Do SVAR-based core inflation measures measure core inflation?

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Abstract

This paper assesses the performance of core inflation measures based on the structural VAR approach. Since core or monetary inflation is not directly observable, we develop a monetary general equilibrium model that fits real aggregated European data and use this model to generate time series for headline as well as core inflation. For five different schemes which attempt to identify core inflation within a SVAR framework it is investigated whether the estimated core inflation series recover the true series sufficiently precise in order to be useful for monetary policy.

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1 Introduction

Since the oil crises of the 70's the term core inflation has played an important role in the monetary policy debate. In particular at central banks various estimators have been developed to measure what is sometimes called core, permanent, underlying or monetary inflation. Although there is no consensus in the literature on what core inflation actually is, all approaches intend to provide an inflation measure which is more informative for monetary policy than the change of the official consumer price index.

There are several reasons why the CPI is not an ideal measure of inflation for monetary policy purposes. Firstly, the CPI is a noisy signal of the inflationary pressures in an economy. For example, seasonal influences, changes of the indirect tax rate, or purely relative price changes affect the CPI, but do not call for monetary policy action. Secondly, the CPI is a cost of living index and measures how much a consumer would have to spend on consumer commodities in e.g. the current period compared to a base period in order to attain the same standard of living. The direct concern of monetary policy, however, is not to stabilise the cost of living, but to create and maintain the conditions for the price mechanism to fulfil its coordinating role. Hence, it would be desirable for monetary policy to have a measure of inflation, which distinguishes between price movements which are essential to the coordinating role of the price mechanism in a market economy and those which are disruptive [1]. Thirdly, monetary policy operates on inflation with a long and variable time lag. Therefore, from the perspective of policy makers a measure of inflation would be useful that is a leading indicator of future CPI inflation [2]. Finally, central banks cannot control inflation as measured by the CPI. At least in the short run the CPI reacts to nearly every shock impinging on the economy and not only to variations of the money stock, for which the central bank is responsible. Since credibility is crucial to central bank performance, it would be desirable to have an operational inflation concept which only reflects price level movements for which the monetary authority is accountable.

Motivated by one or more of these arguments, a host of methods has been developed to estimate core inflation. Most of these methods, however, lack a clear definition of what they are supposed to measure, i.e. which specific quantity in the population they estimate. The methods suggested are either based on cross-sectional information, i.e. the distribution of individual price changes with respect to some reference period, on univariate or multivariate time series or on pooled cross-sectional and time series data [3]. Cross-sectional methods attempt to refine the CPI, aiming to eliminate its transitory movements and to increase the signal-to-noise ratio. Three different types of inflation measures rely on purely cross-sectional information. The most well-known type encompasses price indices that simply exclude allegedly volatile components, such as food or energy prices. A more sophisticated class of measures contains the various trimmed mean estimators. These measures do not a priori exclude specific commodities from the price index once and for all, but remove those commodities of which the observed price change relative to the previous period is an 'outlier' [4]. The weighted median belongs to this class of inflation measures. Finally, there are price indices which use the full cross-sectional information but aggregate the price changes with weights which are inversely related to their volatility. Clearly, since the weights of these price indices are not derived from budget shares, the scope of these inflation measures is not restricted to consumer prices [5].

Univariate time series methods remove high-frequency noise from the CPI-inflation series by smoothing or filtering with, for example, moving averages or Kalman filters. The smoothed series are estimates of the core inflation process. Methods combining cross-sectional and time series information apply the dynamic factor model to price data. The common component in all price changes is interpreted as core inflation [6]. For none of the methods mentioned so far, it is clear

[1] See Howitt (1997).

[2] Cf. Blinder (1997).

[3] This classification is due to Wynne (1999).

[4] Bryan and Cecchetti (1994) started investigating these estimators for the measurement of inflation. See also Bryan, Cecchetti, and Wiggins (1999).

[5] Dow (1994) and Diewert (1995) developed these indices.

[6] Bryan and Cecchetti (1993) and Dow (1994) were the first to use the dynamic factor model in the context of

what exactly they are supposed to measure nor whether they succeed in doing so with sufficient accuracy. At its best, the methods are evaluated more or less informally, by checking whether estimated core inflation series have some predictive power with regard to future CPI-inflation, or whether they approximate some centred moving average of e.g. monthly CPI changes [7].

Besides these instances of measurement without theory, there is one approach to the estimation of core inflation, in which economic theory plays at least some role. These multivariate time series methods use structural vector autoregressive models (SVAR) in an attempt to decompose observed inflation into a core and non-core part. The identification of these two empirically unobservable parts relies on restrictions derived from economic theory. The restrictions generally concern the long-run effects of either supply shocks on observable inflation or of 'core inflation' shocks on the output level. The latter restrictions are motivated by referring to long-run neutrality or super-neutrality of money. Thus, instead of defining core inflation explicitly, these methods characterise core inflation by its long-run properties. For example, Quah and Vahey (1995) characterise core inflation as that component of observed inflation which is output neutral in the long-run.

This approach to the measurement of core inflation has also been criticised. Wynne (1999) pointed out that a core inflation measure relying on an estimated model implies that each time the estimates are updated with new observations, the whole inflation history is revised. Moreover, SVAR-based core inflation measures are not suitable for communication with the public. Faust and Leeper (1997) draw the attention on a weakness of any method, which rely on long-run identifying restrictions. They argue that finite samples contain insufficient information on long-run effects. Therefore, if one imposes long-run restrictions for identification purposes, one may end up with very imprecise estimates. For the SVAR approach to inflation measurement this means that core inflation estimates might deviate considerably from the true core inflation series. Finally, Cooley and Dwyer (1998) have criticised the SVAR approach in general, because the identification in these models relies on several difficult to test or even untestable assumptions. For example, the identification of core inflation requires that inflation is either integrated of order one or stationary. It is well-known that tests between these alternatives lack power. Inferences based on these models, however, are not robust with respect to violations of these assumptions. Consequently, as will be analysed in this paper, the estimated core inflation series may have little in common with the true core inflation process.

The above criticism of SVARs has been formulated qualitatively but the sensitivity or robustness of SVAR based core inflation measures have never been assessed quantitatively. Moreover, at least five different SVAR models have been suggested in the literature for the estimation of core inflation and it is unclear whether one of these models delivers more reliable core inflation estimates than any of the other models. In this paper we want to assess the performance of these different core inflation measures based on the structural VAR approach. Since core or monetary inflation is not directly observable, we develop a monetary general equilibrium model in which we can define a concept of core inflation which corresponds to that in the SVAR literature. Furthermore, using the model to simulate times series we can actually observe the realization of the true core inflation process which the SVAR-based measures attempt to estimate. With this information we can investigate whether the different SVAR models suggested in the literature are capable of recovering the true core inflation series and if not, whether the measurement errors are acceptable. Obviously, analysing the performance of core inflation estimators by a simulation study is only informative if the theoretical model by which the time series are generated, is empirically relevant. We will argue that our general equilibrium model provides a reasonable interpretation of empirical data. Furthermore, we will show that the standard battery of tests applied to the time series generated by our model does not reject the testable implications of the different SVAR models. In this sense, our simulation study yields results which are relevant for actual monetary policy.

The paper is organised as follows. In the next section, Section 2, we present the monetary general equilibrium model that will be used to generate time series for headline and core inflation.

inflation measurement.

[7] See e.g. Le Bihan and Sedilot (2000) and Marques, Neves, and Sarmento (2000) for formal tests and criteria for core inflation measures.

Since this model serves as a laboratory to test the different identification methods, we will not only provide its description and details on its calibration, but we will discuss its empirical plausibility and the theoretical properties of the simulated time series as well. Furthermore, core inflation is defined within the theoretical model such that it matches the definition used in the empirical SVAR literature. Section 3 reviews the various approaches to identify core inflation that have been suggested in the literature. Section 4 contains the discussion of the method by which the core inflation measures are evaluated and reports our simulation results. The conclusions are drawn in the final section.

2 A monetary general equilibrium model with endogenous growth and nominal rigidities

The general equilibrium model outlined in this section is an endogenous growth model of a closed economy with a detailed description of the monetary transmission mechanism. The model extends the recently developed New Keynesian models of e.g. Rotemberg and Woodford (1999), McCallum and Nelson (1999) and King and Wolman (1999) by incorporating money, accumulation of capital and an elastic supply of labour. In particular, capital accumulation and endogenous economic growth are important features of the model. Endogenous growth is a property of the model which makes it suitable to analyse the core inflation measures developed in the SVAR-literature. All these measurement methods assume that output is integrated of order one. If growth were modelled exogenously and deterministically, however, output would be a trend- and not difference stationary process [8]. The fact that the model describes a closed economy is another important feature of the model, since none of the SVAR based core inflation measures considered here takes foreign trade or exchange rates explicitly into account. Therefore, in a closed economy the SVAR based core inflation measures should perform at least as good as in an open economy. Moreover, the model will be calibrated to the EMU for which the closed economy assumption is a reasonable approximation.

The endogenous growth aspect of the model is based on Romer (1986). According to Romer's model, an economy grows because its *aggregate* capital stock exerts a positive effect on the production possibilities of each producer. The capital externality leads to increasing returns to scale with respect to variations of the aggregate factor inputs, although each producer experiences only a proportional output change to variations of his individual factor inputs. Moreover, since movements of the aggregate capital stock affect the production possibilities of all individual producers, transitory shocks have permanent effects on aggregate production, introducing a unit root in the output series.

The description of the transmission mechanism combines features of a standard monetary equilibrium model and the recently developed New Keynesian models. First, we use the cash in advance framework to model the microeconomic motive for households and firms to hold money. Agents hold money in this economy because certain transactions can only be settled in cash. Specifically, it is assumed that households have to pay expenditure on consumer goods and producers a fraction of their wage bill with currency.

Second, we draw on the limited participation framework developed by Fuerst (1992) and Christiano and Eichenbaum (1992) to model the transmission mechanism. The limited participation approach entails three assumptions. The first is that households split their accumulated cash balances at the end of a period into cash needed for next period's transactions and deposits at a financial intermediary. Households need cash in order to buy consumer goods, but they want to hold as little as possible because currency, contrary to deposits, does not earn interest. Households cannot revise their portfolio decision during the period. The second assumption is that firms demand credit from financial intermediaries in order to finance part of their wage bill. The final assumption is that new money is injected into the economy by the central bank through financial intermediaries. Because households have no access to the financial intermediary during the period, newly created funds are available only to potential borrowers, the firms. This set-up can explain why an unexpected monetary expansion lowers the nominal interest rate initially, although it increases expected inflation: only a decline of the interest rate leads firms to absorb the excess liquidity. The limited participation framework alone, however, cannot explain the persistent real effects of money supply shocks which are documented in the empirical literature using e.g. SVAR models [9].

We address the persistence problem by assuming nominal rigidities to which the new Keynesian macroeconomics provide the microeconomic foundations. Nominal rigidities in the model extend

[8] In another project we investigate the performance of core inflation measures when growth is modelled as an exogenous but stochastic process.

[9] See e.g. Christiano, Eichenbaum, and Evans (1999) and Bernanke and Mihov (1998).

to prices and nominal wage rates. Prices are sticky because firms set their prices for several periods in a staggered way. If a nominal or real shock hits the economy, only those firms whose contracts are due to be renewed can adjust their prices, whereas the prices of all other firms remain unchanged [10]. Rigidity of nominal wage rates is not caused by staggered labour contracts but by costly renegotiations of labour contracts. If the costs of negotiating for higher wages increase with the rise of the wage rate, there is an incentive to avoid large and sudden changes of the wage rate. Even for small renegotiation costs the wage rate becomes 'sticky'.

2.1 Description of the model

The model economy is populated by a continuum of households, a representative final good producing firm, a continuum of intermediate good producers, a representative employment agency, a financial intermediary, the central bank and the government. These agents interact on seven markets, a market for differentiated intermediate goods, a market for an aggregated final good used for consumption and investment, a labour market where households offer differentiated labour types and employment agencies hire workers, a labour market on which the employment agency supplies and the intermediate good producers buy labour services, a credit and a money market and a market for capital goods.

Four different types of shocks impinge on the economy, a technological shock, which affects the total factor productivity, a money supply shock, a money demand shock and a government expenditure shock. All shocks are assumed to be stochastically independent from each other and to have stationary AR(1) representations.

It is essential for the microeconomic foundation of nominal rigidities that not all markets are perfectly competitive. In particular, we assume that intermediate goods as well as different types of labour substitute imperfectly for one another. The suppliers of these differentiated commodities have market power and set the price for their product. Monopolistic competition on the intermediate goods market provides also the rationale why optimizing intermediate good producers commit to satisfy all demand for their product at posted prices, even though prices are set for more than one period and may, ex post, turn out to be suboptimal due to unexpected shocks to the economy. Similarly, without monopolistic competition on the labour market it would remain unexplained why it is costly to change the wage rate. Indeed, if markets are perfectly competitive, labour contracts would not be negotiated at all.

2.1.1 The representative final good producing firm

The representative final good producing firm combines a continuum of different intermediate goods to produce an aggregate final good which can be used for consumption and investment purposes. The different intermediate goods are indexed by $i \in [0, 1)$. The technology of the final good producing firm has constant returns to scale and a constant elasticity of substitution θ, which is assumed to be greater than one. Specifically, the production function is [11]

$$Y_t = \left(\int_0^1 y_{i,t}^{\frac{\theta-1}{\theta}} \, di \right)^{\frac{\theta}{\theta-1}}, \qquad \theta > 1, \tag{1}$$

where Y_t and $y_{i,t}$ denote quantities of the final and the intermediate good i, respectively. The representative final good producer is a price taker on the market for final goods and the differentiated market for intermediate goods. From the profit maximization problem of the producer, one obtains the price of the final good as [12]

$$P_t = \left(\int_0^1 p_{i,t}^{1-\theta} \, di \right)^{\frac{1}{1-\theta}}, \tag{2}$$

[10]Taylor (1980) suggested that staggered wage contracts explain persistent real effects of nominal shocks. See Chari, Kehoe, and McGrattan (2000) for an assessment of Taylor's conjecture in the general equilibrium framework.

[11]See Dixit and Stiglitz (1977). This microstructure for production is based on Blanchard and Kiyotaki (1987).

[12]Perfect competition on the final good markets drives profits of the final good producers to zero in equilibrium.

where P_t and $p_{i,t}$ stand for the price of the final and intermediate good i, respectively. Given the price for the final good, the final good producer's profit maximizing demand $y_{i,t}$ for the intermediate good i,

$$y_{i,t} = \left(\frac{P_t}{p_{i,t}}\right)^{\theta} Y_t, \tag{3}$$

depends only on his planned output Y_t and the price $p_{i,t}$ of the intermediate good i.

2.1.2 The intermediate good producers

Each intermediate good producer i produces the quantity $y_{i,t}$ of a unique good. Since intermediate goods substitute imperfectly for one another, each intermediate good producer, facing the downward-sloping demand function (3) with elasticity θ, can set the price of his product. We assume that the intermediate good producers set their prices for one year, or in a quarterly model for four periods. Each period, one quarter of the firms adjusts its prices and commits to satisfy total demand at the posted price during the next four periods. Price setting is staggered because each period a different quarter of the firms sets the price, until after four periods, the cycle starts all over again. Without loss of generality, we assume that all firms with index $i \in [0, \frac{1}{4})$ adjust their prices in period $t = 0, 4, 8, \ldots$, all firms with index $i \in [\frac{1}{4}, \frac{1}{2})$, adjust prices in $t = 1, 5, 9, \ldots$ and so forth.

The production of the intermediate good requires labour L_t and capital K_t. The inputs are hired on perfectly competitive factor markets. The technology of the intermediate good producers is described by a production function which has constant returns to scale in the private inputs K_t and L_t, but as in Romer's (1986) model, aggregate per capita stock $\bar{K}_t$ exerts a positive external effect on the intermediate good producers. Specifically, the production function is

$$y_{i,t} = A\, e^{z_t}\, L_t^{1-\alpha} K_t^{\alpha}\, \bar{K}_t^{1-\alpha}, \tag{4}$$

with A a scale parameter and z_t a technology shock affecting total factor productivity. The technology shock has an unconditional expectation equal to zero, implying that there is no exogenous trend in total factor productivity. Furthermore, we assume that the shock follows a stationary AR(1) process with normally distributed innovations ε_t^z

$$z_t = \rho_z z_{t-1} + \varepsilon_t^z, \qquad \varepsilon_t^z \sim \mathcal{N}(0, \sigma_z^2). \tag{5}$$

All intermediate good producers face the same wage rate W_t and rental price of capital PK_t. Therefore, the cost of producing one unit of the intermediate good is the same for all firms, as are the conditional factor demand functions, that is the cost minimizing combination of factor inputs for a given level of output. The conditional labour and capital demand of each intermediate good producer for one unit of an intermediate good are [13]

$$K(1)_t = \frac{1}{A\, e^{z_t} \bar{K}_t^{1-\alpha}} \left(\frac{\alpha W_t}{(1-\alpha) PK_t}\right)^{1-\alpha} \tag{6}$$

$$L(1)_t = \frac{1}{A\, e^{z_t} \bar{K}_t^{1-\alpha}} \left(\frac{(1-\alpha) PK_t}{\alpha W_t}\right)^{\alpha}, \tag{7}$$

yielding the unit cost function

$$C(PK_t, W_t) = \frac{1}{A e^{z_t} \bar{K}_t^{1-\alpha}} \left(\frac{PK_t}{\alpha}\right)^{\alpha} \left(\frac{W_t}{1-\alpha}\right)^{1-\alpha}. \tag{8}$$

[13] Since the production functions are characterised by constant returns to scale in private inputs, the unconditional demand and cost functions are obtained by multiplying the conditional functions by the output quantity.

Since the intermediate good producer sets his price for four periods, he chooses the price $p_{i,t}$ for his product such that the discounted expected profit over the entire length of the contract

$$\mathrm{E}_t \sum_{j=0}^{3} \beta^j \gamma_{t+j} \Big(p_{i,t} - C(PK_{t+j}, W_{t+j})\Big) \left(\frac{P_{t+j}}{p_{i,t}}\right)^{\theta} Y_{t+j}, \tag{9}$$

is maximal [14]. Clearly, when deciding on the price, the intermediate good producer takes into account how his price affects the demand for his product (see (3)). However, he treats factor prices as well as the quantity and price of the final good as given. Note, that the intermediate good producer discounts profits in period $t+j$ at the same rate $\beta^j \gamma_{t+j}$ as households discount dividend payments. In doing so, the producer behaves in the interest of the shareholders [15].

The price $p_{i,t}$ that solves (9) is

$$p_{i,t} = \frac{\theta}{\theta - 1} \quad \frac{\mathrm{E}_t \left[\sum_{j=0}^{3} \beta^j \, \gamma_{t+j} \, P_{t+j}^{\theta} \, C(PK_{t+j}, W_{t+j}) \, Y_{t+j}\right]}{\mathrm{E}_t \left[\sum_{j=0}^{3} \beta^j \, \gamma_{t+j} \, P_{t+j}^{\theta} \, Y_{t+j}\right]}. \tag{10}$$

Concentrating on a symmetric equilibrium in which all intermediate good producers, which can adjust their price in the same period, set the same price, one can drop the index i. p_t is then interpreted as the price of the intermediate goods with index $i \in [0, \frac{1}{4})$ if $t = 0, 4, 8, \ldots$ and correspondingly for other t. Solving for the partial equilibrium in the production sector, one obtains the price of the intermediate good set in t, the aggregate labour demand, the aggregate capital demand, the price level of the final good, and the aggregate dividend payments of the intermediate good producers:

$$p_t = \frac{\theta}{\theta - 1} \quad \frac{\mathrm{E}_t \left[\sum_{j=0}^{3} \beta^j \, \gamma_{t+j} \, P_{t+j}^{\theta} \, C(PK_{t+j}, W_{t+j}) \, Y_{t+j}\right]}{\mathrm{E}_t \left[\sum_{j=0}^{3} \beta^j \, \gamma_{t+j} \, P_{t+j}^{\theta} \, Y_{t+j}\right]} \tag{11}$$

$$L_t = \frac{1}{4\, A e^{z_t} \bar{K}_t^{1-\alpha}} \left(\frac{\alpha\, W_t}{(1-\alpha)\, PK_t}\right)^{1-\alpha} Y_t\, P_t^{\theta} \sum_{j=0}^{3} p_{t-j}^{-\theta} \tag{12}$$

$$K_t = \frac{1}{4\, A e^{z_t} \bar{K}_t^{1-\alpha}} \left(\frac{(1-\alpha)\, PK_t}{\alpha\, W_t}\right)^{\alpha} Y_t\, P_t^{\theta} \sum_{j=0}^{3} p_{t-j}^{-\theta} \tag{13}$$

$$P_t = \left(\frac{1}{4} \sum_{j=0}^{3} p_{t-j}^{1-\theta}\right)^{\frac{1}{1-\theta}} \tag{14}$$

$$Div_t = \frac{1}{4}\, Y_t\, P_t^{\theta} \left[\sum_{j=0}^{3} p_{t-j}^{1-\theta} - \frac{1}{A\, e^{z_t} \bar{K}_t^{1-\alpha}} \left(\frac{PK_t}{\alpha}\right)^{\alpha} \left(\frac{W_t}{1-\alpha}\right)^{1-\alpha} \sum_{j=0}^{3} p_{t-j}^{-\theta}\right] \tag{15}$$

2.1.3 The representative employment agency

The employment agency combines $l_{h,t}$ units of labour types h to L_t units of aggregated labour services using the production function

$$L_t = \left(\int_0^1 l_{h,t}^{\frac{\theta_l - 1}{\theta_l}} \, dh\right)^{\frac{\theta_l}{\theta_l - 1}}, \qquad \theta_l > 1. \tag{16}$$

[14] Although the producer maximizes the discounted expected profit over all future periods, his decision problem simplifies to (9) because it is time separable.

[15] $\beta^j \gamma_{t+j}$ is the discounted marginal utility in period t of a unit of account received in period $t+j$.

It is assumed that each household h supplies a different type of labour which substitutes imperfectly for other types and that there is a continuum of different households indexed by $h \in [0,1)$. The employment agency supplies the aggregate labour services to the intermediate good producers. The representative agency takes as given the wage rate $w_{h,t}$ it has to pay to household h and the price W_t it obtains for the aggregate labour services L_t.

The agency has to pay at least a fraction ϕ_t of its wage bill $\int_0^1 w_{h,t} l_{h,t} dh$ with currency, which it borrows at the financial intermediary. This fraction is not fixed, but fluctuates stochastically around an unconditional mean $\bar{\phi}$. In particular, the fractions evolves as an AR(1) process

$$\phi_t = (1-\rho_\phi)\bar{\phi} + \rho_\phi \phi_{t-1} + \varepsilon_t^\phi \qquad \varepsilon_t^\phi \sim \mathcal{N}(0, \sigma_\phi^2), \tag{17}$$

with normally distributed innovations ε_t^ϕ. These shocks are interpreted as money demand shocks, because they shift the agencies' demand for cash balances.

The credit from the intermediary has to be repaid with interest at the end of the period. The interest rate the intermediary charges is R_t. Profit maximization implies then that the price for the aggregated labour services W_t is given by [16]

$$W_t = (1+\phi_t R_t)\left(\int_0^1 w_{h,t}^{1-\theta_l}\, dh\right)^{\frac{1}{1-\theta_l}}. \tag{18}$$

Furthermore, given the interest rate R_t and the price W_t for the aggregate labour services, the agency's profit maximizing demand $l_{h,t}$ for labour type h,

$$l_{h,t} = \left(\frac{(1+\phi_t R_t)W_t}{w_{h,t}}\right)^{\theta_l} L_t, \tag{19}$$

depends only on his planned supply of aggregate labour services L_t and the wage rate $w_{h,t}$ for labour type h.

2.1.4 Households

Households differ only with respect to the type of labour they supply. All households have an infinite planning horizon and identical preferences over a consumption aggregate c_t and leisure h_t. These preferences can be represented by an expected utility function

$$\mathrm{E}_t \sum_i \beta^i U(c_i, h_i), \tag{20}$$

where β denotes the rate at which the household discounts future utility and E_t the expectation conditional on the information in period t. This information set contains the realisations of all variables with time index t and earlier. It is assumed that the period utility function $U(c_t, h_t)$ is of the Cobb-Douglas type, i.e.

$$U(c_t, h_t) = \xi \ln c_t + (1-\xi)\ln h_t. \tag{21}$$

Each household's wealth consists of cash, deposits, shares as well as physical and human capital. Except cash balances, each component of wealth is a source of household income. Deposits yield interest income, physical capital is rented to the production sector and earns capital income, shares yield dividend income and by working it earns labour income. The household uses its income for consumption, investment in its physical capital stock and to pay lump-sum taxes. Investment inv_t and depreciation at the rate δ changes the capital stock k_t of the household as

$$k_t = (1-\delta)k_{t-1} + inv_t(1 - ICost_t), \tag{22}$$

[16] Since the agency is a price taker and the its technology is characterised by constant returns to scale, its profits must be zero in equilibrium.

where $ICost_t$ are the costs of installing new or removing old equipment. It is assumed that these costs depend quadratically on investment and are normalised such that the costs are zero along the economy's balanced growth path:

$$ICost_t = \frac{\Psi_K}{2}\Big(\frac{inv_t}{k_{t-1}} - \frac{Inv}{K}\Big)^2, \tag{23}$$

with $\frac{Inv}{K}$ is the constant aggregate investment to capital ratio on the balanced growth path.

As already mentioned in the introductory paragraph, each household holds cash balances, which do not bear interest, because consumption has to be paid in cash. At the end of each period a household splits its money holdings into cash mh_t to finance next period consumption expenditure and deposits d_t. Besides cash balances carried over from the previous period, the fraction ϕ_t of its labour income which the household receives in currency, is available for consumption. Therefore, the cash in advance constraint of a household reads

$$(1+\tau_c)P_t c_t \leq mh_{t-1} + \phi_t w_{h,t} l_t, \tag{24}$$

with P_t the price for the consumption good, τ_c the indirect tax rate, l_t labour supply and $w_{h,t}$ the wage rate, which may differ between households [17].

The final restriction, a household has to take into account, is the flow constraint according to which total income less total outlays equals the change of money holdings

$$mh_t - mh_{t-1} + d_t - d_{t-1} = F_t + Div_t + d_{t-1}R_t + w_{h,t}l_t + PK_t k_{t-1} - (1+\tau_c)P_t c_t - P_t inv_t - TX_t. \tag{25}$$

In this equation, TX_t denotes the lump-sum tax and F_t respectively Div_t denotes dividend payments the household receives from the financial intermediary and intermediate good producer, respectively.

When determining its labour supply, the household exploits its market power due to the fact that its labour is of a unique type for which no perfect substitute exists. Moreover, the household takes into account that changing the wage rate at which it offers to work for the employment agency requires time to renegotiate the contract. The time needed to agree on a new wage rate is assumed to increase quadratically with the wage increase. The costs are again standardised to zero if the economy is on a balanced growth path.

On normalizing total available time of the household to unity, time remaining for leisure is

$$h_t = 1 - l_t - \frac{\Psi_l}{2}\left(\frac{w_{h,t}}{w_{h,t-1}} - \omega\right)^2, \tag{26}$$

with ω the growth rate of nominal wages along the balanced growth path of the economy.

The decision problem of a household is thus to maximise expected utility (20) under the sequence of restrictions (22), (24), (25), (26) and the employment agency's demand function for the labour type h (19), given the initial stocks k_0, mh_0, and d_0 the sequence of prices P_t, W_t, PK_t and interest rate R_t. When a household takes its decisions it uses all available information at date t which includes the realisation of all variables with index t, $t-1$, $t-2$,....

2.1.5 The financial intermediary

The financial intermediary collects deposits D_{t-1} at the end of each period from the households, receives a monetary injection $M_t - M_{t-1}$ from the central bank at the beginning of a period and lends these funds to the employment agencies. At the end of the period, the agencies redeem their loans and the intermediary returns the deposits with interest to the households. The profit maximizing intermediary behaves competitively implying that the interest on loans equals the interest paid on deposits. Because of the monetary injection, the intermediary makes a profit amounting to $(1+R_t)(M_t - M_{t-1})$ which it pays as dividend to the households.

[17] The model imposes enough symmetry on the household sector, however, that there exists an equilibrium in which the wage rate for each labour type is the same.

2.1.6 The government

The role of the government in this model is rather limited. It collects indirect taxes $\tau_c P_t C_t$ on aggregate per capita consumption C_t and lump sum taxes TX_t to finance government consumption $P_t g_t Y_t$. Government expenditure as share of GNP follows a stationary AR(1) process with unconditional mean $\bar{g}$ and normally distributed innovations ε_t^g.

$$g_t = (1 - \rho_g)\,\bar{g} + \rho_g\, g_{t-1} + \varepsilon_t^g \qquad \varepsilon_t^g \sim \mathcal{N}(0, \sigma_g^2). \tag{27}$$

The government adjusts the lump-sum tax each period to balance the budget. The government expenditure shocks represent shocks to aggregate demand.

2.1.7 The central bank

The central bank in this model controls money growth μ_t to achieve its medium-term inflation target $\bar{\pi}$. The money stock M_t evolves according to

$$M_t = e^{\mu_t} M_{t-1} \tag{28}$$

and money growth follows the policy rule

$$\mu_t = \alpha_\pi\,(\pi_t - \bar{\pi}) + \alpha_y \left(\ln\left(\frac{Y_{t-1}}{K_{t-2}}\right) - \ln\left(\frac{Y}{K}\right)\right) + \alpha_R\,(R_t - R_{t-1}) + \zeta_t \tag{29}$$

$$\zeta_t = (1 - \rho_\zeta)\bar{\zeta} + \rho_\zeta \zeta_{t-1} + \varepsilon_t^\zeta, \qquad \varepsilon_t^\zeta \sim \mathcal{N}(0, \sigma_\zeta^2). \tag{30}$$

The monetary authority sets the unconditional mean $\bar{\zeta}$ of the money growth innovations ζ_t such that the inflation target $\bar{\pi}$ will be the inflation rate on the balanced growth path of the economy. The central bank reacts to deviations of the current from the target inflation rate $\pi_t - \bar{\pi}$ and – although with an information lag of one period – to the output gap $\ln\left(\frac{Y_{t-1}}{K_{t-1}}\right) - \ln\left(\frac{Y}{K}\right)$, i.e. the deviation of actual output from its balanced growth path. Furthermore, the central bank adjusts its money supply to smooth interest rate movements, i.e. it responds to $R_t - R_{t-1}$. Finally, money growth is subject to shocks, which represent control errors or discretionary policy actions. These shocks follow an AR(1) process with independent and normally distributed innovations. As already mentioned in the introductory paragraphs, new currency $M_t - M_{t-1}$ is channelled into the economy through the financial intermediary.

The assumption that the central bank controls the money stock and not the short-term interest rate seems not to reflect current practice. However, in forward looking models, interest rate rules may lead to indeterminate or explosive equilibria (see Christiano and Gust (1999), McCallum (1986), Carlstrom and Fuerst (1995)) because they do not necessarily determine the path of the money stock uniquely. On the other hand, each interest rate rule can be replicated by at least one specific money growth reaction function. It is, therefore, no loss of generality to assume that the central bank behaves as if controlling the money supply instead of the short end of the yield curve.

2.1.8 The equilibrium

We concentrate on a symmetric equilibrium where all households set the same wage rate $w_{h,t} = w_t$ and supply the same amount of labour $l_{h,t} = l_t$, and all intermediate good producers which can revise their contracts in the same period, set the same price for their product $p_{i,t} = p_t$ and demand the same amount of factor inputs $L_{i,t} = L_t$, $K_{i,t} = K_t$. Clearly, in such an equilibrium the price for the aggregate labour service (18) is proportional to the wage rate for the different labour types, i.e. $w_t = \frac{1}{1+\phi_t R_t} W_t$.

The equilibrium is then defined by a solution to the first order conditions of the household's decision problem, the partial equilibrium in the production sector (11)–(15), the government budget constraint (27), the monetary policy rule (29) and the market clearing conditions for the

Table 1: Calibrated parameter values

Production sector					*Household sector*			
α	θ	θ_l	δ	A	ξ	β	ψ_w	ϕ_K
0.330	2.25	2.25	0.0156	0.40	0.534	0.993	20.00	60.00
Policy reaction function					*Government*			
α_π	α_Y	α_R			τ_c			
−0.50	−0.20	0.20			0.220			
Shock processes								
$\bar{\zeta}$	ρ_ζ	σ_ζ			$\bar{\phi}$	ρ_ϕ	σ_ϕ	
0.016	0.86	0.0010			0.500	0.20	0.0009	
$\bar{g}$	ρ_g	σ_g			$\bar{z}$	ρ_z	σ_z	
0.228	0.90	0.0033			0.000	0.79	0.0060	

commodity, credit and money market

$$Y_t = Inv_t + C_t + g_t Y_t, \tag{31}$$

$$\phi_t w_t l_t = D_{t-1} + M_t - M_{t-1}, \tag{32}$$

$$M_t = MH_t + D_t, \tag{33}$$

and the condition that individual decisions are consistent. The last condition entails that individual and aggregate per capita decision rules are identical, i.e. $c_t = C_t$, $inv_t = Inv_t$, $k_{t-1} = K_t = \bar{K}_t$, $d_t = D_t$ and $mh_t = MH_t$, where the uppercase variables on the right hand side denote aggregate per capita variables.

In order to simplify solving for the equilibrium, all variables with a positive equilibirium growth rate are transformed such that they converge to a steady state in the deterministic version of the model. This is accomplished by substituting the following relations $\hat{Y}_t = \frac{Y_t}{K_{t-1}}$, and analogously for $\hat{C}_t$, $\hat{K}_t$, $\hat{Inv}_t$, $\hat{P}_t = \frac{P_t}{M_t}K_{t-1}$, and analogously for $\hat{p}_t$, $\hat{PK}_t$, and $\hat{MH}_t = \frac{MH_t}{M_t}$, and analogously for $\hat{W}_t$, $\hat{w}_t$, $\hat{D}_t$. The ***recursive equilibrium*** of this economy is then a set of stationary decision rules $\hat{Y}_t$, $\hat{C}_t$, $\hat{K}_t$, $\hat{Inv}_t$, $\hat{p}_t$, $\hat{w}_t$, $\hat{MH}_t$, $\hat{D}_t$ and pricing functions $\hat{P}_t$, $\hat{PK}_t$, $\hat{W}_t$ which solve the transformed equilibrium conditions enumerated above.

2.2 Calibration and solution of the model

For the model evaluation and the simulation of time series, the structural parameters have been calibrated to (per capita) long-run averages of aggregated data from the eight largest countries of the European Monetary Union (EMU8), viz. Austria, Belgium, Finland, France, Germany, Italy, the Netherlands, and Spain. These countries represent more than 95% of total GDP of the EMU. Calibrating a closed economy model to EMU data should not be overly restrictive, because similar to the US, exports and imports of goods represent a relatively small fraction of GDP (approximately 13% of the EMU's GDP). The calibrated parameter values are summarised in Table 1. The area-wide data are aggregated national quarterly data for the period 1979:II–1999:IV, beginning with the start of the EMS. Nominal variables, for example GDP, were first converted to Deutsche Mark using the 1990 purchasing power parities. The area-wide nominal interest rate has been constructed as a weighted average of the national 3-month rates using 1990 GDP shares as weights, with national GDP figures converted to Deutsche Mark using 1990 purchasing power parities. The same weights have been used to aggregate national GDP deflators for the calculation of the EMU8 inflation rates [18].

The average nominal interest rate, the average inflation rate and average per capita real growth rate of GNP, which were used to calibrate A, ζ and β, are 2.28%, 1.11%, and 0.47% on a quarterly

[18] See Winder (1997) on the aggregation of area-wide data.

basis. For the calibration of ξ we used that the fraction of total available time, i.e. of the time not required for sleeping and eating, allocated by households to working in the production sector is roughly 23%. This fraction is based on microeconomic evidence for working age men and women in Netherlands for 1975–1995 [19]. Microeconomic evidence from other European countries (Finland, Denmark, Sweden) reported by Juster and Stafford (1991) seems to indicate that the data for the Netherlands may not be representative. However, the results presented in Juster and Stafford are obtained from time allocation surveys that do not cover unemployed men, male students or men unable to participate in the labour market. Therefore, these statistics are likely to overestimate the fraction of time that the working age population spent in working in the production sector.

The capital share parameter in the intermediate goods producing sector has been set to $\alpha = 0.33$ which is the long run average capital share of area-wide GDP. Based on data on investment and the capital stock, as far as the latter were available, the empirical depreciation rate has been estimated at $\delta = 1.56\%$ per quarter [20]. The autocorrelation coefficient of the technological shock is derived from an analysis of the Solow residuals, whereas the variance was chosen such that the variance of observed GDP matches the variance of output in the model. The elasticities of the final good producer and employment agency, θ and θ_l are set to the values suggested by Chari, Kehoe, and McGrattan (2000).

In order to calibrate the policy reaction function governing the money growth, we estimated equation (29) using area-wide per capita M1 data [21]. In order to account for seasonality in the M1 series, we took annual differences and used an instrumental variable estimator [22]. We found an autocorrelation coefficient of 0.86 and a standard deviation of 0.00101 as well as the reported reaction coefficients on the current inflation rate and the lagged output gap. The weight in the reaction function on interest rate smoothing was found to be insignificant. For the numerical simulations we attached nevertheless some weight to interest rate smoothing.

Government expenditure parameters were calibrated on OECD data for the period 1980–1999. The fraction of the employment agency's wage bill which has to be financed with currency has not been calibrated to empirical data, but its mean, autocorrelation and standard deviation has been set in an ad-hoc way, such that the impulse response of the economy to a money demand shock is reasonable. Similarly, we choose values for the installation cost parameter Ψ_K and the wage adjustment cost parameter Ψ_l. The chosen values imply that installation costs are 0.3% of total investment if the growth of investment exceeds its steady state growth rate by one percentage point. The wage adjustment costs amount to 0.1% of total household time if the growth of the nominal wages exceed their steady state growth rate by one percentage point [23].

2.3 Properties of the model

In this section we discuss some of the model's properties. Among these properties are the impulse responses to the four different shocks, some characteristics of the time series the model generates such as the order of integration of output, money, inflation and interest and their second moments. Finally, the question is addressed whether the model features (super-)neutrality of money. The discussion of the impulse responses and the second moments intends to show that the model is not only a theoretically consistent, but also a reasonable interpretation of actual data. Hence, using the model as a laboratory to evaluate core inflation is a meaningful exercise.

[19] See Van den Broek, Knulst, and Breedveld (1999) and Statistics Netherlands (2000, p. 147–148).

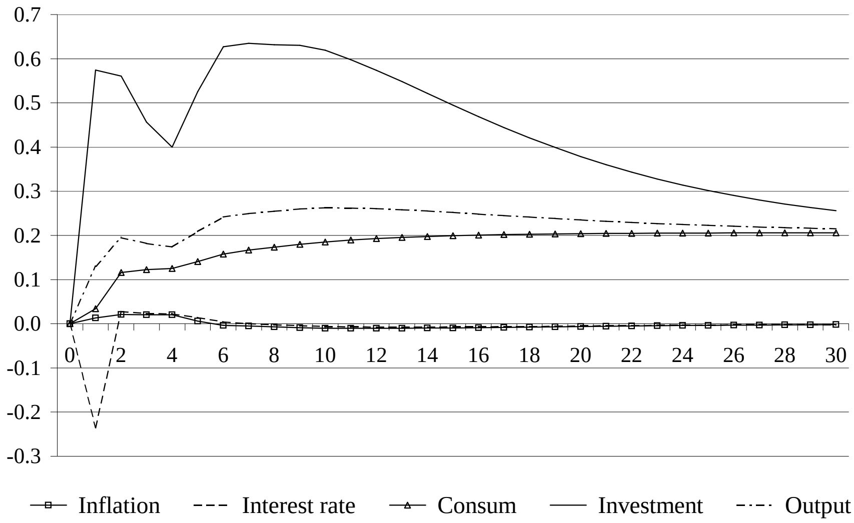
[20] Reliable data on the capital stock are scarce. For some EMU countries, i.e. Belgium, Finland, France, Germany, and Italy annual capital stock data exist (OECD 1997). The annual depreciation rate of the capital stock (exclusive dwellings and government sector) according to OECD data for Belgium, Finland, France and Germany for the sample period 1979–1995 is 6.5% per year. We did not use Italian data for our estimation because the depreciation rate for Italy is implausibly low (1.7% per year), which is probably due to the fact that the capital stock data cover also dwellings which have a much lower depreciation rate than equipment.

[21] Time series on area-wide M1 have been published by the ECB, see European Central Bank (1999).

[22] Using annual (log-)differences to estimate (29) cause a non-zero correlation between the money growth shocks and the lagged money growth rate.

[23] If the annual working time is roughly 1800 hours, negotiation costs are 1.8 hours per year.

Figure 1: Impulse response to a monetary shock



Explanatory note: The vertical axis measures percent respectively percentage point deviations from the pre-shock balanced growth path. The size of the shock is one standard deviation.

The discussion of the order of integration and the superneutrality of money prepares the ground for the interpretation of our simulation results later on.

2.3.1 Impulse response functions

We start by investigating the dynamic properties of the model economy numerically. First, the effects of an unexpected rise of the money growth rate by 1 standard deviation is considered. Then we describe the effects of a shock to total factor productivity, to government expenditure and money demand. In all exercises, we solved for the equilibrium path using a log-linear approximation around the steady state[24].

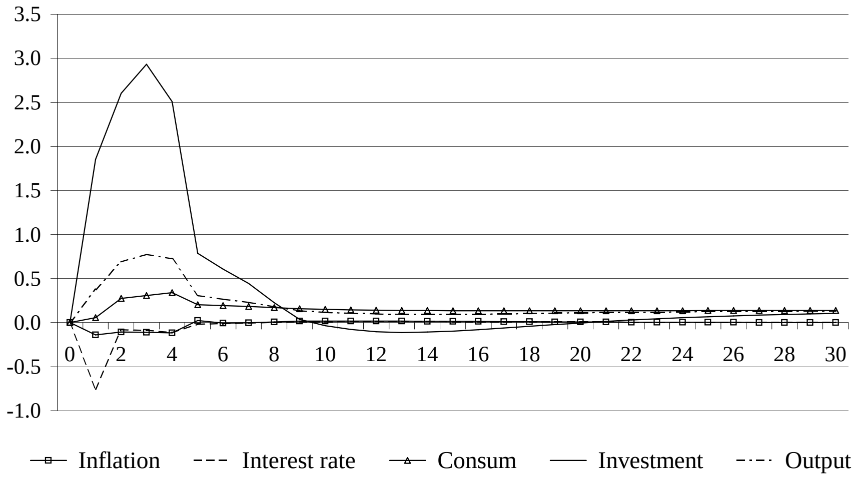
The response of the economy to an unexpected monetary expansion is depicted in Figure 1. The effect of the shock on key variables is shown as deviation from the balanced growth path along which the economy would have evolved in the absence of the shock. The deviation of those variables which are stationary without prior transformation (see Section 2.1.8), such as the nominal interest rate, the inflation rate and the fraction of time allocated to working are expressed in percentage points.

Figure 1 shows that the model calibrated to the European Monetary Union exhibits a liquidity effect. The unexpected rise of the money stock in period 1 lowers immediately the nominal interest rate and boosts employment and output. The downward pressure on the nominal interest rate, which is caused by the reluctance of firms to absorb the excess liquidity in the credit market, dominates the effect of increased inflation expectations. In a model with staggered price contracts, the liquidity effect becomes much more likely than in a model without staggering, because the stickyness of the price level keeps expected inflation low.

A lower interest rate decreases the costs to finance the wage bill and reduces ceteris paribus the real wage rate as perceived by the production sector in general and the employment agency in particular. Therefore, equilibrium employment tends to rise and with the physical capital stock predetermined, this tends to increase output.

[24]The solution of the log-linear system was calculated by the algorithm of Klein (2000). Our solution method assumes that the cia-constraint always binds. The validity of this assumption has been tested ex-post for all simulations.

Figure 2: Impulse response to a technological shock



Explanatory note: The vertical axis measures percent respectively percentage point deviations from the pre-shock balanced growth path. The size of the shock is one standard deviation.

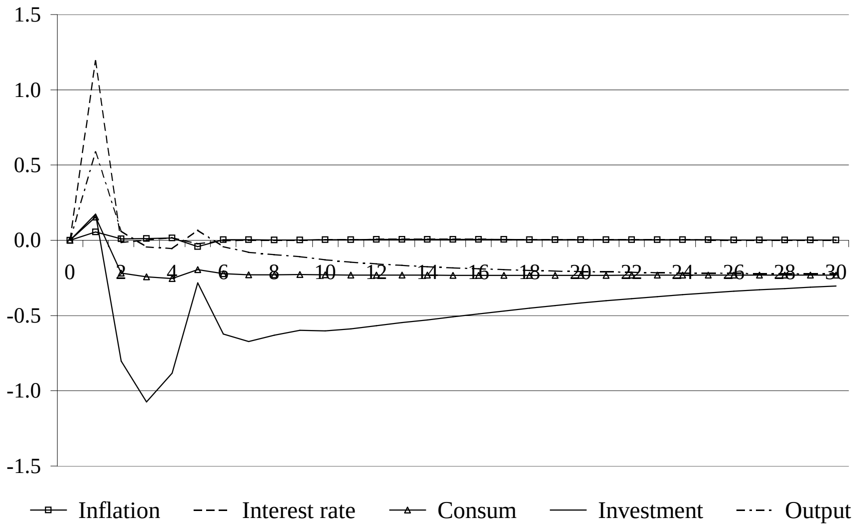
The decline of real production costs as a short-run effect of the money shock, implies as well that households earn higher dividends from the intermediary good producers. The money injection itself leads to a rise in dividends paid by the financial intermediary. Household can only save this additional income by investing in their capital stock. Since the enlargement of the aggregate capital stock affects total factor productivity positively, investing will allow to produce more output in the future with the same amount of labour but without diminishing marginal returns to capital. This wealth effect induces households to substitute current leisure for future consumption: households increase their labour supply slightly during the first periods after the monetary policy shock has hit the economy, although this tends lowers the equilibrium wage rate.

Note, that the effect of investment on the long-run output level is quite pronounced. Hence, the price level, which could not rise sharply in the short-run due to the staggered contracts, will not catch up in the long-run. This explains the minor response of the inflation rate to a temporary money growth shock. The long-run effect of a money shock on the output level also shows that money is not neutral in this model, a topic to which we will return at the end of this section.

The consequences of a *technological shock* in our model are depicted in Figure 2. An increase of the productivity of both input factors boosts ceteris paribus output and lowers production costs. The latter leads, although sluggishly, to a decline of the price level and an immediate rise of dividend payments by the intermediate good producers to the households. The transitory nature of the shock to household income induces utility maximizing households to invest in order to smooth consumption over time. As in the case of a money supply shock, investment increases the aggregate capital stock and the output level permanently, since the marginal return to aggregate capital is not diminishing but constant. Note that the decline of the nominal interest rate in the period when the technological shock occurs is due to the decline in expected inflation which lowers the demand for money of the employment agency.

The response of the economy to an unexpected rise of government expenditure is shown in Figure 3. The increase of government consumption leads to an upward pressure on the price level. Since the intermediate good producers aggreed to satisfy total demand to the posted price, they have to employ more workers, bidding up the wage rate and, because the wage bill has to be financed by borrowing from the financial intermediary, the nominal interest rate. After the initial rise in output, however, the negative wealth effect of the tax increase to finance the government expenditure shocks drives the response: consumption is reduced and households dissave to dis-

Figure 3: Impulse response to a government expenditure shock



Explanatory note: The vertical axis measures percent respectively percentage point deviations from the pre-shock balanced growth path. The size of the shock is one standard deviation.

tribute the consumption reduction over time. Since dissaving affects the aggregate capital stock but not the return on capital, the government expenditure shock leads to a permanently lower level of output, consumption and investment.

The final graph in this section, Figure 4, is the impulse response function to a money demand shock. As is shown in the chart, a money demand shock bids up the interest rate. Since a larger part of the wage bill has to be financed by currency, the higher interest rate leads to a significant rise in the cost of labour from the viewpoint of the production sector. Therefore, prices start to rise and the real wage rate as perceived by the households tends to fall, with a lower equilibrium employment and output level. In order to mitigate the immediate effect of a money demand shock on consumption, households replace part of their labour income by dissaving. As in all previous cases, it is the indirect effect of the shock on aggregate capital stock which explains why the shock lowers the output level permanently.

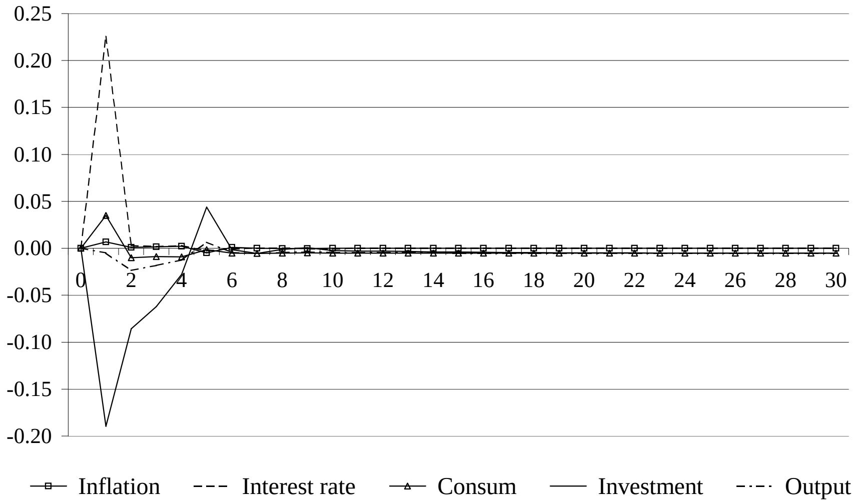
2.3.2 Time series properties

Empirical and model based second moments. In Figure 5 the stylised facts of the European business cycle are confronted with the properties of the model. As is common in the real business cycle literature, these stylised facts are summarised by the standard deviations, autocorrelations and the cross-correlations of detrended time series of key variables [25]. The trend in the observed and simulated time series have been removed with the aid of a Hodrick-Prescott filter. This figure illustrates that the model succeeds in going quite a long way in explaining observed business cycle facts. The standard deviation, autocorrelation and cross-correlation of real variables with current output is captured quite well. Only, the degree of consumption smoothing implied by the model is roughly half of the empirical observed value.

With regard to the nominal variables the model performs less well. The nominal interest rate tends to be pro-cyclical instead of a- or anti-cylcical and shows too little persistence. The low autocorelation is especially surprising because some degree of interest rate smoothing has been incorporated in the policy reaction function. Finally, although the model replicates the standard deviation and autocorrelation of the inflation rate found in aggregated EU8 data, the model

[25] See Section 2.2 for a description of the data.

Figure 4: Impulse response to a money demand shock



Explanatory note: The vertical axis measures percent respectively percentage point deviations from the pre-shock balanced growth path. The size of the shock is one standard deviation.

predicts that inflation is anti-cyclical but not acyclical. A possible interpretation of this last result is that the fraction of the inflation variability which is explained by supply shocks, is significantly higher in the model than in the data [26].

Order of integration of key variables. As will be described in Section 3, all VAR-based identification schemes for core inflation are based on assumptions concering the order of integration of the time series. For example, all schemes assume that (log-)output is integrated of order one. Since we will use our monetary general equilibrium model as a data generating mechanism for the simulation exercises, the true order of integration of output, the inflation and interest rate as well as the money stock can be derived. For the derivation of the order of integration, some details of the solution methods have to be described.

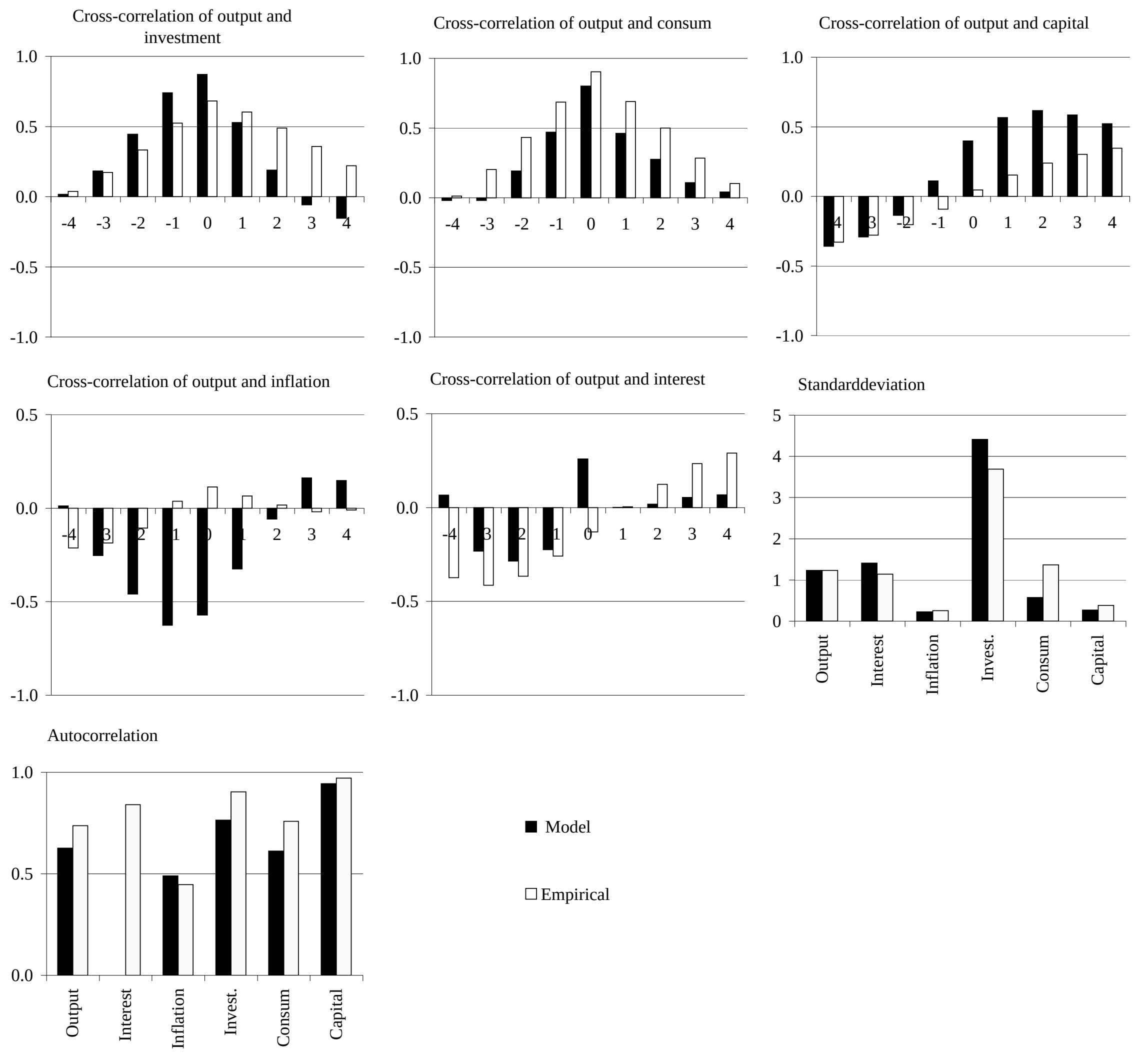
The first step to solve the model is an analysis of the *deterministic* version of the model to establish the existence of a balanced growth path. In our model this path exists along which all real variables, in particular capital and output grow with the same positve constant rate, whereas inflation and the nominal interest rate are constant. For the numerical analysis and simulation of the *stochastic* version of the model, we solve a log-linear approximation of the equilibrium conditions. This approximation, however, requires a transformation of all variables such that they would converge to a steady state in the absence of any shocks. Thus, instead of output and capital, the equilibrium conditions are solved, for example, for the output capital ratio $\hat{Y}_t = \frac{Y_t}{K_{t-1}}$, the growth rate $\hat{K}_t = \frac{K_t}{K_{t-1}}$ and transformed prices $\hat{P}_t = \frac{P_t}{M_t} K_{t-1}$. Clearly, the existence of a balanced growth path is a necessary condition for convergence of the transformed variables in the deterministic version of the model.

The algorithm by which we then solve the transformed equilibrium conditions numerically, establishes the existence of a unique stationary equilibrium, which means that in equilibrium the transformed endogenous variables of the linearised model are stationary stochastic processes.

From the existence of an equilibrium it follows immediately, that the nominal interest rate and the inflation rate are stationary processes. Moreover, since $\frac{K_t}{K_{t-1}}$ is a stationary random variable – by the existence of an equilibrium – we have that $\ln K_t - \ln K_{t-1}$ is stationary. Hence, the (log-)capital stock is – by construction – integrated of order one. The order of integration of

[26] Figure 6 also illustrates the contribution of supply shocks to inflation variability in the model.

Figure 5: Second moments of model economy and from aggregated EU8 data



Explanatory note: White bars correspond to the moments calculated from observed time series, solid black bars correspond to moments calculated from simulated time series (1500 periods). The first five panels show the cross-correlations of current output with the indicated aggregates at different leads and lags.

output follows from the stationarity of $\frac{Y_t}{K_{t-1}}$. The latter implies that $\ln Y_t - \ln K_{t-1}$ is stationary. Furthermore, since $\ln K_t$ is integrated of order one, one has that (log-)output is integrated of order one and cointegrated with the (log-)capital stock. The same reasoning establishes that in this endogenous growth model (log-)consumption and (log-)investment are integrated of order one, cointegrated with K_t and thus with each other and (log-)output.

The growth rate of money is stationary in our model, which follows from equation (29) and the previous discussion. Since the money stock evolves as

$$M_t = e^{\mu_t} M_{t-1} \tag{34}$$

one concludes that the (log-)money stock is integrated of order one, and not cointegrated with the capital stock or any other real variables in the model.

Obviously, with the nominal interest and the inflation rate stationary and the money stock as well as the capital stock and other real variables integrated of order one, neither the nominal interest rate nor the inflation rate is cointegrated with either the money stock or any real variable. However, money, prices and output are cointegrated, since the (log-)velocity of money $\ln v_t = \ln Y_t + \ln P_t - \ln M_t$ can be rewritten as the sum of two stationary random variables $\ln v_t = \ln \hat{Y}_t + \ln \hat{P}_t$ and is thus stationary.

2.3.3 Non-Neutrality of money

In this general equilibrium model money is ***not*** neutral, as has been documented in Section 2.3.1, nor is it super-neutral. Non-neutrality of money means that a permanent change of the level of the money stock affects the real allocation of the economy even in the long run. In contrast, in our general equilibrium model, a money supply shock of one standard deviation which increases the money stock permanently, increases the output level in the long-run by 0.21%. Clearly, the steady state ***growth rate*** cannot be influenced by a permanent change of the money stock. Therefore, a once and for all shock to the money stock changes the level of real variables but not their steady state growth rate. This type of non-neutrality of money is not a peculiarity of our model, but is a property which it shares with monetary general equilibrium models in general, as far as they include endogenous growth [27]. A once and for all change of the money stock, affects the real allocation even in the long-run, because the short-run transmission of a monetary shock affects the level of the aggregate capital stock. Since the marginal product of aggregate capital in endogenous growth models is non-decreasing, there is no mechanism which restores the capital stock and thus output to their original levels, even in the long-run.

Super-neutrality entails that a change in the growth rate of the money stock leaves the real allocation of the economy unaffected, at least in the long-run. Money is not super-neutral in our model, since accelerating the money growth implies that the steady state inflation rate goes up as well. A higher inflation rate affects growth negatively, however, because inflation acts as a distortionary tax on cash requiring transactions.

Numerically, the growth effects of inflation are small in our model calibrated to the EU8 countries. Increasing the steady state inflation rate by 1 percentage point per year, reduces the annual growth rate by 0.016 percentage points and a 5 percentage point higher inflation rates reduces the growth rate by 0.07 percentage points.

2.4 Core inflation

As has already been discussed in the introduction, no definition of core inflation on which all or even a majority of economists would agree upon has emerged in the literature. There is, however, one basic characteristic of core inflation which seems to be undisputed. Core inflation is some concept of monetary inflation which is distinct from the inflation measured by a cost of living index such as the cpi. Moreover, all attempts to define core inflation refer either to the quantity theory of money to link the money stock to the price level, or to an aggregate output demand and supply model to distinguish between price movements caused by demand or supply factors.

A characterisation which probably encompasses most of the existing definitions referring to the quantity theory framework, is that any change of prices is an instance of core inflation if they are caused by a variation of the supply of money or a shift of the (income compensated) money demand function. According to an alternative but much narrower definition, price changes constitute core inflation as far as these changes are brought about by variations of money supply. This latter definition seems especially interesting for monetary policy purposes since money supply is controllable by the central bank. For the same reason the concept might also be useful for evaluating a central bank's performance and for settling disputes concerning the accountability of the central bank for deviations of the headline inflation rate from its target.

In the literature on measuring core inflation with structural VAR models, core inflation is defined differently. The SVAR approach assumes that movements of output, inflation and possibly other aggregates are generated by uncorrelated structural shocks. One then refers to monetary

[27] See Lau (2000) for a formal argument.

theory in order to isolate more or less explicitly one of these shocks as supply shocks having permanent effects on the level of output. In particular, all SVAR models considered in the literature include at least output growth and inflation and represent (the change of) observed inflation as

$$\pi_t = \sum_{i=0}^{\infty} d_{i,1}\varepsilon^y_{t-i} + \sum_{j=2}^{J}\sum_{i=0}^{\infty} d_{i,j}\varepsilon^j_{t-i} \tag{35}$$

where ε^y_t denotes the structural shock to output growth, ε^j_t for $j = 2, \ldots, J$ all other shocks driving the endogenous variables and $d_{i,j}$ the coefficients of these shocks in the moving average representation of observed inflation. Core inflation is then defined in this literature as being that part of measured inflation which is not due to supply or output growth shocks. The question what, on the other hand, exactly drives core inflation is generally left unspecified. However, in bivariate SVAR models involving not the level but the change of the inflation rate one refers implicitly to the view that core inflation is generated by money supply shocks [28]. Indeed, at least for bivariate SVAR models explaining output growth and the *change* of inflation, it is difficult to come up with a different interpretation. If inflation is a monetary phenomenon and the effects of real shocks as explaining changes of the inflation rate are controlled for, what else except innovations to the money growth rate could the remaining shock series represent? Arguably, therefore, in bivariate SVAR models involving the change of the inflation rate one can equivalently define core inflation as that component of observed inflation which is *not* due to real shocks or as that part which is caused by monetary shocks.

One, if not the most important difference between the quantity theory and the SVAR-based definitions is the treatment of systematic or predictable monetary policy on the price level. If, for example, monetary policy attempts to stabilise output fluctuations, supply shocks will affect money supply and very likely the price level through the central banks reaction function. According to the SVAR literature the effect of systematic monetary policy responses to a supply shock is not considered as core inflation, since it is an indirect effect of that shock. However, the systematic component of monetary policy would contribute to core inflation as defined within the quantity theory framework.

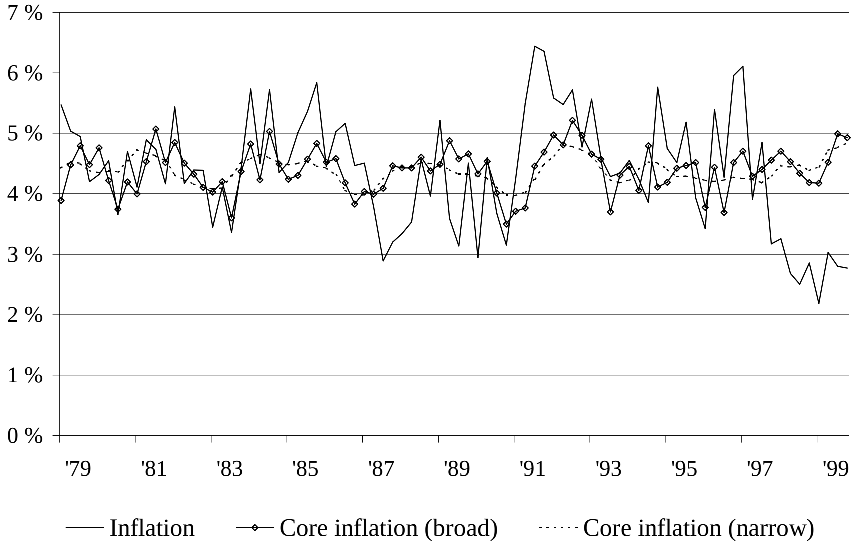
Clearly, none of these concepts of core inflation is directly measurable. Indeed, the main reason for applying the SVAR approach to the measurement of inflation is that it provides a method to measure or, more precisely, to estimate core inflation. Although core inflation is not observable empirically, core inflation as defined in the SVAR literature has a direct counterpart in our monetary equilibrium model. Indeed, in equilibrium all endogenous variables of our model can be represented by an infinite moving average process of structural shocks. In particular, for inflation this process has the form

$$\pi_t = \sum_{i=0}^{\infty} d_{i,1}\varepsilon^z_{t-i} + \sum_{i=0}^{\infty} d_{i,2}\varepsilon^\zeta_{t-i} + \sum_{i=0}^{\infty} d_{i,3}\varepsilon^g_{t-i} + \sum_{i=0}^{\infty} d_{i,4}\varepsilon^\tau_{t-i} \tag{36}$$

where ε^j_t for $j = z, \zeta, g, \tau$ denotes the shock to total factor productivity, money supply, government expenditure and money demand, respectively, and $d_{i,j}$ are the corresponding coefficients of these shocks in the solution for inflation. It can be seen immediately that observed inflation is generated as the sum of structural shocks which are independent at all leads and lags, as assumed in the SVAR literature. The correspondence is exact, if it is assumed that the shocks are also contemporaneously uncorrelated. Therefore, core inflation, as defined in the SVAR literature, corresponds in our model either to the inflation series which results after setting the shocks to total factor productivity to zero or, alternatively, to the core inflation series which results after setting all except the money supply

[28]For example Quah and Vahey (1995, p. 1131) 'Although our method is reconcilable with a monetary view of inflation, we do not impose this in our measurement procedure. We prefer to be agnostic on the exact determinants of underlying inflation.' But on page 1136 they write 'The assumption that the concept of core inflation is meaningful at all is an assumption that there is a unique core inflationary process in a macroeconomy – across all sectors and all regions. While this might, at first, seem improbable, that a common monetary base exists provides some basis for such an assumption.'

Figure 6: Simulated series for headline and core inflation according to the narrow and broad definition



shocks to zero. We will call core inflation according to the former definition core inflation in the broad sense and according to the latter definition core inflation in the narrow sense. Figure 6 shows one realisation of inflation and both core inflation concepts generated by the general equilibrium model.

3 Identification of core inflation: SVAR Methods

The idea to measure core inflation by means of a structural vector autoregressive (SVAR) model is due to Quah and Vahey (1995). They use a SVAR model to explain movements of headline inflation by two types of shocks which differ in their effect on output. The shock which drives the core inflation process is characterised by having no effect on the level of output in the long-run. This section describes the basic features of the SVAR-framework in general and how it is used by Quah and Vahey to identify core inflation in particular. Moreover, we review the various modifications and extensions of Quah and Vahey's approach suggested in the literature. This review is organised according to the type of restrictions that identify the shocks driving core inflation: long-run restrictions in the sense of Blanchard and Quah (1989), long-run as well as contemporaneous restrictions as proposed by Galí (1992) and cointegration restrictions as in Warne (1993).

3.1 The SVAR framework

The underlying idea of the SVAR methodology is the view that movements of economic aggregates can be modelled as resulting from current and past structural shocks. Thus, a vector of n variables y_t corresponding to certain economic aggregates can be written as the sum of all past and present shocks [29]

$$y_t = \nu + A_0 e_t + A_1 e_{t-1} + A_2 e_{t-2} + A_3 e_{t-3} + \cdots , \tag{37}$$

where A_i $(i = 0, 1, 2, \ldots)$ are coefficient matrices and e_t a vector of n structural shocks. It is assumed that these shocks have zero expectation and are uncorrelated at all leads and lags with a contemporaneous covariance matrix $\mathrm{E}[e_t e_t']$ equal to the identity matrix. The assumption that the structural shocks are orthogonal, i.e. that the covariance matrix equals the identity matrix is motivated by the view that the shocks are exogenous and arise from independent sources, e.g. shocks to the supply of oil, to labour productivity, to the money stock. Given that the shocks are uncorrelated, it does not restrict the generality of the model to assume that the covariance matrix equals the identity matrix since it is a simple normalization of the variables. If the true shocks and coefficients in (37) were known, movements of the variables in y_t could be attributed to the different economic shocks. All SVAR based core inflation measures use this feature to decompose measured inflation into its core and non-core component.

Clearly, the structural vector moving average (VMA) representation in (37) is not known and has to be estimated. The true process can be conveniently estimated from the reduced form vector autoregressive model

$$y_t = \mu + D_1 y_{t-1} + D_2 y_{t-2} + \ldots + D_p y_{t-p} + \varepsilon_t, \tag{38}$$

with $\mathrm{E}[\varepsilon_t] = 0$ and $\mathrm{E}[\varepsilon_t \varepsilon_t'] = \Sigma_\varepsilon$ and the coefficient matrices D_i. Note that the reduced form VMA representation, which one obtains by inverting (38) under the assumption that the system (37) is stable,

$$y_t = \nu + \varepsilon_t + C_1 \varepsilon_{t-1} + C_2 \varepsilon_{t-2} + \cdots \tag{39}$$

is not identical to (37). An identification problem arises since the structural shocks e_t and the structural form parameters A_i in (37) are not uniquely determined by the estimate of (38). Indeed, from equations (37) and (39) it can be seen that $\varepsilon_t = A_0 e_t$ and $A_i = C_i A_0$ for $i = 1, 2, \ldots$. Hence, it is the contemporaneous impact matrix A_0 which is undetermined. However, since it is assumed throughout that the underlying structural shocks are orthogonal, the covariance matrix of the reduced form VAR (38) $\Sigma_\varepsilon = A_0 A_0'$ contains some information on the contemporaneous impact matrix. In order to exactly identify the structural parameters in A_0 and consequently the structural

[29] Without loss of generality, we assume that all variables are detrended.

shocks, additional information is required [30]. One possibility is to impose so-called short-run or contemporaneous restrictions on the impact matrix A_0, i.e. to assume that certain shocks have no immediate effect on some variables. Another possibility is to assume that the cumulative effect of a shock on some variables of the system is zero, i.e. that some element of the long-run impact matrix $A(1) = \sum_{i=0}^{\infty} A_i$ equals zero. Assumptions of the latter type are called long-run identifying restrictions. Note, that these assumptions as well as the assumption that the structural shocks are orthogonal are identifying assumptions and cannot be tested.

3.2 Different approaches to identify core inflation

3.2.1 Long-run restrictions

Quah and Vahey Quah and Vahey (1995) assume that movements of inflation are explained by two structural shocks which are distinguished by their effect on output: the first shock may affect the level of output in the long-run, but the second or core shock does not [31]. Therefore, their structural model (see equation (37)) is given by

$$\begin{bmatrix} \Delta \ln Y_t \\ \Delta \pi_t \end{bmatrix} = \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix} + \sum_{j=0}^{\infty} \begin{bmatrix} a_{11,j} & a_{12,j} \\ a_{21,j} & a_{22,j} \end{bmatrix} \begin{bmatrix} e_{1,t-j} \\ e_{2,t-j} \end{bmatrix}, \tag{40}$$

where inflation π_t and output $\ln Y_t$ are I(1) but not cointegrated. The assumption that a core shock is output neutral implies that the cumulative effect of the second shock on output is zero, i.e. $\sum_{j=0}^{\infty} a_{12,j} = 0$. Referring to economic theory they define core inflation as that component of measured inflation which is output neutral in the long run, that is the part corresponding to the effect of the second shock

$$\Delta \pi_t^c = \nu_2 + \sum_{j=0}^{\infty} a_{22,j} e_{2,t-j}. \tag{41}$$

Two remarks are in order. Firstly it should be noted, that in this framework core inflation is only identified up to a constant, i.e. only the change in core inflation is determined by the identification scheme but not its level. Secondly, core inflation is identified by assuming the super-neutrality of money, or more specifically that changing the core inflation rate from, for example, 2 to 50% has no long-run effect on the level of output.

Álvarez and Matea (1999) suggested a slightly different structural model for core inflation. Although they assume as Quah and Vahey that movements of inflation are explained by two structural shocks, they distinguish the shocks according to their long-run effect on inflation itself and not on output. The first or non-core shock in their model has only transitory effects on the level of inflation or is 'inflation neutral' in the long-run, whereas the second shock may influence the inflation rate permanently [32]. Therefore, their structural model implies the restriction that the cumulative effect of the non-core shock on inflation is zero, i.e. $\sum_{j=0}^{\infty} a_{21,j} = 0$. Core inflation is again defined by (41). However, core inflation in this case does not represent the output-neutral part of measured inflation but its permanent component. Note that in contrast to all other identification schemes discussed in this paper, the scheme of Álvarez and Matea does not assume neutrality or even super-neutrality of money in the sense defined above. However, as in Quah and Vahey the scheme only determines the change in core inflation and not its level.

Gartner and Wehinger Gartner and Wehinger (1998) analyse core inflation in selected European countries based on a bivariate and – extending Quah and Vahey's approach – a trivariate

[30] n^2 independent restrictions are required to identify A_0 completely. The maintained assumption that the structural shocks are uncorrelated with unit variance imposes $n(n+1)/2$ independent restrictions. Thus, one needs to provide $n(n-1)/2$ further restrictions.

[31] This identification scheme has also been used by, for example, Fase and Folkertsma (2001) and Jacquinot (1998).

[32] They call the corresponding inflation concept not core but 'permanent' inflation. A similar identification scheme for the decomposition of measured inflation has been used by Claus (1997).

system. The latter includes the change in a short-term interest rate ΔR_t in addition to output growth and inflation. In contrast to Quah and Vahey, Gartner and Wehinger find evidence that inflation is trend-stationary and not a unit root process. Accordingly, both their structural models contain the level of the detrended inflation rate instead of the change of inflation. Since ADF and Perron unit root tests do not reject that output and the interest rate are I(1), Gartner and Wehinger's trivariate structural model is

$$\begin{bmatrix} \Delta \ln Y_t \\ \Delta R_t \\ \pi_t \end{bmatrix} = \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} + \sum_{j=0}^{\infty} \begin{bmatrix} a_{11,j} & a_{12,j} & a_{13,j} \\ a_{21,j} & a_{22,j} & a_{23,j} \\ a_{31,j} & a_{32,j} & a_{33,j} \end{bmatrix} \begin{bmatrix} e_{1,t-j} \\ e_{2,t-j} \\ e_{3,t-j} \end{bmatrix}. \tag{42}$$

Inflation in this model is thus generated by three shocks, a supply shock, a monetary policy shock and a real demand shock. These shocks differ according to Gartner and Wehinger in their long-run effects on the interest rate R_t and output. They assume that the real demand shock has no long-run impact on the output level nor on the interest rate, whereas a monetary policy shock cannot change the long-run output level. Formally, the cumulative effects of these shocks on the relevant variables are zero, or $\sum_{j=0}^{\infty} a_{12,j} = 0$, $\sum_{j=0}^{\infty} a_{13,j} = 0$, and $\sum_{j=0}^{\infty} a_{23,j} = 0$. Core inflation is defined by Gartner and Wehinger as that part of measured inflation which is due to shocks without a permanent effect on output, i.e. monetary policy and real demand shocks

$$\pi_t^c = \nu_3 + \sum_{j=0}^{\infty} a_{32,j} e_{2,t-j} + \sum_{j=0}^{\infty} a_{33,j} e_{3,t-j}. \tag{43}$$

Note that their models do not assume super-neutrality but the much less restrictive neutrality of money. More precisely, the implicit assumption is that a once and for all change of the price level caused by a monetary policy shock has only transitory effects on the output level. Another advantage of Gartner and Wehinger's approach is that core inflation is identified completely, not only the change in core inflation. The main weakness of their trivariate specification is that the non-stationarity of the nominal interest rate when the inflation rate is stationary implies the non-stationarity of the real interest rate. Economically, this is not very plausible (see Galí (1992)).

3.2.2 Long-run and contemporaneous restrictions

Dewachter and Lustig Dewachter and Lustig (1997) also extend Quah and Vahey's model to a trivariate system by adding the short-term interest rate as a monetary policy indicator. Although they confirm the finding of Gartner and Wehinger that the nominal interest rate is I(1), they cannot reject the hypothesis that inflation is non-stationary. To incorporate this finding in their structural model Dewachter and Lustig assume further that the real interest rate is stationary, i.e. that inflation and the nominal interest rate are cointegrated. This relation is taken into account by including directly the real interest rate in their system in addition to output growth and the change in the nominal interest rate

$$\begin{bmatrix} \Delta \ln Y_t \\ R_t - \pi_t \\ \Delta R_t \end{bmatrix} = \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} + \sum_{j=0}^{\infty} \begin{bmatrix} a_{11,j} & a_{12,j} & a_{13,j} \\ a_{21,j} & a_{22,j} & a_{23,j} \\ a_{31,j} & a_{32,j} & a_{33,j} \end{bmatrix} \begin{bmatrix} e_{1,t-j} \\ e_{2,t-j} \\ e_{3,t-j} \end{bmatrix}. \tag{44}$$

Three types of shocks drive the variables in this system: a supply shock, a real demand shock and a monetary policy shock. The real demand shock and monetary policy shock are assumed to be output neutral in the long-run ($\sum_{j=0}^{\infty} a_{12,j} = 0$ and $\sum_{j=0}^{\infty} a_{13,j} = 0$). Moreover, a monetary policy shock is assumed to have no *contemporaneous* effect on output $a_{13,0} = 0$.

As other authors, Dewachter and Lustig define core inflation as that part of measured inflation which is due to the output neutral monetary policy and real demand shock

$$\Delta\pi_t^c = \nu_3 + (a_{32,0} - a_{22,0})e_{2,t} + (a_{33,0} - a_{23,0})e_{3,t} + \sum_{j=1}^{\infty}(a_{32,j} + a_{22,j-1} - a_{22,j})e_{2,t-j}$$
$$+ \sum_{j=1}^{\infty}(a_{33,j} + a_{23,j-1} - a_{23,j})e_{3,t-j}. \tag{45}$$

Note, that Dewachter and Lustig's model assumes the super-neutrality of core inflation and does only identify the change but not the level of core inflation.

3.2.3 Cointegration and long-run restrictions

Blix Blix (1995) extends the Quah and Vahey model in two directions [33]. Firstly, he considers a trivariate system, including the logarithm of output, of the price level and of the money stock. Hence, this model provides a direct link between the money stock as a policy variable and core inflation. However, Blix does not further exploit this link to interpret his results. Secondly, Blix assumes stationarity of the velocity of money, implying a cointegration relationship between output, prices and money. Therefore, the system including the level of (log-)output, (log-)prices and the level of the (log-)money stock is driven by one shock with purely transitory effects, called a price shock, and two common trends, a technology shock and a money shock. The two stochastic trends differ with respect to their effect on output. The money shock is output neutral in the long run, whereas the technology shock may have a permanent effect on output.

The level of core inflation is identified within the following transformed structural model including the stationary variables output growth, inflation and the velocity of money

$$\begin{bmatrix} \Delta\ln(Y_t) \\ \Delta\ln(P_t) \\ (\ln(Y_t) + \ln(P_t) - \ln(M_t)) \end{bmatrix} = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix} + \sum_{j=0}^{\infty} \begin{bmatrix} a_{11,j} & a_{12,j} & a_{13,j} \\ a_{21,j} & a_{22,j} & a_{23,j} \\ a_{31,j} & a_{32,j} & a_{33,j} \end{bmatrix} \begin{bmatrix} e_{1,t-j} \\ e_{2,t-j} \\ e_{3,t-j} \end{bmatrix}. \tag{46}$$

The assumption concerning the long-run effect of a monetary shock on the level of output implies $\sum_{j=0}^{\infty} a_{12,j} = 0$. Since the price shock has only transitory effects on the level of output and prices, its cumulative effect on these variables is zero, i.e. $\sum_{j=0}^{\infty} a_{13,j} = 0$ and $\sum_{j=0}^{\infty} a_{23,j} = 0$. As in nearly every other model discussed here, Blix defines core inflation as driven by the two shocks which are output neutral in the long-run, that is the monetary shock, having a permanent effect on inflation, and a price shock with only a transitory effect:

$$\pi_t^c = \theta_2 + \sum_{j=0}^{\infty} a_{22,j}e_{2,t-j} + \sum_{j=0}^{\infty} a_{23,j}e_{3,t-j}. \tag{47}$$

As most of the other approaches to estimate core inflation presented in this section, Blix implicitly assumes the neutrality of money.[34]

[33] Very similar identification schemes for core inflation have been developed by Roberts (1993) and Fisher, Fackler, and Orden (1995).

[34] Blix (1995), who uses the Warne (1993) approach to estimate the system, imposes and tests another overidentifying restriction that prevents reverse causality, i.e. that output causes money. In our application of Blix's approach to simulated data this overidentifying restriction has been ignored.

4 Assessment of the core inflation measures

This section describes our method to assess the performance of core inflation measures and its results when applied to the measures reviewed in the last section. The first step is to simulate the relevant time series – including core inflation – by our general equilibrium model with its parameters calibrated to European data. These time series are then tested for their order of integration. In empirical applications of the SVAR technique these pre-tests are used to check the necessary conditions for the applicability of a specific identification scheme. If, for example, unit root tests indicate unambiguously that inflation is stationary, one should be careful when applying the model of Quah and Vahey that presupposes a difference-stationary inflation rate. The third step is to estimate the vector autoregressive model. The number of lags included in the VAR were chosen data-dependent using the standard lag selection criteria. Finally, we estimate core inflation using the different identification schemes reviewed in the previous section.

We employ three different methods to evaluate the competing approaches to identify core inflation within the SVAR framework: a comparison of the true and estimated impulse responses, summary statistics evaluating the deviation between estimated and true core inflation as well as the probability of a measurement error of the respective core inflation measure.

The analysis and evaluation of the different identification approaches are based on data generated by our general equilibrium model that is driven by four shocks. However, since one main criticism of the SVAR approach is that the true number of shocks in the economy is generally greater than the number of shocks in the SVAR, we also investigate the performance of core inflation measures when the number of shocks in the data generating model is the same as the number of shocks in the SVAR. For that purpose two shocks are set to zero in the theoretical model and a 2-dimensional SVAR is fitted to the resulting simulated small sample of data due to a monetary and a technology shock. Furthermore, a very large sample is generated to investigate whether performance deficiencies of the SVAR approaches are due to small sample problems.

4.1 Data generation

In order to generate our benchmark sample of 84 observations, we calculate the effects of 284 independent successive draws from the distribution of the four shocks in our monetary general equilibrium model. The first 200 realisations are then discarded, eliminating the influence of the initial state of the economy on the time series. The reason to use a sample of 84 observations for the simulation study is that it matches the length of quarterly time series covering the EMS period 1979:I–1999:IV and that this size lies within the range of samples used in the core inflation literature. In addition a sample of 84 observations has been generated in the same way as above on the basis of the general equilibrium model with only two shocks affecting the economy, where the remaining two shocks, the government expenditure and the money demand shock, are set to zero. For investigating the performance of an SVAR approach to identify core inflation in a very large sample, we also generated a sample with 2400 observations based on the model with two shocks.

4.2 The initial VAR: Unit root tests and lag order choice

To analyse the properties of the data simulated on the basis of the general equilibrium model, Augmented Dickey Fuller (ADF) tests have been carried out to test for the order of integration of the variables. The ADF test has been chosen since it has been used most often in empirical research. The results of these tests are reported in Appendix A. Additionally, we performed the LR cointegration rank tests (Johansen 1995) for the systems of variables considered by the respective core inflation identification schemes. If the results of this latter test indicate a full rank, i.e. that the number of variables is equal to the number of cointegration relations, this would indicate stationarity of all variables in the model (see Appendix B for the results).

For the benchmark sample of 84 observations we find that money and output are I(1), whereas the nominal interest rate is stationary. These findings are exactly in line with the theoretical properties of the simulated data. This contrasts with the finding for the inflation rate: on the basis of the ADF test we conclude that the inflation rate is I(1), although the economic model generates a stationary inflation rate. This latter result can be explained by the low power in small samples of unit root tests in general and the ADF tests in particular [35]. For all two- and three-dimensional SVAR systems Johansen's LR rank test indicates full cointegration rank indicating that the included variables are stationary [36]. Since some of these systems involve the level of the inflation rate, these outcomes contradict the result of the ADF test for inflation. Two other hypotheses relevant for some of the identification schemes, the non-stationarity of the velocity and of the real interest rate have also been tested. Both hypotheses were rejected by the ADF test. Again these results comply with the theoretical properties of the data generating model.

Unit root tests are also carried out for a small (84 observations) and very large (2400 observations) sample of data generated by the monetary equilibrium model driven only by two disturbances, a technology and a money supply shock. The results of the tests for the small sample broadly replicate the results obtained on the benchmark sample, although the non-stationarity of inflation is not rejected by either the ADF nor the LR rank test. Thus both tests fail to recover the true property of the inflation process [37]. On the basis of the very large sample the tests recover for all variables the true order of integration although the non-stationarity of money is only rejected on a 5% but not a 1% significance level.

Therefore, with a few exceptions the pre-test results do not reject the assumptions underlying the identification schemes outright. Neither the hypotheses that inflation is stationary as required by some schemes nor that it is non-stationary as required by other schemes is unambiguously rejected on the benchmark sample. Only the finding of a stationary nominal interest rate casts doubt on the applicability of the trivariate identification schemes of Gartner and Wehinger and Dewachter and Lustig. The finding that the real interest rate is stationary is another indication that one should be careful when applying the trivariate system of Gartner and Wehinger to these samples. However, the ambiguous results obtained by different tests, as often encountered in empirical work, and the lack of power of unit root tests imply that a decision whether the assumptions underlying an identification scheme are satisfied or not, cannot be based on purely statistical evidence. This conclusion remains valid if one considers other specification tests as well. For each VAR-model we checked the residuals on heteroskedasticity, non-normality and autocorrelation and found no clear indications of a misspecification. In view of this fact and keeping the concerns with regard to the trivariate Gartner and Wehinger scheme in mind we proceed to investigate the core inflation estimates obtained by the different schemes [38].

4.3 Assessment

4.3.1 Comparing the different identification approaches

First, we evaluate the performance of the core inflation estimators outlined in Section 3.2 by comparing the respective empirical impulse responses of inflation to a money and a productivity shock with the true impulse responses generated by our economic model. In order to make the impulse response functions comparable, we trace the effect of a money and productivity shock that raise the output level by 1 percent respectively the inflation rate by 1 percentage point on impact. If the estimated response to the productivity shock closely matches the true response, the identification scheme would qualify as a possible estimator of the core inflation in the broad sense. Indeed, recall that core inflation in the broad sense equals measured inflation excluding the effects of productivity shocks (see Section 2.4) [39]. Obviously, if the estimated response recovers the true

[35] see e.g. Schwert (1989)

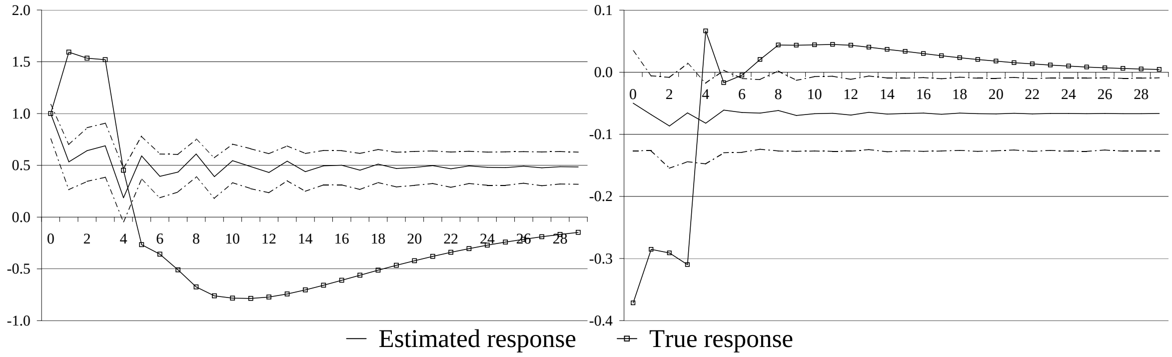
[36] Johansen's LR test has been found to exhibit power advantages over competing rank tests in small sample simulation studies (see e.g. Hubrich, Lütkepohl, and Saikkonen (2001)). In general, however, standard rank tests do not perform very well, if the cointegration rank is greater than one (see Toda(1994, 1995)).

[37] Appendix A presents detailed test results.

[38] The results concerning the lag-order of the different SVAR models are summarised in Appendix B. The remaining test results are available on request.

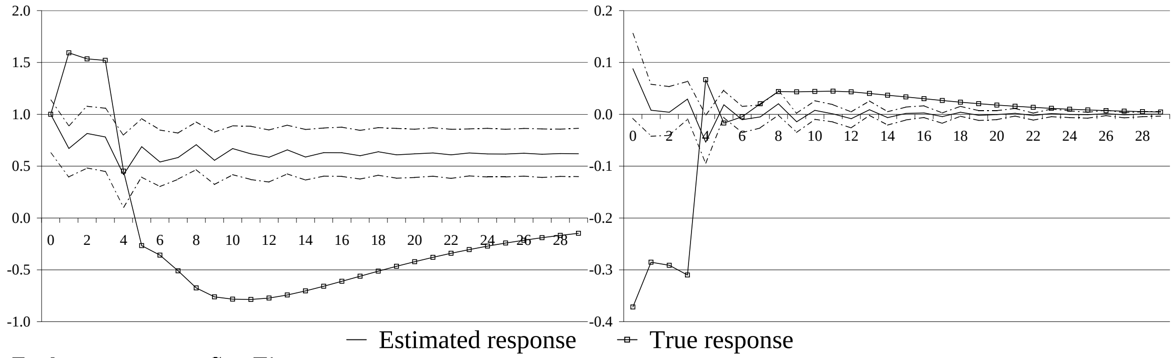
[39] All other impulse responses are available from the authors upon request.

Figure 7: True and estimated impulse response of inflation: Quah and Vahey's scheme



Explanatory note: The vertical axis measures percent respectively percentage point deviations from the pre-shock balanced growth path. The figures show the response of headline inflation to a money supply shock (left figure) and to a productivity shock (right figure) as well as the bootstrapped 95% confidence bands.

Figure 8: True and estimated impulse response of inflation: Alvarez and Matea's scheme



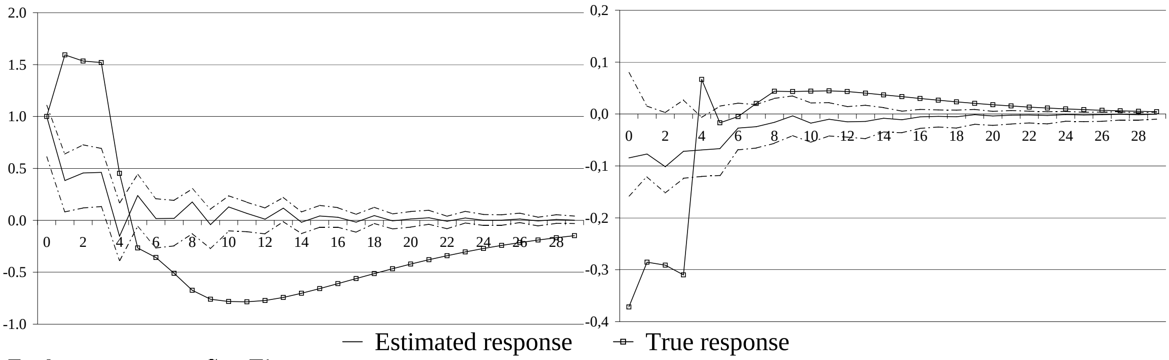
Explanatory note: See Figure 7

response to a monetary shock, the scheme qualifies as an estimator of core inflation in the narrow sense. Besides the point estimate of the impulse responses, we will also show their bootstrapped 95% confidence intervals based on 1000 replications (for details on the setup, see Runkle (1987)).

The results are presented in Figures 7 to 12. Examining the impulse response functions to a productivity shock, we find that the approach of Quah and Vahey, Álvarez and Matea and both approaches of Gartner and Wehinger fail to capture the sign and size of the true responses. Most of the time the true impulse response is outside the confidence bounds. The fact that for Álvarez and Matea's and Gartner and Wehinger's scheme the estimated response converges to the true response is not surprising, since inflation in the data generating model is stationary and the first scheme imposes that productivity shocks have only transitory effects on inflation, whereas the other assumes a stationary inflation rate. The models of Blix and Dewachter and Lustig perform considerably better. At least the true response is covered by the confidence bands and the size and sign of the initial effect of the shock on inflation is recovered. Even the general shape of the impulse response function is approximated. Surprisingly, the long-run response in the Dewachter and Lustig model returns to zero, although the model does not impose stationarity of the inflation rate. The qualitative results for the impulse responses to a monetary shock are very similar to those regarding the productivity shock. However, the general impression is that the schemes have greater difficulties to recover the effects of a monetary shock than of a productivity shock.

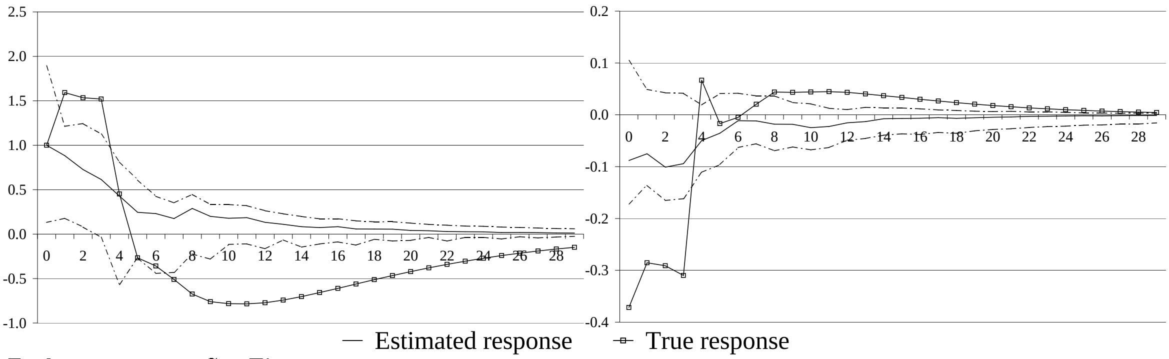
As a second performance test, we investigate the measurement errors, i.e. the difference be-

Figure 9: True and estimated impulse response of inflation: Gartner and Wehinger's scheme in a 2-dimensional system



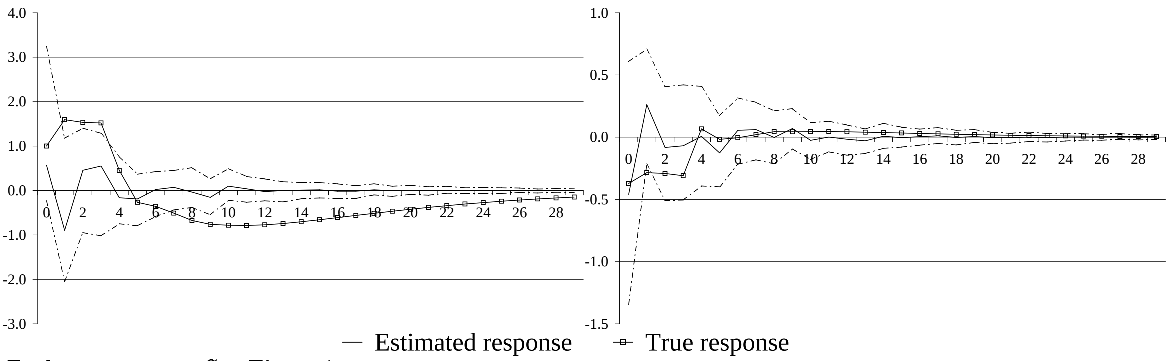
Explanatory note: See Figure 7

Figure 10: True and estimated impulse response of inflation: Gartner and Wehinger's scheme in a 3-dimensional system



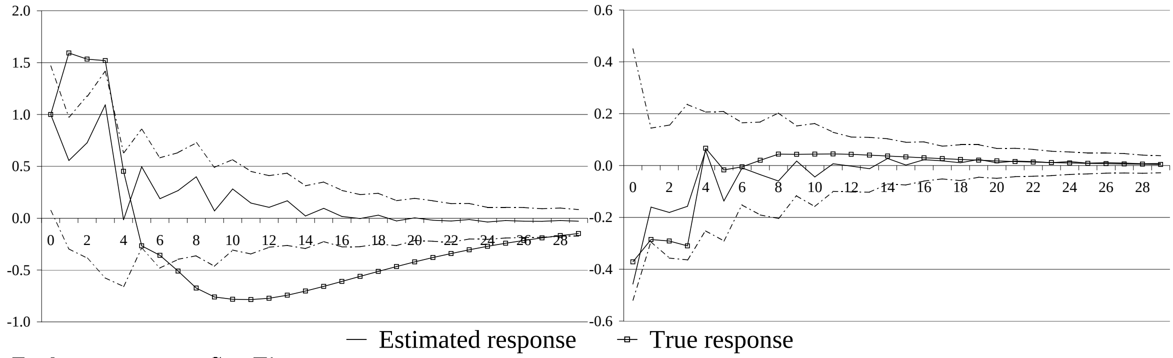
Explanatory note: See Figure 7

Figure 11: True and estimated impulse response of inflation: Dewachter and Lustig's scheme



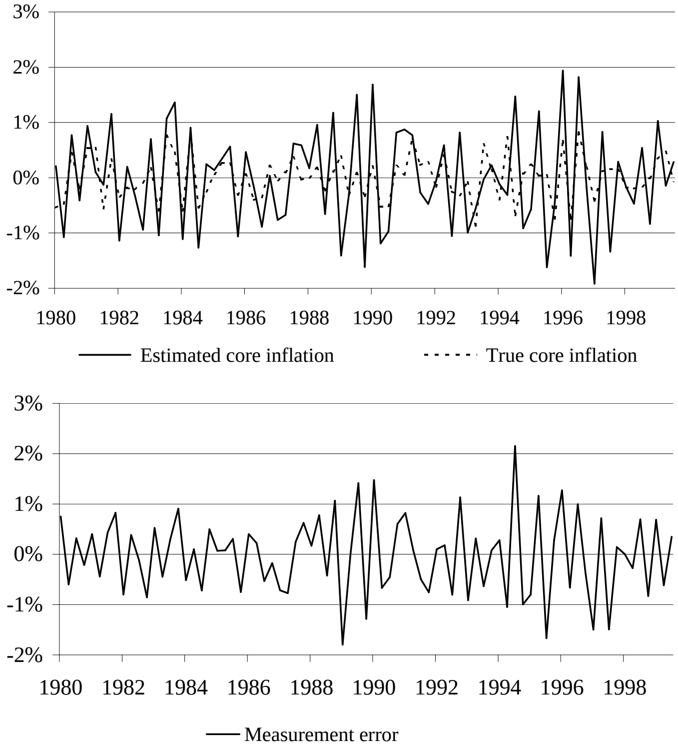
Explanatory note: See Figure 7

Figure 12: True and estimated impulse response of inflation: Blix's scheme



Explanatory note: See Figure 7

Figure 13: Change of true and estimated core inflation – broad concept: Quah and Vahey's scheme

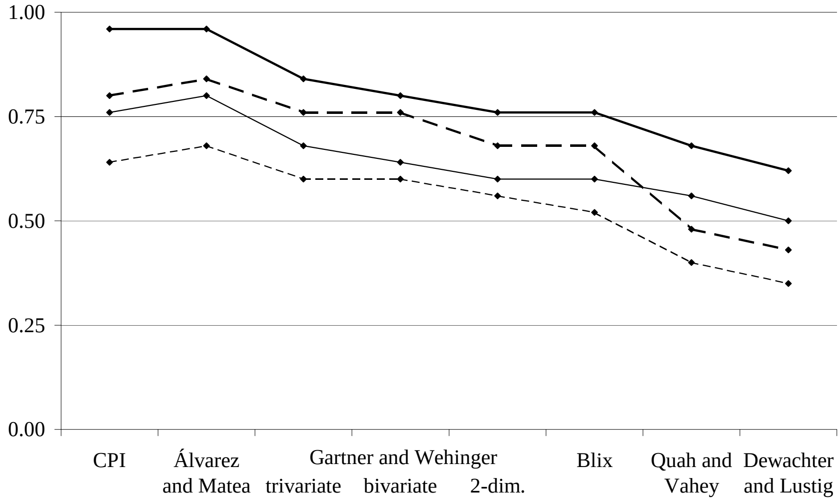


Explanatory note: The units on the vertical axis are percentage points. Inflation is measured in percent on an annual basis.

tween the true and estimated core inflation for each of the methods. The measurement error has been calculated for the level as well as the change of core inflation. For those identification schemes which identify only the change but not the level of core inflation, we constructed the level assuming that the sample mean of *headline* inflation equals the sample mean of core inflation. Figure 13 illustrates the measurement errors for the Quah and Vahey approach.

Not surprisingly, this figure shows that the distribution of measurement errors is stationary. Therefore, one can assess the performance of different core inflation measures by characteristics of the measurement error distribution, such as the mean absolute deviation, the root mean square error and the probabilities of measurement errors exceeding a certain size.

Figure 14: Distance measures for broad core inflation concept



Explanatory note: Thick lines show the mean absolute deviation of estimated from true core inflation, whereas thin lines show the root mean squared error. The deviations are calculated for annualised inflation rates based on 1000 replications. Solid lines show the distance measures for level comparisons, whereas the dashed lines show the distance when comparing changes of broad core inflation.

The average mean absolute deviation as well as the the root mean squared error are calculated in a simulation experiment for each of 1000 generated samples of 84 observations and then averaged across all samples [40]. Figure 14 presents results for the broad core inflation concept. Comparing the measurement errors for the narrow concept yields qualitatively the same results, although the size of the measurement errors is even larger [41]. Besides the statistics for the core inflation measures, the figure shows the mean absolute deviation and root mean squared error for the distance between headline or CPI inflation and core inflation for comparison. Such a comparison shows, whether and by how much the sophisticated SVAR methods improve on this naive measure of 'core inflation' [42]. Judging by the absolute measurement errors and the root mean square error, the method of Dewachter and Lustig outperforms the other approaches. Note, however, that even with this method one over- or underestimates on average the *change* of broad core inflation by more than 0.35 percentage points, and the *level* of broad core inflation by more than 0.5 percentage points. According to these criteria the method of Álvarez and Matea performs worse. On average their core inflation estimate is even worse than the naive approach which estimates core by headline inflation.

Finally, based on the same 1000 samples used to estimate the expected absolute measurement errors we also constructed the empirical probability distribution of the measurement errors. The probabilities of measurement errors exceeding certain values are depicted in Figure 15 for the level and in Figure 16 for the change in broad core inflation [43].

The graphs show that all identification methods perform quite similar for very low and relatively high measurement errors. However, there appear to be remarkable differences in the range of measurement errors that are of interest to monetary policy, that is between 0.5% and 1.0%. The probability of a measurement error exceeding 1% when estimating the level of broad core inflation

[40] The lag order of the underlying vector autoregressive model is kept constant over all generated samples. For each sample we generated 284 observations, discarding the first 200 in order to eliminate any influence of the initial state of the economy.

[41] Details are covered in Appendix C.

[42] Note, that in this model all estimators of core inflation based on purely cross sectional information, such as the trimmed mean or the median, perform exactly as the CPI itself, since the cross sectional distribution of consumer prices is degenerate.

[43] Detailed results, also for the narrow concept of core inflation, can be found in Appendix C.

Figure 15: Probability of measurement error: Core inflation

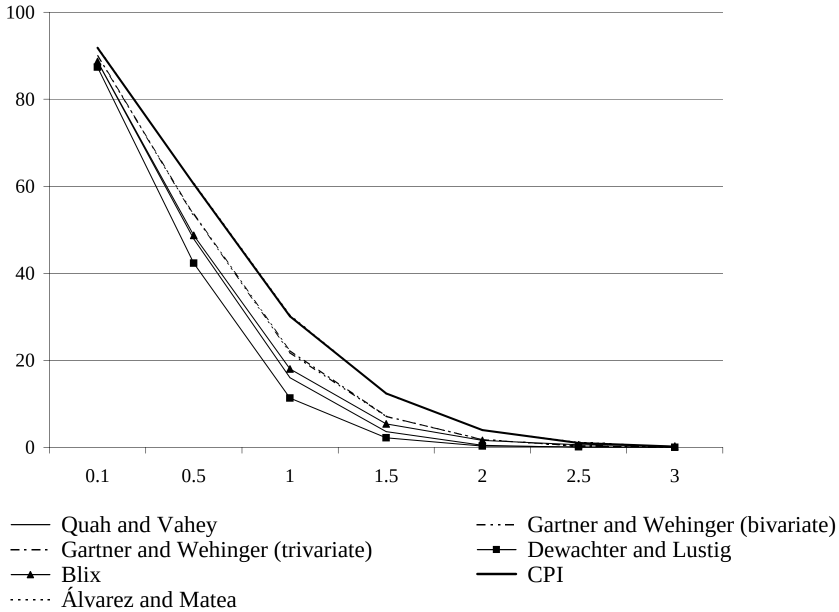
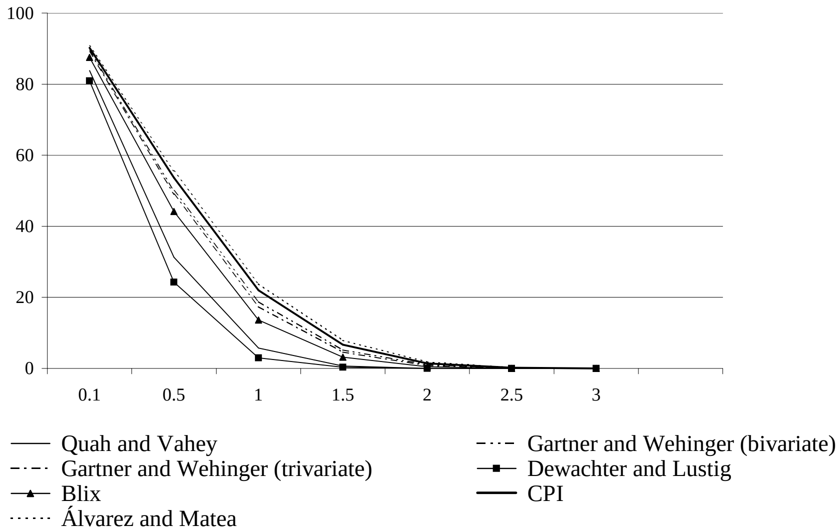


Figure 16: Probability of measurement error: Change of core inflation



varies with the identification scheme between 11.3% and 30.5% and for a measurement error exceeding 0.5% between 42.3% and 60.6%. Figure 15 and Figure 16 show that Dewachter and Lustig exhibits the lowest probabilities of measurement error, followed by Quah and Vahey and Blix. Worst of all is the scheme of Álvarez and Matea which does not even improve on the CPI. This ranking holds, whether one uses the level or the change of core inflation as the estimation target.

Overall and according to all criteria the Dewachter and Lustig scheme seems to outperform all other schemes, whereas the orginal Quah and Vahey method and the Blix approach perform second best.

The reason why some of the identification schemes perform better than others is not clear.

Surprisingly the assumptions regarding the order of integration of the variables seems to play a minor role. The methods of Dewachter and Lustig and Quah and Vahey assume both non-stationarity of inflation and the former method also assumes the non-stationarity of the nominal interest rate, although both series are stationary in our simulation. Nevertheless, these methods outperform the bivariate model of Gartner and Wehinger that is based on the correct time series properties.

Furthermore, an implicit assumption of most approaches is that core inflation is output neutral (Gartner and Wehinger and Blix) or even super-neutral (Quah and Vahey and Dewachter and Lustig). Both assumptions are not satisfied by the data generating model. Nevertheless, two of the models imposing even super-neutrality (Dewachter and Lustig and Quah and Vahey) outperform the models which only require neutrality. The model which does neither presuppose neutrality nor superneutrality, namely the model of Álvarez and Matea, on the other hand performs worst of all. One reason for the poor performance of the last model might be the assumption that the only the shock driving core inflation has a permanent effect on inflation. However, in the data-generating model inflation is stationary and no shock affects inflation permanently. Therefore, the data does not permit to distinguish the shocks according to this criterion.

Our results also indicate that the precision of core inflation estimates does not necessarily improve if it is based on a trivariate instead of a bivariate system, when the actual data are generated by four shocks. For example, both models of Gartner and Wehinger perform nearly identically.

Finally, note that the Dewachter and Lustig model entails a third assumption which is not valid in the true model, namely that a monetary policy shock has no immediate effect on output. Thus, guided by the number of assumptions that are not supported by the data-generating model, one would expect the Dewachter and Lustig model to perform much worse than it actually does.

Apart from the fact that some measures of core inflation seem to be better than others, we find that even the best method is very imprecise. When using the Dewachter and Lustig method to measure the change of broad core inflation in 25% of all cases the true change of core inflation is over- or underestimated by at least 0.5 percentage points. Furthermore, in order to be reasonably certain that the core inflation rate has changed at all, the estimated change of the core inflation rate must be close to a full percentage point [44]. Recalling that the core inflation measures have been estimated on a time series representing a period of 20 years without seasonality or structural breaks, the uncertainty in actual applications is likely to be even larger. The size of the uncertainty with regard to the core inflation suggests that the measures reviewed in this paper are not useful for monetary policy purposes.

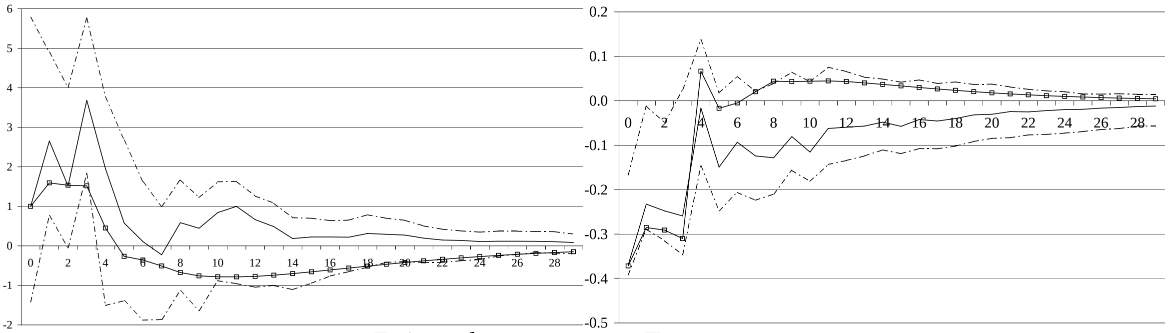
4.3.2 Simulations for different samples: True model driven by two shocks only

One main criticism of SVAR models is that they only allow for a number of shocks equal to the number of variables in the estimated system, but that the true number of shocks affecting the economy will actually be much larger. To evaluate the effect of deviations of the number of shocks in the estimated system from the true number of shocks, we have carried out an experiment based on data generated by our general equilibrium model when it is only driven by two shocks, a productivity and a money supply shock. For this experiment we choose the 2-dimensional Gartner and Wehinger method because it is largely based on valid assumptions regarding the time series properties and merely presupposes that core inflation is neutral but not superneutral. The impulse responses of inflation are depicted in Figure 17.

The response of inflation to a productivity shock for the data generated by an economic model driven by two shocks is better captured by the 2-dimensional Gartner and Wehinger method than for the data generated by the model driven by four shocks. Furthermore, the true response of inflation is covered by the confidence intervals of the empirical response in case of the truly 2-dimensional system. It appears that also the mean absolute deviation, the root mean square error

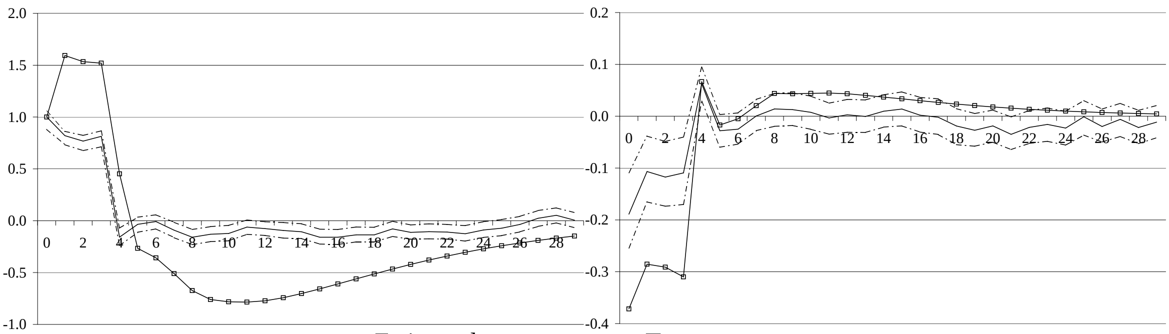
[44] More precisely, in order to reject the hypothesis at a 5% level that the core inflation rate remained constant during the last quarter, the estimated core inflation must change by roughly a full percentage point

Figure 17: True and estimated impulse response of inflation: Gartner and Wehinger's scheme in a truly 2-dimensional system



Explanatory notes: See Figure 7

Figure 18: True and estimated impulse response of inflation: Gartner and Wehinger's scheme in a truly 2-dimensional system (large sample)



Explanatory notes: See Figure 7

and the probability of measurement error improve slightly if the true number of shocks impinging on the economy equals the number of shocks in the SVAR model (cf. Appendix C).

A final experiment has been carried out to assess the sensitivity of the performance of a core inflation measure to the sample size. We reestimated the Gartner and Wehinger model on a very large sample of 2400 observations generated by the model driven by two shocks. The estimated impulse response of inflation to a productivity shock captures the true response better in terms of sign and size than in the small sample (Figure 18) after the fourth period. For the first periods the true response is not well replicated on the basis of this identification method even in case of a very large sample. The mean absolute deviation between estimated and true level of core inflation on this very large sample is 0.68 percentage points and the root mean squared error 0.85. For more than 46% of the time, the estimate of the level of core inflation deviates by at least 0.5 percentage point from the actual core inflation. Hence, even when substantially more information on the data generating proces becomes available, the core inflation estimates do not become much more precise. These results raise substantial doubts about the usefulness of at least the bivariate SVAR approaches to the measurement of core inflation.

5 Conclusions

In this paper we have investigated the performance of SVAR-based measures of core inflation. Since core inflation is not empirically observable, we have developed a monetary general equilibrium model in which we can define core inflation and observe the corresponding series in stochastic simulations. Furthermore, this core inflation concept corresponds to that used in the SVAR literature. Different identification schemes for core inflation that have been proposed in this literature, have been applied to time series generated by our model. We have analysed whether the schemes succeed in recovering the true core inflation series. It turned out that in this setting the core inflation estimates are very imprecise and therefore unlikely to be useful for monetary policy.

This result illustrates the problems of using the SVAR approach in the context of core inflation measurement. Faust and Leeper (1997) and Cooley and Dwyer (1998) have pointed out that applications of SVAR-models rely on long-run identifying restrictions or on time series properties which are either impossible or inherently difficult to test. Our study shows quantitatively how existing SVAR-based core inflation measures are affected by departures from these assumptions.

In our experiments, we show that the standard battery of tests does not conclusively reject any of the testable assumptions underlying the different SVAR-based core inflation measures. Based on purely statistical evidence it seems therefore impossible to decide whether any of the identification schemes is not applicable. Hence, although each of the considered identification schemes entails at least one assumption, which is not satisfied by the data-generating model, these departures are likely to remain unnoticed when estimating core inflation from real data.

The actual size of the measurement error clearly depends on the data generating model. The data in this study have been generated by a monetary equilibrium model that has been designed to meet two objectives. On the one hand it should reflect the properties required by the identification schemes for core inflation as closely as possible. On the other hand it should provide a theoretically consistent interpretation of European time series. In this sense the model and the results of this study are empirically relevant and fair to the SVAR-based core inflation methods.

Nevertheless, a SVAR-based core inflation measure may perform better than our results suggest, if its underlying assumptions exactly match the properties of the data-generating process. Especially, the fact that our model features non-neutrality of money, whereas nearly all of the considered SVAR-based core inflation measures assume neutrality, may have a significant effect on the size of the measurement error. Therefore, future research should investigate the robustness of our findings further. From a monetary policy perspective it is even more interesting to develop identification schemes with an acceptable performance for a broad range of models.

A Unit root and cointegration tests for simulated time series

Table 2: Augmented Dickey-Fuller test for time series generated by the model with four shocks

Variable	Deterministic terms	k	t-statistic	Critical value (5%)
$\ln Y$	c, t	0	-3.15	-3.461
$\ln M$	c, t	4	-3.00	-3.463
$\ln P$	c, t	5	-2.49	-3.463
R	c	5	-4.77^{**}	-2.896
$\Delta \ln P$	c	4	-2.45	-2.896
$\Delta \ln Y$	c	2	-6.57^{**}	-2.896
$\Delta \ln M$	c	0	-11.55^{**}	-2.896
$\Delta\Delta \ln P$	c	3	-6.57^{**}	-2.896
$R - \Delta \ln P$	c	5	-4.99^{**}	-2.896
$(\ln Y - \ln P - \ln M)$	c, t	2	-3.35^{*}	-2.896

Explanatory Notes: k is the number of lagged differences included in the DF/ADF test (according to the highest significant number of lags with a maximum of 5 lags); ** and * indicate significance at a 1% and 5% level, respectively. Critical values are from MacKinnon (1991). c denotes a constant and t a linear trend. The sample size is 84 observations.

Table 3: Augmented Dickey-Fuller Test for time series generated by the model with two shocks

Variable	Deterministic terms	k	t-statistic	Critical value (5%)
$\ln Y$	c, t	5	-2.29	-3.463
$\ln M$	c, t	4	-2.65	-3.463
R	c	0	-9.32^{**}	-2.895
$\Delta \ln P$	c	4	-1.62	-2.896
$\Delta \ln Y$	c	4	-3.85^{**}	-2.896
$\Delta \ln M$	c	3	-2.28	-2.896
$\Delta\Delta \ln P$	c	3	-7.44^{**}	-2.896
$\Delta\Delta \ln M$	c	3	-8.29^{**}	-2.896

Explanatory Notes: See Table 2.

Table 4: Augmented Dickey-Fuller test for time series generated by the model with two shocks

Variable	Deterministic terms	k	t-statistic	Critical value (5%)
$\ln Y$	c, t	13	-3.33	-3.414
$\ln M$	c, t	6	-3.76^{*}	-3.414
R	c	2	-23.81^{**}	-2.863
$\Delta \ln P$	c	4	-16.82^{**}	-2.863

Explanatory Notes: See Table 2, the sample size, however, is 2400 observations.

B Lag order test results

Data generating model	Model with 4 shocks					Model with 2 shocks	
Identification approach	Quah & Vahey (1995)[a]	Gartner & Wehinger (1998) bivariate	Gartner & Wehinger (1998) trivariate	Dewachter & Lustig (1997)	Blix (1995)	Gartner & Wehinger (1998) bivariate	
Variables	$\Delta \ln Y$, $\Delta\Delta \ln P$	$\Delta \ln Y$, $\Delta \ln P$	$\Delta \ln Y$, ΔR, $\Delta \ln P$	$\Delta \ln Y$, $(R - \Delta \ln P)$, ΔR	$\Delta \ln Y$, $\Delta \ln P$, $(\ln Y + \ln P - \ln M)$	$\Delta \ln Y$, $\Delta \ln P$	$\Delta \ln Y$, $\Delta \ln P$
No. of observations	84	84	84	84	84	84	2400
Lag order	4	5	4	4	5	5	38
Cointegration rank[b]	2	2	3	3	3	1	2
Cf. Section	3.2.1	3.2.1	3.2.1	3.2.2	3.2.3	3.2.1	3.2.1

Explanatory note: [a] Álvarez and Matea (1999) use the same model specification. [b] the cointegration rank was tested by the LR rank test (trace statistic), including an unrestricted constant (see Johansen (1995, Tab.15.3)). Lag orders were chosen according to the Akaike criterion as well as an F-test (5% significance level) and tests of autocorrelation.

C Probability of measurement error

Table 5: Characteristics of measurement error distribution

Core inflation concept			Measurement error [a]							MAD	RMSE
			0.10	0.50	1.00	1.50	2.00	2.50	3.00		
CPI											
	level	narrow	92.0	62.0	32.6	14.1	5.0	1.4	0.3	0.80	1.00
		broad	91.8	60.5	30.1	12.4	4.0	1.0	0.2	0.76	0.96
	change	narrow	91.4	58.5	27.4	10.3	3.0	0.6	0.1	0.72	0.92
		broad	90.2	53.7	22.0	6.7	1.4	0.2	0.0	0.64	0.80
Quah and Vahey (1995)											
	level	narrow	90.2	54.0	22.3	6.8	1.5	0.2	0.0	0.64	0.80
		broad	88.7	47.9	16.0	3.6	0.5	0.0	0.0	0.56	0.68
	change	narrow	88.7	47.9	16.2	4.0	0.7	0.1	0.0	0.56	0.72
		broad	83.8	31.3	5.7	0.7	0.0	0.0	0.0	0.40	0.48
Álvarez and Matea (1999)											
	level	narrow	91.8	61.5	31.7	13.2	4.4	1.2	0.2	0.80	1.00
		broad	91.8	60.6	30.5	12.3	4.0	1.1	0.2	0.80	0.96
	change	narrow	90.6	55.7	24.2	8.0	2.0	0.3	0.0	0.68	0.84
		broad	90.7	55.5	23.8	7.9	1.8	0.3	0.0	0.68	0.84
Gartner and Wehinger (1998)											
2-dimensional model											
	level	narrow	90.9	56.6	25.3	8.9	2.4	0.5	0.0	0.68	0.88
		broad	89.8	53.3	21.8	7.1	1.8	0.3	0.0	0.64	0.80
	change	narrow	90.4	54.8	23.0	7.3	1.8	0.3	0.0	0.68	0.84
		broad	89.4	50.0	18.8	5.2	1.1	0.1	0.0	0.60	0.76
2-dimensional model with 2 shocks [b]											
	level		89.03	49.46	18.36	5.34	1.20	0.20	0.03	0.60	0.76
	change		87.48	43.90	13.52	3.11	0.53	0.06	0.01	0.56	0.68
3-dimensional model											
	level	narrow	90.9	56.7	25.8	9.3	2.5	0.5	0.1	0.72	0.88
		broad	89.9	53.5	22.3	7.2	1.8	0.3	0.0	0.68	0.84
	change	narrow	90.2	54.3	22.8	7.3	1.8	0.3	0.0	0.68	0.84
		broad	89.0	49.0	17.4	4.6	0.8	0.1	0.0	0.60	0.76
Dewachter and Lustig (1997)											
	level	narrow	88.4	47.1	15.6	3.7	0.7	0.1	0.0	0.56	0.69
		broad	87.4	42.3	11.3	2.2	0.3	0.1	0.0	0.50	0.62
	change	narrow	85.8	38.6	10.2	2.0	0.3	0.0	0.0	0.48	0.59
		broad	80.9	24.3	3.0	0.3	0.0	0.0	0.0	0.35	0.43
Blix (1995)											
	level	narrow	90.0	53.2	21.8	7.1	2.1	0.7	0.3	0.68	0.80
		broad	88.7	48.7	18.0	5.4	1.6	0.6	0.3	0.60	0.76
	change	narrow	89.4	51.2	19.8	5.8	1.2	0.2	0.0	0.60	0.76
		broad	87.5	44.2	13.6	3.2	0.5	0.0	0.0	0.52	0.68

Explanatory notes: The table shows the probabilities in percent of a measurement error exceeding the values given in the top row as well as the mean absolute deviation and the root mean square error of the measurement error.

[a] absolute deviation of estimated from true (change of) annualised core inflation in percentage points.

[b] since the model contains only two shocks, the measurement errors with respect to the broad and narrow core inflation concept are identical.

Level and *change* indicate that the measurement error is calculated by comparing the levels respectively the change of estimated and true core inflation. *Broad* and *narrow* indicate that the measurement error is calculated by comparing estimated core inflation with the narrow and broad concept for the true core inflation, respectively.

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