not *visa versa* (see Pesaran and Ron Smith, 1997). In this paper, we are only concerned with the core model of the macroeconomy, which can be dealt with independently of the satellites under the assumption that there are no feedbacks from the variables in the satellites into the core model. This assumption could be tested in principle. However, given the limited length of the time series available, and in the interest of transparency of the model's long-run properties and their theoretical coherency, we do not propose that such a test must be carried out. Insisting on two-way feedbacks between the core and the satellites will result in models that are too large for the application of the econometric techniques favoured in this paper, and takes us back to the difficulties faced by the large-scale SEMs. In our approach, it is made explicit that the variables of the core macroeconomic model can be decoupled from any potential *satellite* to allow full information maximum likelihood estimation of the model under fairly general short-run dynamics, but restricted (to the extent supported by the data) to ensure cohesion with a long-run structural view of the macroeconomy.

Comparison with unrestricted and structural VAR modelling

One of the primary advantages of the structural cointegrating VAR approach to macroeconomic modelling is that it provides an explicit link between the estimated model residuals and the structural shocks of the underlying economic model. This explicit link indicates very clearly the restrictions that are required for identification of the effects of specific innovations to the model. In general it is unlikely that such restrictions are available, and it is for this reason that a more general method of analysing impulse responses is required, one which does not rely on the use of identifying restrictions. The Generalized Impulse Response analysis, introduced in Koop *et al.* (1996) and developed in Pesaran and Shin (1998), provides such a method. The GIR analysis describes the effects of a shock to an equation in the model on all of the variables in the system without giving an economic interpretation to the shock. So long as the mapping between the structural shocks and the shocks to the equations of the model remains constant, the analysis of the shocks to the estimated equations provides insights into the response of the macroeconomic model to the underlying structural shocks, taking into account the contemporaneous effects that such shocks might have on the different variables in the model. While this analysis cannot provide an understanding of the response of the macroeconomy to specified structural shocks, therefore, it does provide a meaningful characterisation of the dynamic responses of the macroeconomy to 'realistic' shocks (meaning shocks of the type that are typically observed).

Comparison with DSGE modelling

In DGSE modelling, the derivation of the long-run, steady state relations of the macro model starts with the inter-temporal optimization problems faced by households and firms and then solves for the long-run relations using the Euler first-order conditions and the stock-flow constraints. Given the invariably non-linear nature of the Euler equations and the linear forms of the constraints, the resultant relations of the model economy are generally highly non-linear and are usually approximated by log-linear relations (the real business cycle literature follows this methodology). The long-run relations are then obtained by ignoring expectational errors and assuming that the model economy is stationary and ergodic in certain variables, such as growth rates, capital per effective worker and asset-income ratios. The structural cointegrating VAR approach, on the other hand, works directly with the arbitrage conditions which provide inter-temporal links between prices and asset returns in the economy as a whole. The arbitrage conditions, however, must be appropriately modified to allow for the risks associated with market uncertainties.

Clearly, the above two approaches are closely related and yield similar results as far as the long-run relations are concerned. The main difference between the two approaches lies in their treatment of short-run dynamics. The strength of the inter-temporal optimization approach lies in the explicit identification of macroeconomic disturbances as shocks to tastes and technology, rendered possible by the explicit statement on the form of the short run dynamics. This is, however, achieved at the expense of often strong assumptions concerning the form of the underlying utility and cost functions, expectations formation, and the process of technological change. In contrast, the cointegrating VAR approach advanced in this paper is silent on short-run dynamics, but is in line with the DGSE model as far as the long-run relations are concerned.

4 A Core Macroeconometric Model of the U.K. Economy

In this section, we illustrate the structural cointegrating VAR approach to macroeconometric modelling in the context of a small quarterly "core" macroeconometric model of the U.K., estimated over the period 1965q1-1995q4, described in detail in Garratt *et al.* (1998a,b). The model is based on five long-run equilibrium relations derived from production, trade, arbitrage (in goods and capital markets), solvency and portfolio balance conditions. The model contains five domestic variables, whose developments are widely regarded as essential to a basic understanding of the behaviour of the U.K. macroeconomy, namely output, the domestic price level, the nominal interest rate, the exchange rate and real money balances.

It also contains four foreign variables, namely foreign output, the foreign nominal interest rate, the foreign price level and oil prices. To simplify the analysis, and to avoid working with possibly I(2) price levels the model is constructed in terms of domestic and foreign price variables measured relative to oil prices (in logs). As a result there are only eight variables in the core model. The five long-run relationships are then embodied in a cointegrating VAR model with the relative foreign price variable treated as a weakly exogenous I(1) variable (see below for an elaboration). The order of the VAR model is chosen using familiar model selection criteria, otherwise its short-run dynamics are left unrestricted. In this way we are able to capture the complicated dynamic relationships that exist between the domestic and foreign variables while at the same time maintaining a transparent and theoretically coherent long-run foundations.

4.1 The Core Macroeconomic Model

The five long-run equilibrium relationships are given by:

$$\begin{aligned}
(p_t - p_t^o) - (p_t^* - p_t^o) - e_t &= a_{10} + a_{11}t + \beta_{18}(p_t^* - p_t^o) + \varepsilon_{1,t+1}, && (4.1)\\
r_t - r_t^* &= a_{20} + \varepsilon_{2,t+1}, && (4.2)\\
y_t - y_t^* &= a_{30} + \varepsilon_{3,t+1}, && (4.3)\\
(p_t - p_t^o) - (p_t^* - p_t^o) - e_t &= a_{40} + a_{41}t + \beta_{43}r_t + \beta_{45}y_t + \beta_{48}(p_t^* - p_t^o) + \varepsilon_{4,t+1}, && (4.4)\\
h_t - y_t &= a_{50} + a_{51}t + \beta_{53}r_t + \beta_{55}y_t + \varepsilon_{5,t+1}. && (4.5)
\end{aligned}$$

where p_t is the logarithm of domestic prices, p_t^* is the logarithm of foreign prices, p_t^o, the logarithm of oil prices, e_t is the logarithm of nominal effective exchange (defined as the domestic price of a unit of foreign currency, so that an increase represents a depreciation of the home currency), y_t is the logarithm of real per capita domestic output, y_t^* is the logarithm of real per capita foreign output, r_t is the domestic nominal interest rate variable, r_t^* is the foreign nominal interest rate variable, h_t is the logarithm of the real per capita money stock, and the $\varepsilon_{i,t+1}$, $i = 1, 2, .., 5$, are stationary reduced form errors. (see Table 1 for more details).

A complete description of the framework for long-run macromodelling, describing the economic theory that underlies the relationships in (4.1) - (4.5), is provided in Garratt *et al.* (1998b). In brief, we note here that the first relationship relates to a (modified) Purchasing Power Parity (PPP) relationship, based on international goods market arbitrage, but modified to take into account the potential effects of oil prices on the measured relationship given the different baskets of commodities used to measure prices in different countries; equation (4.2) sets out the Interest Rate Parity (IRP) relationship and is based on arbitrage between domestic and foreign bonds; (4.3) relates to an 'output gap' (OG) equation derived from a stochastic version of the Solow growth model in which there is common technological progress in production at home and abroad;[21] the fourth and fifth equations (4.4) and (4.5) relate to

[21] Our use of the term 'output gap relationship' to describe (4.3) should not be confused with the more usual use of the term which relates more specifically to the difference between a country's actual and potential output levels (although clearly the two uses of the term are related).

a trade balance (TB) and a real money balance (RMB) relationship, respectively, both of which are based on the condition that the economy must remain solvent in the long-run . The relationships in (4.4) and (4.5) are obtained by modelling the equilibrium portfolio balance of private sector assets, which are assumed can be held in the form of high-powered money, domestic bonds or foreign bonds, and augmenting the solvency condition with assumptions on the determinants of the demand for money and for foreign assets.

The five long-run relations of the core model, (4.1) - (4.5), can be written compactly as

$$\boldsymbol{\varepsilon}_t = \boldsymbol{\beta}'\mathbf{z}_{t-1} - (\mathbf{a}_0 - \mathbf{a}_1) - \mathbf{a}_1 t, \tag{4.6}$$

where

$$\mathbf{z}_t = (p_t - p_t^o, e_t, r_t, r_t^*, y_t, y_t^*, h_t - y_t, p_t^* - p_t^o)'.$$

$$\mathbf{a}_0 = (a_{10}, a_{20}, a_{30,}a_{40}, a_{50})', \;\; \mathbf{a}_1 = (a_{11}, 0, 0, a_{41}, a_{51}),$$

$$\boldsymbol{\varepsilon}_t = (\varepsilon_{1t}, \varepsilon_{2t}, \varepsilon_{3t}, \varepsilon_{4t}, \varepsilon_{5t})',$$

and

$$\boldsymbol{\beta}' = \begin{pmatrix} 1 & -1 & 0 & 0 & 0 & 0 & 0 & -(1+\beta_{18}) \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 1 & -1 & -\beta_{43} & 0 & -\beta_{45} & 0 & 0 & -(1+\beta_{48}) \\ 0 & 0 & -\beta_{53} & 0 & -\beta_{55} & 0 & 1 & 0 \end{pmatrix}. \tag{4.7}$$

Our modelling strategy involves partitioning $\mathbf{z}_t = (\mathbf{y}_t', \, p_t^* - p_t^o)'$, where $\mathbf{y}_t = (p_t - p_t^o, \, e_t, \, r_t, \, r_t^*, \, y_t, \, y_t^*, \;\; h_t - y_t)'$ is treated as an $I(1)$ vector of endogenous variables, and $p_t^* - p_t^o$ as a weakly exogenous $I(1)$ variable, in the sense that changes in $p_t^* - p_t^o$ have a direct influence on $\mathbf{y}_t$, but $p_t^* - p_t^o$ is not affected by error correction terms which measure the extent of disequilibria in the U.K. economy.[22] We then embody $\boldsymbol{\varepsilon}_t$ in an otherwise unrestricted $VAR(s-1)$ in $\Delta\mathbf{y}_t$:

$$\Delta\mathbf{y}_t = -\boldsymbol{\alpha}\boldsymbol{\varepsilon}_t + \sum_{i=1}^{s-1} \boldsymbol{\Gamma}_i \Delta\mathbf{z}_{t-i} + \boldsymbol{\psi}\Delta(p_t^* - p_t^o) + \mathbf{u}_t, \tag{4.8}$$

where $\mathbf{u}_t$ is an 7×1 vector of serially uncorrelated shocks, $\boldsymbol{\alpha}$ is an 7×5 matrix of error-correction coefficients, $\{\boldsymbol{\Gamma}_i, i = 1, 2, ..., s-1\}$ are 7×8 matrices of short-run coefficients, and $\boldsymbol{\psi}$ is an 7×1 vector representing the impact effects of changes in the relative foreign price variable on $\Delta\mathbf{y}_t$. Using equation (4.6) we have

$$\Delta\mathbf{y}_t = \boldsymbol{\alpha}(\mathbf{a}_0 - \mathbf{a}_1) + \boldsymbol{\alpha}\mathbf{a}_1 t - \boldsymbol{\alpha}\boldsymbol{\xi}_t + \sum_{i=1}^{s-1} \boldsymbol{\Gamma}_i \Delta\mathbf{z}_{t-i} + \boldsymbol{\psi}\Delta(p_t^* - p_t^o) + \mathbf{u}_t, \tag{4.9}$$

where $\boldsymbol{\xi}_t = \boldsymbol{\beta}'\mathbf{z}_{t-1}$ are the error correction terms. By construction, the above specification embodies the economic theory's long-run predictions, in contrast to the more usual approach where the starting point is an unrestricted VAR model, with some vague priors about the nature of the long-run relations.

[22] For details of the econometric formulation see Pesaran, Shin and Richard Smith (1997).

Estimation of the parameters of the core model, (4.9), can be carried out using the long-run structural modelling approach described in Pesaran and Shin (1997) and Pesaran, Shin and Richard Smith (1997). Following this approach, having selected the order of the underlying VAR model (using model selection criteria such as the Akaike Information Criterion (AIC) or the Schwartz Bayesian Criterion (SBC)), we first test for the number of cointegrating relations among the 8 variables in $\mathbf{z}_t$. When performing this task, and in all the subsequent empirical analysis, we work in the context of a VAR model with no restrictions on the intercept terms, $\boldsymbol{\alpha}(\mathbf{a}_0 - \mathbf{a}_1)$, but with the trend coefficients restricted so that $\boldsymbol{\alpha}\mathbf{a}_1 = \boldsymbol{\Pi}\boldsymbol{\gamma}$, where $\boldsymbol{\Pi} = \boldsymbol{\alpha}\boldsymbol{\beta}^{'}$ and $\boldsymbol{\gamma}$ is an 8×1 vector of unknown coefficients. These restrictions ensure that the solution of the model in levels of $\mathbf{z}_t$ will not contain quadratic trends. We then compute Maximum Likelihood (ML) estimates of the model's parameters subject to exact and over-identifying restrictions on the long-run coefficients.[23] Assuming that there is empirical support for the existence of five long-run relationships, as suggested by theory, exact identification in our model requires five restrictions on each of the five cointegrating vectors (each row of $\boldsymbol{\beta}$), or a total of twenty-five restrictions on $\boldsymbol{\beta}$. These represent only a subset of the restrictions suggested by economic theory as characterized in (4.7), however. Estimation of the model subject to all the (exact- and over-identifying) restrictions given in (4.7) enables a test of the validity of the over-identifying restrictions, and hence of the economic theory, to be carried out.

This entire exercise was conducted using U.K. data over the period 1965q1-1995q4, and this is described in detail in Garratt *et al.* (1998a). Here, we provide a brief summary. Having first confirmed that a VAR(2) model is appropriate, the cointegration tests were carried out. The results of these tests are presented in Table 2. These provide relatively good evidence to support the prediction of the theory that there are five cointegrating relationships among the eight variables. The model was then estimated, first subject to twenty-five restrictions which exactly identify the system, and then subject to a further fourteen over-identifying restrictions as suggested by the economic theory and contained in (4.7). The test of the over-identifying restriction produced a statistic of 39.15. The statistic is asymptotically distributed as a chi-squared variate with fourteen degrees of freedom, although the asymptotic result is unreliable in cases like this one, where the number of parameters of the underlying VAR model, and the number of restrictions, is large relative to the sample of data available. The extent of the small sample bias of the chi-squared tests in (small) cointegrating VAR models is illustrated, for example, by Gredenhoff and Jacobson (1998) who suggest the use of bootstrapped critical values. In our application the bootstrapped critical values were 53.97 and 59.28 at the 10 and the 5 per cent significance levels, respectively, so that there is no evidence with which to reject the validity of the theory-restrictions incorporated in the core model. The estimated long-run relationships, and the associated error correction equations are summarized in Table 3.

4.2 Impulse Responses and Forecasting

Having estimated our structural cointegrating VAR model, we are now in a position to use the model in the examination of the economy's short-run dynamic properties. To illustrate how

[23] The computations were carried out using Microfit 4.0. See Pesaran and Pesaran (1997).

we might use the model in this way, in what follows, we illustrate three (complementary) ways in which to characterise the model's properties; further details of the methods are provided in Garratt *et al.* (1998a). The first two make use of 'Persistence Profiles' and 'Generalised Impulse Responses' to examine the effect of system wide shocks in causing deviations from the long-run equilibrium relations and the time profile of the model variables when subject to shocks to the core model equations, respectively. The third approach to characterising the model's properties involves out of sample forecasting, describing some probability forecasts, with which the uncertainties surrounding forecasts from a macroeconomic model can be conveyed in a straight forward manner.

In order to compute these measures we first need to supplement the core model with equations for the exogenous variables. We therefore assume that both oil price changes and foreign price relative to the oil price changes are strictly exogenous. After some experimentations we arrived at the following specification for Δp_t^o estimated over the period 1965q1-1995q4:

$$\begin{aligned}
\Delta p_t^o &= \underset{(.0150)}{.01678} + \hat{u}_t^o, \\
\hat{\sigma}_{uo} &= .1676,\ \chi^2_{SC}[4] = 1.58,\ \chi^2_N[2] = 6361.9,
\end{aligned}$$

To model $\Delta(p_t^* - p_t^o)$ over the same period, we estimated autoregressive distributive lag models, ARDL(s_1, s_2), in $\Delta(p_t^* - p_t^o)$ and Δp_t^o for all orders $s_1 \leqq 4$ and $s_2 \leqq 4$, and then selected s_1 and s_2 using the Akaike Information Criteria. The result was the following ARDL$(2,2)$ specification:[24]

$$\begin{aligned}
\Delta(p_t^* - p_t^o) &= \underset{(.0007)}{.0022} + \underset{(.0898)}{5693}\ \Delta(p_{t-1}^* - p_{t-1}^o) + \underset{(.0853)}{.2083}\ \Delta(p_{t-2}^* - p_{t-2}^o) - \underset{(.0023)}{.9607}\ \Delta p_t^o \\
&\quad + \underset{(.0863)}{5585}\ \Delta p_{t-1}^o + \underset{(.0827)}{2039}\ \Delta p_{t-2}^o + \hat{u}_t^*,
\end{aligned}$$

$$\bar{R}^2_{\Delta p^*} = .848,\ \hat{\sigma}_{u*} = .0042,\ \chi^2_{SC}[4] = 3.80,\ \chi^2_{FF}[1] = .31,\ \chi^2_N[2] = 387.7,\ \chi^2_H[1] = .013.$$

4.2.1 Persistence Profiles

Persistence profiles (PP) provide information on the speed with which deviations from the long-run relations in the model, due to system-wide shocks, are eliminated. The profiles are constructed so that they take the value of unity on the impact of the shock and tend to zero as the time horizon tends to infinity, assuming that the long-run relationship in question is in fact cointegrating.

Figure 1 plots the PP of two of the five long-run relations of the model; namely the (modified) PPP and IRP relations. In the case of the modified PPP, the profile shows a steady decline towards its equilibrium value, with approximately 80 per cent of the adjustment taking place within 9 quarters, and the full adjustment taking about five years to complete.[25]

[24] The $\overline{R}^2$ for the $\Delta(p_t^* - p_t^o)$ equation is computed with respect to Δp_t^*. The diagnostics are chi-squared statistics for serial correlation (SC), functional form (FF), normality (N) and heteroscedasticity (H). See Pesaran and Pesaran (1997, pp. 349-352).

[25] It is also possible to compute standard error bounds around the point estimates of the persistence profiles displayed in Figures 1, but we found that their use does not materially alter our main conclusions. See Pesaran and Shin (1996) for further discussion.

The fact that the persistence profile of the modified PPP relation tends to zero is in line with our earlier conclusion (based on formal statistical tests) that the modified PPP relationship is in fact cointegrating. The PP profile of the IRP relationship shows a more rapid rate of adjustment towards its long-run value, with approximately 80 per cent of the adjustment having been completed within 6 quarters and full adjustment occurring within three to four years. These results are consistent with those found in the literature. Notice, however, that the speed of convergence of the modified PPP towards its equilibrium is much faster than the ones reported in the literature for the PPP (unmodified). The existing results put half life of deviations from PPP at about four years for the major industrialised countries (see, for example, Johansen and Juselius,1992, Pesaran and Shin, 1996, or Rogoff, 1996), while for the modified PPP this figure is much shorter.

4.2.2 Generalised Impulse Response: Shocking the Foreign Output Equation

The Generalised Impulse Response (GIR) functions describe the time profile of the effect of a unit shock to a *particular equation* on all the model's endogenous variables. The dynamics which result from the shock will embody the contemporaneous interactions of all the endogenous variables of the system, as captured by the elements of the estimated covariance matrix of the shocks to the endogenous variables, $\mathbf{u}_t$. There are many issues that could be analysed through the GIR analysis and here we focus on the effects of shocks to the foreign output equation. We assume that the shock (which can also be viewed as an intercept shift) is sufficiently small so that it does not materially alter the parameters of the underlying VAR model.

In Figures 2-4, we report the GIR's for a unit shock to the foreign output equation, where the size of the shock is scaled so as to ensure that foreign output rises by one standard error on impact; this corresponds to a 1.9% increase in foreign output per annum. Note that because of the strict exogeneity of oil and foreign prices changes, the particular specification of these two variables does not effect the GIRs.

Given the strong positive correlation that exists between foreign and domestic output innovations, the effect of the foreign output shock is to cause domestic output to increase by approximately 1.37% (see Figure 2).[26] These effects continue to persist over the subsequent quarters. In the long-run, the effect of a unit shock to the foreign output equation is to increase both domestic and foreign output by 0.8% above their base-line values, as predicted by equation (4.3). However, it is important to note that the gap between domestic and foreign output growths persists even after 20 quarters, with the foreign output growth exceeding domestic output growth often by as much as 0.75% per annum.

The GIRs for the foreign output shock on the domestic price level, the nominal and the real exchange rates are displayed in Figure 3. The shock initially reduces domestic prices by 0.34%, appreciates the nominal exchange rate on impact by 0.4%, and therefore leaves the real exchange rate almost unchanged.

The effects of the shock on domestic inflation, domestic interest rate and foreign interest rates are displayed in Figure 4. The initial response to the shock is to increase domestic and foreign interest rates by 18 and 4 basis points, respectively. Initially, the foreign interest rate

[26] All percentage changes quoted in this section are computed at annual rates.

rises above the domestic interest rate, but eventually this gap disappears, as predicted by the long-run interest parity relation embodied in the core model.

The initial effect of the foreign output shock on domestic inflation is to decrease the rate of inflation by 0.34%, followed by a further fall over the next quarter. The reduction in inflation is reversed from this point onwards, with the inflation rate returning to its base-line value after about 12 quarters. In the long-run, the effect of the foreign output shock on the domestic inflation rate is zero, so that the effects are purely temporary.

4.2.3 Probability Forecasts

Recently there have been a number of welcome developments in macroeconomic forecasting the aim of which is to convey to the public the potentially large degree of uncertainty that is associated with central or point forecasts. For example, in the area of policy making the Bank of England now produces a range of outcomes around their central forecasts for future inflation and output growth in its quarterly *Inflation Reports* (see Britton, Fisher and Whitley, 1998). In academia, Fair (1993) was one of the first to compute probability forecasts, using a macroeconometric model of the U.S. economy. The NIESR, using their large-scale SEM, now publish probability statements along side their central forecasts (their methods are described in Blake, 1996 and Poulizac *et al.,* 1996), and in the financial sector, J.P. Morgan presents 'Event Risk Indicators' in its analysis of foreign exchange markets.

In this section, we briefly report the probability forecasting exercise performed using our core U.K. model.[27] A probability forecast (PF) is a statement of the likelihood of a specified event taking place and can be estimated given a model specification and its underlying error assumptions. The event can be defined with respect to the values of a single variable or set of variables, measured at a particular point in time, over a sequence of time periods, or over particular time intervals in the future. Here we provide probability estimates of two separate events; namely, the probability of 4-quarter moving average inflation falling below 2.5% per annum (the current inflation target in the U.K.) and the probability of 4-quarter moving average output growth falling below 0% per annum over a number of forecast horizons.[28]

In this illustrative exercise, we use an updated version of the model presented in Section 4.1, where the estimation period is extended to cover 1965q1-1998q1.[29] The forecasts are then computed over the period 1998q2 - 2004q1, conditional on the oil price index being at their 1998q1 level, and using an updated version of the relative foreign price equation given above to forecast the foreign price variable. In this application, we assume the form of the model is given, but allow for two sources of forecast uncertainties: future uncertainties due to unknown values of the future shocks and the uncertainties surrounding the model's parameter values. In order to take account of the parameter uncertainty on forecasts we undertake a bootstrap exercise which makes use of a non-parametric resampling technique. Accordingly, we estimate the short-run parameters of the model for each bootstrap sam-

[27]The probability forecasts reported here were made in early August 1998 when a complete set of quarterly observations on output growth and inflation for the first quarter of 1998 became available.

[28]The event of 4-quarter moving average output growth falling below 0% per annum, is intended to represent a 'recession', although other definitions, such as quarterly output growth falling below 0% in two successive quarters, have also been used.

[29]The details of the analysis of the extended data set are reported in Garratt *et al.* (1998c).

ple. Then for each of these bootstraps, we repeatedly simulate the future values of $\mathbf{z}_t$, for t =1998q2, 1998q3,...,2004q1, by resampling from the past residuals of the estimated model. The probabilities plotted in Figures 5 and 6 are the averages computed using all the bootstrap samples, and their associated 90 per cent confidence intervals. The computational details can be found in Garratt *et al.* (1998c).[30]

Inflation Figure 5 provides the estimated probabilities of the 4-quarter moving average of producer price inflation, $\pi_{t+h} = (p_{T+h} - p_{T+h-4})/4$, falling below 2.5% over the horizon t =1998q2, 1998q3,..., 2004q1. This figure shows the empirical mean of the bootstrapped probability forecasts and the associated 90% confidence intervals. The results suggest the probability of the producer price inflation falling below the 2.5% threshold value is very high during the second and the third quarters of 1998, but it starts to fall thereafter. The initial high probability of the producer price inflation hitting its target largely reflects the recent history. However, the probability of π_{t+h} falling below 2.5% decreases as the forecast horizon is extended, reaching around 0.56 at a end of the year 2000. In the long-run, the probability that inflation is less than 2.5% falls to 0.29. The uncertainty around this estimate is relatively large, however.[31] Only at short forecast horizons are these 90% confidence bands reasonably tight.

Output Growth Figure 6 shows the estimates of the probability that 4-quarter moving average aggregate output growth, $g_{t+h} = (y^a_{t+h} - y^a_{t+h-4})/4$, where y^a_t is aggregate real output rather than per capita real output, falls below 0% for the forecast horizons t =1998q2, 1998q3,...,2004q1. Here, the probabilities are affected by the fact that, while output growth has been relatively high during the recent past, the model predicts a low level of growth over the near future. Hence, the estimate of g_{t+h} falling below zero in 1998q2 is 0.04, but this rises to a peak of 0.62 over the first year of the forecast horizon. From this point on the probability of output growth being less than 0% remains high, and then starts to decline from around 0.55 in the second year of the forecast to a long-run value of 0.15. The uncertainty associated with these probabilities again is relatively large, particularly over the short to medium term forecast horizons, but is reduced at the longer forecast horizon as output growth converges to its steady state value.

5 Concluding Comments

In this paper we discuss the structural cointegrating VAR approach to macroeconometric modelling and compare it to a number of alternative modelling approaches. We then il-

[30]In Garratt *et al.* (1998c), we consider a range of issues relating to forecasting the probability of an event. We also consider the various forms of uncertainty surrounding forecasts, including 'future uncertainty', 'parameter uncertainty' and 'model uncertainty', and discuss alternative ways of taking them into account.

[31]It is worth noting that we could not reject the hypothesis that the difference between the producer and retail price inflation is stationary with a zero mean. Therefore, it is likely that the probability statements for producer price inflation will also apply to retail price inflation in the long-run. However, persistent short-run deviations exist between the two inflation rates, and probability statements relating to the producer price inflation need not carry over to the retail price inflation in the short-run.

lustrate the structural cointegrating VAR approach in the context of a model of the U.K. economy based on data covering the period 1965q1-1995q4. In this exercise, the long-run relationships, derived from macroeconomic theory, are based on production, trade, arbitrage, solvency and portfolio balance conditions. This application, described in more detail in Garratt *et al.* (1998b), constitutes the first attempt to make use of the structural cointegrating VAR approach in the context of a relatively comprehensive core macro model of a small open economy. This paper also illustrates how a model of this type can be used for impulse response analysis and probability forecasting.

In practice, it is fully recognized that a model, or indeed a modelling approach, can only be judged in terms of its relevance to the question at hand. This has been a recurring theme in the literature on model comparison in economics (see, for example, Pesaran and Smith, 1985,1995). A particular model or modelling approach might be more or less relevant for a given purpose, but it seems unlikely that one single model could be found to suit all purposes. The cointegrating VAR modelling approach advanced in this paper should be viewed as one, among many possible approaches that could be fruitfully employed. But it is hoped that the core model of U.K. economy which is described in the paper will motivate others to explore this approach to macroeconomic modelling (examining alternative economic frameworks, or through the development of satellite models for use with the core model, for example). In this way, its advantages and disadvantages will be more fully understood and its contribution to the already-rich field of macroeconometric modelling will be more clearly defined.

Table 1: **List of Variables and their Descriptions in the Core Model**

y_t : natural logarithm of the UK real per capita GDP at market prices $(1990 = 100)$.

p_t : natural logarithm of the UK Producer Price Index $(1990 = 100)$.

r_t : is computed as $r_t = 0.25\ln(1 + R_t/100)$, where R_t is the 90 day Treasury Bill average discount rate per annum.

h_t : natural logarithm of UK real per capita M0 money stock $(1990 = 100)$.

e_t : natural logarithm of the nominal Sterling effective exchange rate $(1990 = 100)$.

y_t^* : natural logarithm of the foreign (OECD) real per capita GDP at market prices $(1990 = 100)$.

p_t^* : natural logarithm of the foreign price index $(1990 = 100)$. Where the index is an import weighted average of 42 countries prices indices (where the countries are the OECD, oil producing and a number of other countries with relatively large values of imports and exports with the UK).

r_t^* : is computed as $r_t^* = 0.25\ln(1 + R_t^*/100)$, where R_t^* is the weighted average of 90 day interest rates per annum in the United States, Germany, Japan and France.

p_t^o : natural logarithm of oil prices, measured as the Average Price of Crude Oil.

t : time trend, taking the values $1, 2, 3, \ldots$, in $1965q1, 1965q2, 1965q3, \ldots$, respectively.

Notes: For the data sources and a detailed description of the construction of foreign prices and interest rates see the Data Appendix in Garratt *et al* (1998a).

Table 2: **Cointegration Rank Statistics for the Core UK Model - 1965(1)-95(4)**

$(p_t - p_t^o, e_t, r_t, r_t^*, y_t, y_t^*, h_t - y_t, p_t^* - p_t^o)$

		Trace			Max		
H_0	H_1	Statistic	95% cv	90% cv	Statistic	95% cv	90% cv
$r = 0$	$r = 1$	234.44	163.01	157.02	61.09	52.62	49.70
$r \leq 1$	$r = 2$	173.35	128.79	123.33	45.41	46.97	44.01
$r \leq 2$	$r = 3$	127.93	97.83	93.13	41.85	40.89	37.92
$r \leq 3$	$r = 4$	86.08	72.10	68.04	38.49	34.70	32.12
$r \leq 4$	$r = 5$	47.59	49.36	46.00	26.24	28.72	26.10
$r \leq 5$	$r = 6$	21.35	30.77	27.96	13.28	22.16	19.79
$r \leq 6$	$r = 7$	8.08	15.44	13.31	8.08	15.44	13.31

Notes: The underlying VAR model is of order 2 and contains unrestricted intercepts and restricted trend coefficients, with $p_t^* - p_t^o$ treated as exogenous $I(1)$ variable. The statistics are computed using 124 observations for the period 1965q1-1995q4. "Trace" and "Max" represent Johansen's log-likelihood-based trace and maximum eigenvalue statistics, respectively, and 'cv' stands for critical value of the tests, which are obtained from Pesaran, Shin and Smith (1997).

Table 3: **Error Correction Specification for the Core UK Model - 1965(1)-95(4)**

Equation	$\Delta(p_t\text{-}p_t^o)$	Δe_t	Δr_t	Δr_t^*	Δy_t	Δy_t^*	$\Delta(h_t\text{-}y_t)$
$\hat{\varepsilon}_{1,t}$	-.021 (.016)	- .002 (.070)	-.024† (.005)	-.008† (.003)	.011 (.021)	.004 (0.010)	-.035 (.034)
$\hat{\varepsilon}_{2,t}$	-.518† (.223)	.023 (.996)	.021 (.075)	.067* (.035)	.850† (.300)	.560† (.148)	.068 (.489)
$\hat{\varepsilon}_{3,t}$	.125† (.030)	-.195 (.135)	-.021† (.010)	-.005 (.005)	-.128† (.041)	-.004 (.020)	.044 (.066)
$\hat{\varepsilon}_{4,t}$	-.043† (.021)	.101 (.095)	.035† (.007)	.013† (.003)	-.028 (.029)	-.011 (.014)	.028 (.047)
$\hat{\varepsilon}_{5,t}$	.005 (.016)	.011 (.069)	.009* (.005)	.006† (.003)	-.081† (.021)	-.046† (.010)	- .003 (.034)
$\Delta(p_{t-1}\text{-}p_{t-1}^o)$	.337† (.092)	.511 (.412)	-.007 (.031)	-.015 (.014)	-.007 (.124)	.022 (.061)	-.400* (.202)
Δe_{t-1}	-.015 (.027)	.262† (.119)	.011 (.009)	.005 (.004)	- .002 (.036)	-.007 (.018)	.031 (.058)
Δr_{t-1}	.116 (.295)	-1.09 (1.32)	.141 (.100)	-.084* (.048)	.581 (.398)	.316 (.196)	-.630 (.649)
Δr_{t-1}^*	-.492 (.605)	2.12 (2.70)	.299 (.204)	.275† (.097)	.838 (.814)	.668* (.400)	-1.36 (1.33)
Δy_{t-1}	.087 (.089)	- .091 (.398)	-.031 (.030)	-.005 (.014)	-.085 (.120)	- .041 (.059)	-.069 (.195)
Δy_{t-1}^*	-.229 (.152)	-.167 (.679)	-.037 (.051)	.077† (.024)	.030 (.204)	.135 (.101)	.344 (.334)
$\Delta(h_{t-1}\text{-}y_{t-1})$	.115† (.051)	.219 (.228)	.012 (.017)	.008 (.008)	.077 (.069)	-.044 (.034)	-.142 (.112)
$\Delta(p_t^*\text{-}p_t^o)$	1.03† (.004)	.021 (.019)	- .002 (.001)	- .001* (.0007)	.011* (.006)	.003 (.003)	-.023† (.010)
$\Delta(p_{t-1}^*\text{-}p_{t-1}^o)$	.345† (.094)	.517 (.423)	.009 (.032)	.014 (.015)	- .003 (.128)	- .026 (.063)	.429† (.208)
$\overline{R}^2$	.764^a	.024	.241	.373	.208	.368	.110
$\hat{\sigma}$	.007	.032	.002	.001	.010	.005	.016
$\chi^2_{SC}[4]$	2.91	3.23	5.23	10.6†	5.66	2.25	3.70
$\chi^2_{FF}[1]$	0.10	0.54	0.73	5.31†	0.02	0.55	0.12
$\chi^2_{N}[2]$	13.4†	24.7†	14.8†	15.4†	109.1†	10.1†	8.06†
$\chi^2_{H}[1]$	0.49	0.50	4.81†	10.9†	0.33	2.63	0.18

Notes: The five error correction terms are given by

$$\hat{\varepsilon}_{1,t+1} = p_t - p_t^* - e_t - \underset{(0.0311)}{0.1156}\,(p_t^o - p_t^*) - 4.9291,$$

$$\hat{\varepsilon}_{2,t+1} = r_t - r_t^* - 0.0054, \quad \hat{\varepsilon}_{3,t+1} = y_t - y_t^* - 4.6024,$$

$$\hat{\varepsilon}_{4,t+1} = p_t - p_t^* - e_t - \underset{(5.0640)}{16.1737}\,r_t + \underset{(0.4353)}{1.9047}\,y_t - \underset{(0.0021)}{0.0098}\,t - 12.3178,$$

$$\hat{\varepsilon}_{5,t+1} = h_t - y_t + \underset{(4.9506)}{20.1465}\,r_t + \underset{(0.0005)}{0.0102}\,t + 0.5154.$$

Standard errors are given in parenthesis. "$*$" indicates significance at the 10% level, and "$\dagger$" indicates significance at the 5% level. The diagnostics are chi-squared statistics for serial correlation (SC), functional form (FF), normality (N) and heteroscedasticity (H). "a" The $\overline{R}^2$ for the $\Delta(p_t - p_t^o)$ equations refers to the Δp_t equation.

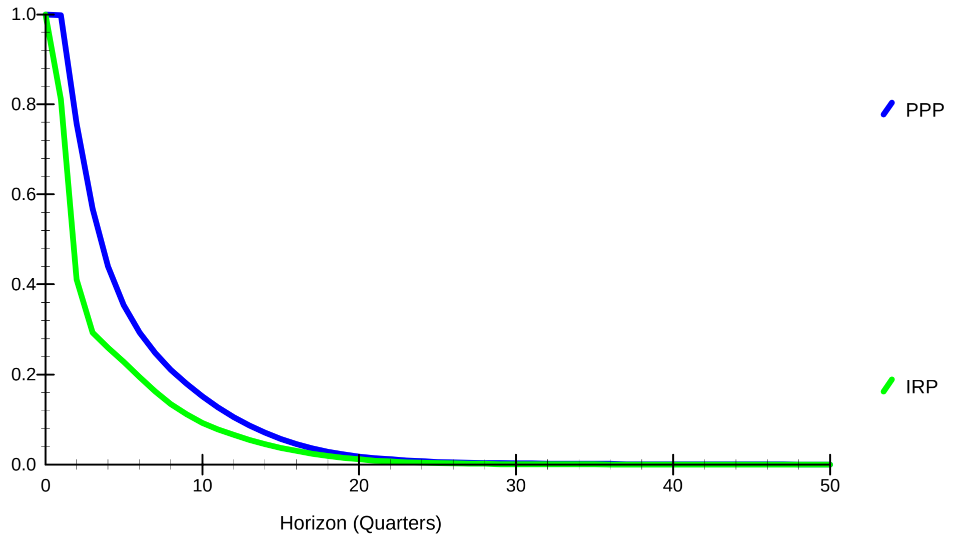

Figure 1. Persistence Profiles of the Modified Purchasing Power Parity (PPP, black) and Interest Parity Relations (IRP, dark grey) in the Core Model

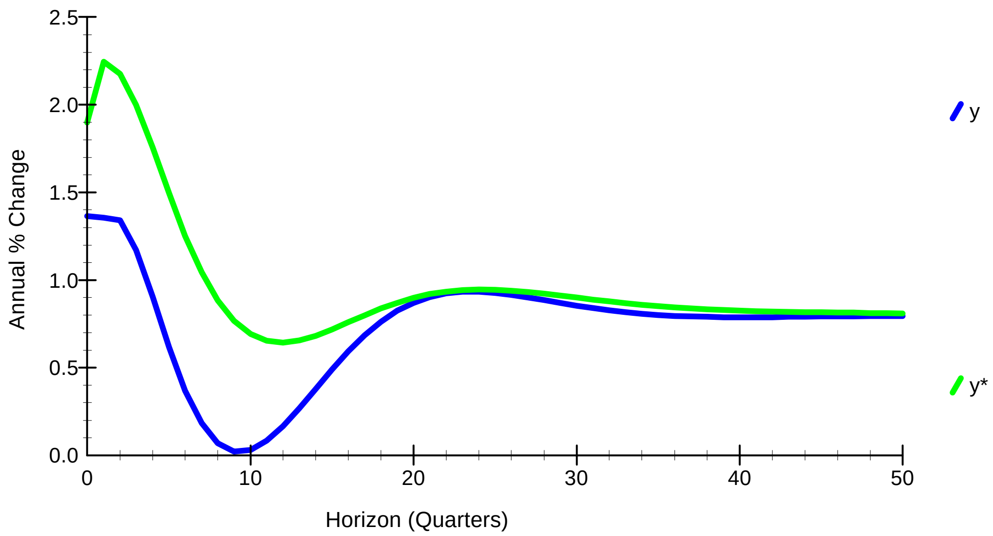

Figure 2. Generalised Impulse Responses of Domestic Output (black) and Foreign Output (dark grey) to a One S.E. Shock to the y_t^* Equation in the Core Model

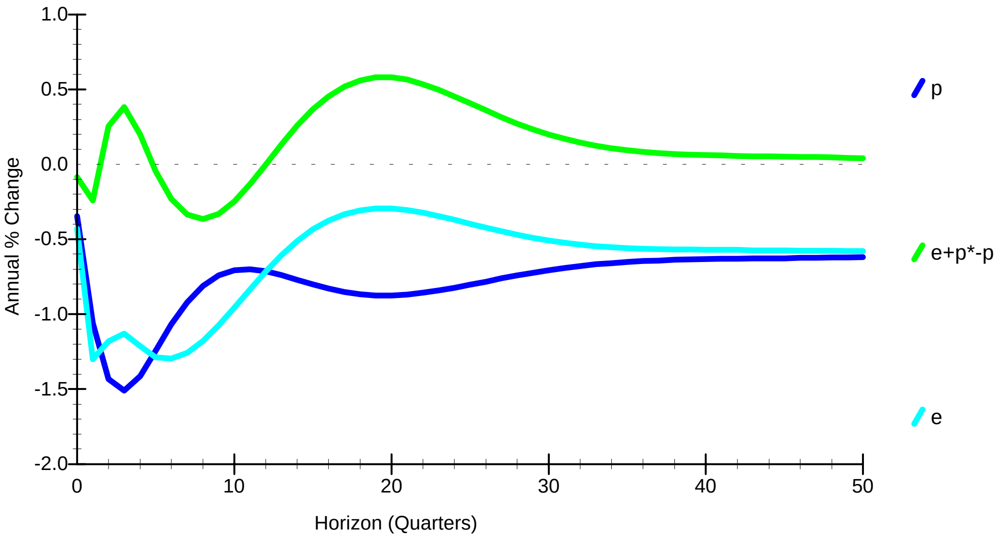

Figure 3. Generalised Impulse Responses of Domestic Prices (black), Real (dark grey) and Nominal (light grey) Exchange Rates to a One S. E. Shock to the y_t^* Equation in the Core Model

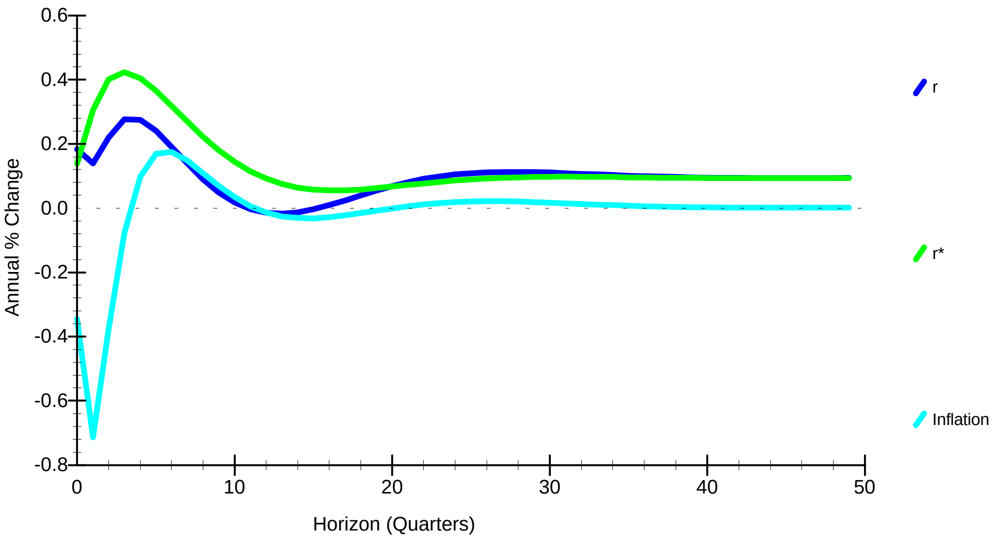

Figure 4. Generalised Impulse Responses of Domestic (black) and Foreign (dark grey) Nominal Interest Rates and Inflation (light grey) to a One S.E. Shock to the y_t^* Equation in the Core Model

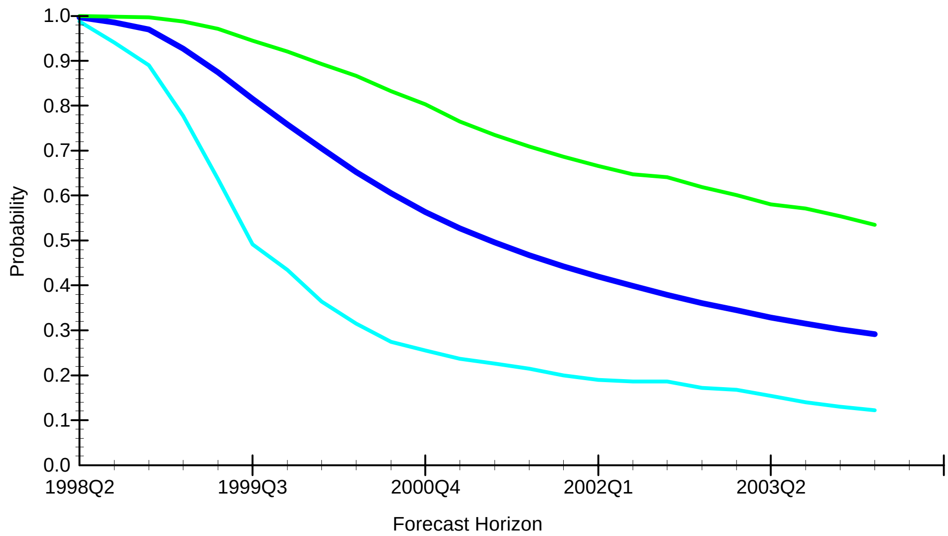

Figure 5. Mean Probability Estimate (black) and 90% Confidence Intervals of 4-quarter Average Inflation (based on producer prices) Falling Below 2.5%

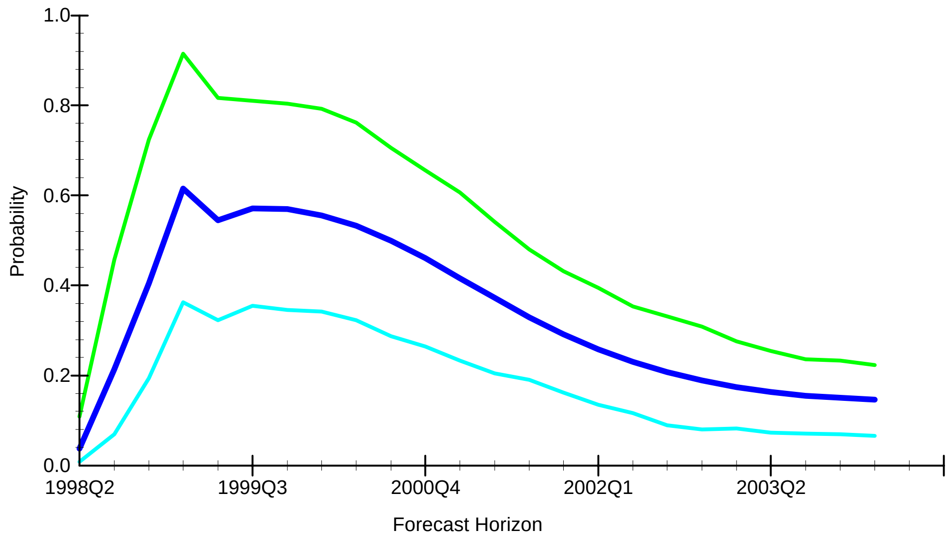

Figure 6. Mean Probability Estimate (black) and 90% Confidence Intervals of 4-quarter Average Output Growth Falling Below 0%

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