Instability and Nonlinearity in the Euro-Area Phillips Curve*

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This paper provides a comprehensive analysis of the functional form of the euro-area Phillips curve over the past three decades. In particular, compared with previous literature, we analyze the stability of the relationship in detail, especially as regards the possibility of a time-varying mean of inflation. Moreover, we conduct a sensitivity analysis across different measures of economic slack. Our main findings are two. First, there is strong evidence of time variation in the mean and slope of the Phillips curve occurring in the early to mid-1980s, but not in inflation persistence once the mean shift is allowed for. As a result of the structural change, the Phillips curve became flatter around a lower mean of inflation. Second, we find no significant evidence of nonlinearity—in particular, in relation to the output gap.

JEL Codes: E52, E58.

1. Introduction

The dynamics of inflation have changed substantially in many, if not all, advanced economies over the past four decades. For example, the average level of inflation has been subject to dramatic shifts over time (Cecchetti et al. 2007). Moreover, in recent years a number

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of studies have documented important changes also in the degree of inflation persistence (Cecchetti and Debelle 2006). In addition, the volatility of inflation has changed during the past three decades, with a large decline observed since the mid-1980s to early 1990s, depending on the country (van Dijk, Osborn, and Sensier 2002). As a result of these changes, modeling and forecasting inflation dynamics has become an arduous task. The complexity in modeling inflation dynamics relates not only to the various types of above-mentioned structural changes in the statistical properties of inflation, but also to the fact that to some extent these changes are related to one another in various ways. For example, a key result of the Eurosystem Inflation Persistence Network (IPN) is that estimates of the euro-area inflation persistence tend to be rather high unless shifts in the mean of inflation (for which there is clear statistical evidence) are allowed for (Altissimo, Ehrmann, and Smets 2006). Hence, it is important to analyze these changes jointly. At the same time, modeling inflation is complicated also by the fact that in addition to its (potential) instability, different forms of nonlinearity can be relevant. For example, some studies have pointed out the possibility that the response of inflation to changes in economic activity may be asymmetric, with demand increases having a stronger impact on prices than demand decreases (Laxton, Rose, and Tambakis 1999).

While much effort has been devoted to analyzing the inflation process for the U.S. economy, much less research has been undertaken for the euro area. As a result, it is still uncertain how to best model euro-area inflation. This gap is rather unfortunate, given the mandate of the European Central Bank (ECB), whose primary objective is to ensure price stability at the euro-area aggregate level. Some efforts have been directed in recent years to analyzing euro-area inflation dynamics, especially in the context of the so-called New Keynesian Phillips curve (NKPC) framework, with mixed results, as discussed in more detail below. As regards the traditional Phillips-curve approach, relatively little has been done to assess its usefulness for the euro area. The few existing studies, such as Aguiar and Martins (2005), Dolado, Maria-Dolores, and Naveira (2005), Rudd and Whelan (2005), and Baghli, Cahn, and Fraisse (2007), include only a limited analysis of possible instability and nonlinearities. As a result, several questions remained unanswered regarding the most appropriate way to model inflation dynamics in the euro area.

Although an assessment of the functional form of the Phillips curve is fraught with empirical difficulties, the policy implications of this question are extremely important. Let us consider, for example, the situation of a policymaker who is uncertain as to whether the Phillips curve has a linear or, alternatively, a piecewise linear form as in Filardo (1998) and Barnes and Olivei (2003). In the first case, the policymaker is confronted with a trade-off between stimulating demand and creating inflation, while in the latter case there is the possibility of pushing demand at least up to a certain limit without causing a significant increase in inflation. Therefore, a careful empirical modeling of the functional form of the Phillips curve is of paramount importance.

Against this background, the aim of the present paper is to provide a comprehensive analysis of euro-area inflation dynamics, focusing on the functional form of the Phillips curve. We explicitly and carefully address the stability of the relationship between inflation and economic activity, accounting for the possibility of structural change in the mean, persistence, and volatility of inflation, as well as in the slope of the curve. In addition, we examine the appropriate functional form of the curve by means of the methodology of smooth transition regression (STR) models, which allows for both convex and concave shapes of the curve. Although our main analysis is conducted on quarterly inflation based on the GDP deflator, we also analyze the price index that is preferred by the ECB, the Harmonised Index of Consumer Prices (HICP). For the latter indicator, we also analyze the possible presence of nonlinearity in the effect of additive price shocks stemming from oil and exchange rate developments. Finally, we conduct a thorough sensitivity analysis across different possible measures of economic slack.

The paper is structured as follows. In section 2 we present a review of the literature. The data are described in section 3. Section 4 presents the results for a linear Phillips-curve specification for the euro-area GDP deflator inflation. In section 5 we assess the stability and linearity of this curve. In section 6 we model the HICP inflation rate indirectly, by modeling the spread between the HICP and the GDP deflator. Finally, section 7 concludes.

2. Literature Review and Modeling Issues

2.1 Inflation Modeling

The focus of this paper is on the general class of traditional backward-looking Phillips curves. This choice is suggested by a number of considerations. First, survey-based inflation-forecast data for the euro area starting from the 1970s are not available. Second, alternative estimation approaches based on the generalized method of moments which abstract from inflation forecasts are surrounded by a number of controversial econometric aspects, limiting the reliability of NKPC estimates. Third, recent studies—in particular, by Rudd and Whelan (2007)—cast doubt on the ability of the NKPC (including its hybrid form, i.e., with added lags of inflation) to provide a useful empirical characterization of the inflation process and present evidence in support of the traditional Phillips curve for both the United States and the euro area. While we do not take a stand on this debate, we note that it makes the estimation of a backward-looking Phillips curve at least not a clearly suboptimal choice. Finally, it should be emphasized that we conduct a thorough stability analysis in this paper, and in so doing we cater for the possible impact of the Lucas critique, which is often mentioned as the main shortcoming of backward-looking macroeconomic models.

Although traditional Phillips-curve relationships are building blocks of a number of macroeconomic models for the euro area, including the area-wide model (AWM), relatively few studies have provided a detailed modeling assessment of this key relationship. A number of studies providing estimates of the traditional Phillips curve in the euro area have been published in recent years.[1] However, no consensus seems to prevail as regards the most appropriate specification of the relationship. For example, Dolado, Maria-Dolores, and Naveira (2005) and Baghli, Cahn, and Fraisse (2007) provide some evidence for the relevance of nonlinearity in the euro-area Phillips curve, while Aguiar and Martins (2005) suggest that the empirical evidence against the linear specification is weak. Rudd and Whelan (2005) do not consider nonlinear specifications but

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[1] Other papers include a euro-area Phillips curve as a component of a broader, multivariate framework, such as Rünstler (2002), Fabiani and Mestre (2004), Fagan, Henry, and Mestre (2005), and Proietti, Musso, and Westermann (2007).

conduct an extensive stability analysis of the linear Phillips relationship and find little evidence of instability. The main reasons for these contrasting results can be related to different sample periods and different specifications, but data issues also may play a role. In particular, the measures used for capturing economic slack tend to differ and range from output-gap estimates based on simple filters (Dolado, Maria-Dolores, and Naveira 2005; Rudd and Whelan 2005) to estimates based on more structural unobserved-components models (Aguiar and Martins 2005; Baghli, Cahn, and Fraisse 2007). Sensitivity analysis to assess how results vary using alternative slack estimates is typically very limited or even missing in these studies. Given the uncertainty surrounding these estimates, this could turn out to be a significant limitation.

2.2 Instability

As discussed in the Introduction, various forms of instability in inflation dynamics have been documented for most advanced economies, including structural changes in the mean, persistence, and volatility of inflation. Focusing on the euro area, Corvoisier and Mojon (2005) find three breaks for the euro-area inflation rate: in 1972 and 1985 with reference to the CPI/HICP, and in 1993 using the GDP deflator. Angeloni, Aucremanne, and Ciccarelli (2006) present evidence of a permanent decline in the persistence of inflation in the euro area after the mid-1990s, even after allowing for breaks in the mean of inflation.

While it is important to take into account these instabilities, it is questionable whether the most appropriate way to detect and model them is via structural-break tests assuming *abrupt* changes. In particular, consistent with the idea that most regime changes tend to be gradual, several studies (especially on the United States) adopt modeling approaches based on smoothly time-varying coefficients, rather than assuming abrupt changes (see, for example, Stock and Watson 2007). We follow this suggestion here by adopting the smooth transition regression framework.

Several papers have found evidence of instability also in the slope of the Phillips curve, i.e., on the response of inflation to demand pressures. In particular, some studies have highlighted the possibility that the Phillips curve may have flattened—i.e., the slope may have decreased—in several advanced economies (Borio and Filardo 2007). The interpretation of this change in the slope of the Phillips curve is still an open issue. A hypothesis which has received much attention is that the source of this flattening may be related to the process of globalization (Melick and Galati 2006). Other authors, such as Roberts (2006), attribute the reduction in the slope to changes in monetary policy. However, there does not seem to be robust evidence for this hypothesis, as recently shown by Ihrig et al. (2007).

Some evidence for significant changes over time also has been uncovered with regard to the impact of oil and exchange rate shocks to inflation. For example, a number of studies have documented a significant decline in the pass-through of oil prices to consumer price inflation in several advanced economies since the 1980s (De Gregorio, Landerretche, and Neilson 2007). Blanchard and Galí (2007) confirm this finding and conclude that various forces have caused this decline, including improved monetary policy, more flexible labor markets, and a smaller dependence on oil. Other studies have provided evidence for a reduced exchange rate pass-through to consumer price inflation in advanced economies after the 1980s, although this decline is not always statistically significant (Ihrig, Marazzi, and Rothenberg 2006).

2.3 Nonlinearity and Asymmetry

There is a long tradition of thought in monetary economics, going back at least to the times of John Maynard Keynes, suggesting that the Phillips curve may be nonlinear and, in particular, have a *convex* shape, reflecting the existence of discontinuity in firms' price adjustment costs—for example, due to downward wage rigidity (e.g., Clark and Laxton 1997). A convex Phillips curve implies that inflation may fail to decline in response to a shortfall of excess demand but pick up significantly should demand exceed a certain threshold: the marginal reaction of inflation to a spending stimulus—for example, coming from monetary policy—is therefore path dependent. An extreme form of convexity is an *asymmetric* curve, where inflation reacts to excess demand only if the latter is above a certain level. It is worth noting that, in fact, the relationship initially proposed by Phillips was, indeed, a curve.

The existing empirical evidence for the United States and other industrialized economies is, however, mixed. Akerlof, Dickens, and Perry (1996) and Debelle and Laxton (1997), among others, suggest that a convex Phillips curve is appropriate, while Gordon (1997) argues in favor of a linear curve and Stiglitz (1997) even of a concave one. The evidence on the functional form of the Phillips curve is particularly scant and controversial in the euro area, partly reflecting the challenges associated with gathering appropriately harmonized and long time series of data for this economy compared, for example, with the United States. Interestingly, research conducted within the Eurosystem IPN has found that prices in the euro area appear to respond more strongly to cost increases than to decreases but, at the same time, more to a fall in demand than to a rise (Fabiani et al. 2006). Transposing this micro evidence to the macroeconomic level, the first bit of evidence would point to a convex Phillips curve, while the second bit suggests a concave curve. On the whole, therefore, the IPN evidence does suggest the existence of some interesting nonlinearity, but the implications at the aggregate level are unclear.

Aguiar and Martins (2005) test the linearity of the euro-area Phillips curve using data from 1970 to 2002 and find that there is not enough statistical evidence for rejecting the null of linearity. However, Dolado, Maria-Dolores, and Naveira (2005) suggest that nonlinearities may be present, working on data from 1984 to 2001. In particular, in their specification, the square value of the output gap enters significantly and with a positive coefficient in the equation, suggesting a convex Phillips curve.

3. Data

The data for our empirical analysis is obtained from the area-wide model (AWM) database[2] and has quarterly frequency, spanning the period 1970:Q1–2005:Q4. We focus on the two main measures of inflation for the euro area, which are based on the GDP deflator and the Harmonised Index of Consumer Prices (HICP). Although the latter is the main indicator referred to by the ECB and is the

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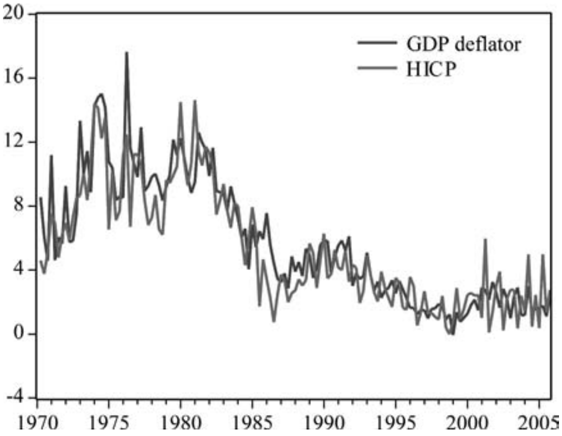
[2] For more details on the AWM database, see Fagan, Henry, and Mestre (2005). We make use of the database version released in September 2006, which extends through 2005:Q4.

Figure 1. GDP Deflator and HICP Inflation



Note: The graph shows annualized quarter-on-quarter inflation rates for the euro-area GDP deflator and HICP for the period 1970:Q2–2005:Q4.

ultimate target of our analysis, as discussed below there are certain benefits in starting from a model for the former and then analyzing the link between these two price series.[3] Figure 1 shows the developments of the GDP deflator and the HICP over the sample period in terms of annualized quarter-on-quarter inflation rates. Although the two series move closely together[4] and follow broadly similar patterns, sizable deviations can be observed over some prolonged periods such as the late-1970s and mid-1980s. Moreover, while the GDP deflator also is available in seasonally adjusted form, the HICP only comes in seasonally unadjusted form, a fact that has to be borne in mind in the modeling process.

Typical measures of the output gap are surrounded by a large degree of uncertainty; see Camba-Méndez and Rodriguez-Palenzuela (2003) and Orphanides and van Norden (2005), among others. For that reason, we consider several alternative indicators of economic slack. First, we employ three alternative estimates of the output gap based on the multivariate unobserved-components model of

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[3] This approach is frequently adopted in several macroeconomic models that specify a Phillips-type relationship, including the AWM.

[4] Over the complete sample period, the correlation between GDP deflator and HICP inflation is 0.89.

Proietti, Musso, and Westermann (2007).[5] Second, we use three frequently used measures based on statistical filters applied to real GDP: the Baxter-King band-pass filter, the Hodrick-Prescott filter, and a univariate unobserved-components model.[6]

Figure 2 displays the output-gap measures that we consider, while table 1 reports summary statistics. From the graph it appears that although all six variables are highly correlated, their amplitude tends to vary. The large positive cross-correlations in table 1 confirm that there is a great deal of co-movement across the different output-gap measures. At the same time, it is also clear that there is no perfect collinearity among them. To avoid the peculiarities of a specific output-gap measure, in the empirical analysis in the following sections we will make use of their first principal component, which is shown in figure 3. In section 5.1 we conduct a sensitivity analysis where we consider the individual output-gap estimates and an alternative summary measure based on their simple average.

In part of the analysis, two common indicators of additive price shocks also are included—namely, the quarter-on-quarter growth rates in the euro nominal effective exchange rate (standardized to equal 100 in 1970:Q1) and the price of oil (in euros per barrel). The levels of these variables are plotted in figure 4. The nominal effective exchange rate largely resembles the movements of European currencies against the U.S. dollar, reaching a low value of 82

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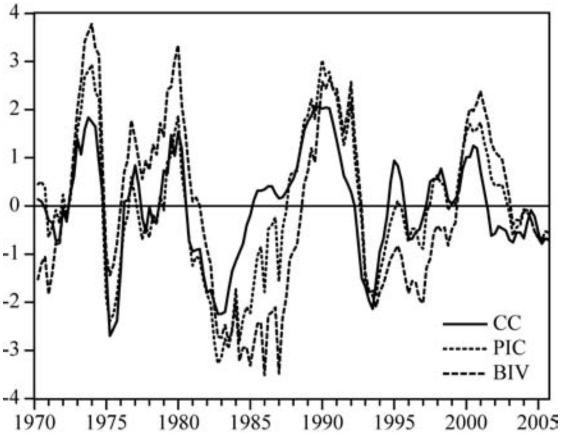
[5] The three versions of the multivariate unobserved-components model, based on the production function approach, consist of the common cycles (CC) version, the pseudo-integrated cycles (PIC) version, and the bivariate (BIV) version. The CC specification is estimated under the assumption that all cyclical variables in the system (total factor productivity, unemployment, and labor force participation) follow the relatively short cycle in capacity utilization. The PIC specification is estimated under the assumption that the cycles in the labor variables are more persistent. The BIV specification is based on a bivariate system for inflation and output only. See Proietti, Musso, and Westermann (2007) for more details.

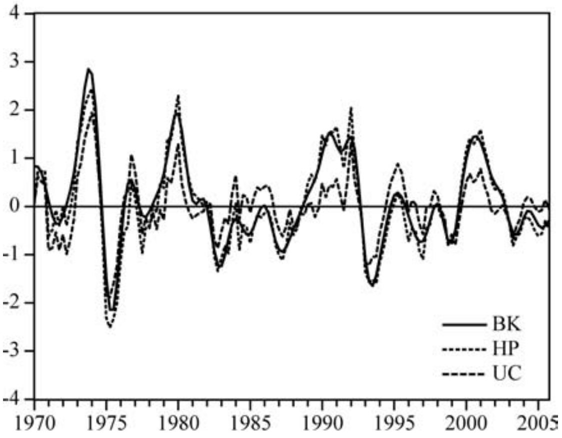
[6] The three univariate filters are applied to real GDP, extended backwards (using a euro-area aggregate based on OECD data) and projected forwards (with a simple autoregressive model) by three years. Subsequently, the first and last three years of the estimated cycles were discarded, as recommended by Baxter and King (1999) for the band-pass filter. The univariate unobserved-components model was specified as a basic smooth unobserved-components model (fixed level, stochastic slope) with a stochastic cycle (with damping factor equal to 0.9 and period equal to 20) and outlier corrections (found via tests based on the auxiliary residuals) in 1974:Q3, 1986:Q1, and 1987:Q1.

Figure 2. Output-Gap Measures

A. Multivariate UC Model



B. Univariate Filters



Note: The graphs show measures of the quarterly output gap. In panel A, CC, PIC, and BIV denote measures obtained from the common cycles, the pseudo-integrated cycles, and the bivariate versions, respectively, of the multivariate unobserved-components model of Proietti, Musso, and Westermann (2007). In panel B, BK denotes the Baxter-King band-pass filter, HP the Hodrick-Prescott filter, and UC a univariate unobserved-components model applied to quarterly read GDP.

in 1985, followed by a rapid increase due to the Plaza Agreement, then a substantial depreciation following the introduction of the euro in 1999, and with the subsequent recovery during 2001–03. The oil

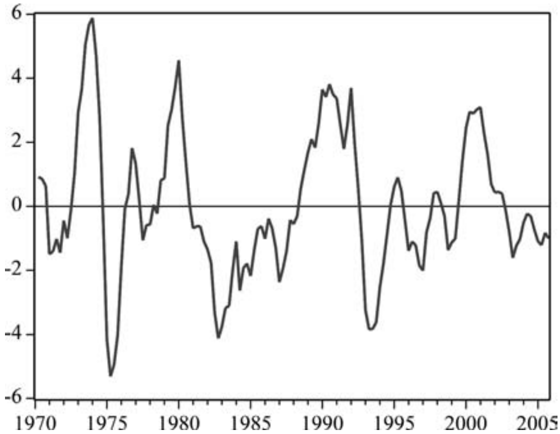
Table 1. Output-Gap Measures—Summary Statistics

					Correlation					
	Mean	**St. Dev.**	**Skewness**	**Kurtosis**	**CC**	**PIC**	**BIV**	**BK**	**HP**	**UC**
CC	−0.01	1.07	−0.22	2.78		0.87	0.61	0.75	0.74	0.63
PIC	−0.03	1.42	0.03	2.62			0.83	0.81	0.82	0.59
BIV	−0.06	1.76	0.15	2.16				0.82	0.79	0.52
BK	0.11	0.92	0.43	3.39					0.97	0.81
HP	0.02	0.97	0.25	3.06						0.83
UC	−0.01	0.63	−0.01	4.07						

Note: The table presents summary statistics for quarterly output-gap measures for the euro area for the period 1970:Q1–2005:Q4. CC, PIC, and BIV are obtained from the common cycles, the pseudo-integrated cycles, and the bivariate versions, respectively, of the multivariate unobserved-components model of Proietti, Musso, and Westermann (2007). BK denotes the Baxter-King band-pass filter, HP the Hodrick-Prescott filter, and UC a univariate unobserved-components model applied to quarterly real GDP.

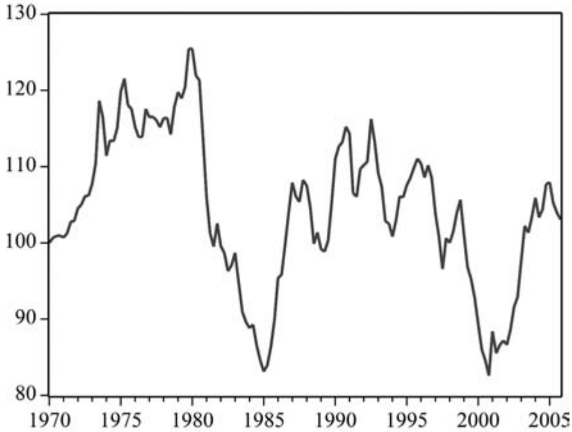
price clearly shows the OPEC-induced price jumps in 1973 and 1979, the rapid decline in 1985–86 following the increase in production initiated by Saudi Arabia, and the price hikes around the turn of the millennium and in 2004–05.

Figure 3. Principal Component of Output-Gap Measures

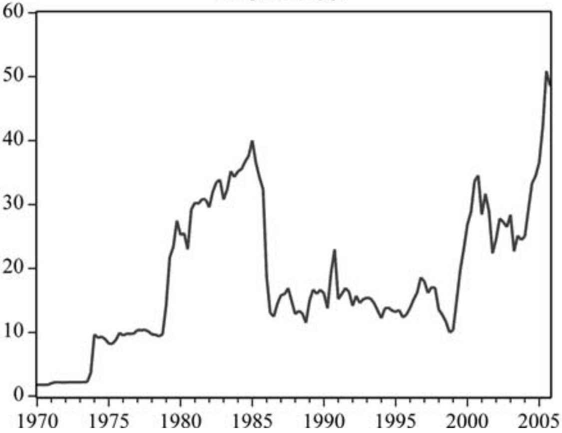


Note: The graph shows the first principal component of the six output-gap measures for the period 1970:Q1–2005:Q4.

Figure 4. Price Shocks: Euro Nominal Effective Exchange Rate and Oil Price



A. Euro Nominal Effective Exchange Rate



B. Oil Price

Note: The graphs show the quarterly euro nominal effective exchange rate and oil price for the period 1970:Q1–2005:Q4.

4. Linear Phillips-Curve Specification

The main conclusion that we draw from the literature review in section 2 is that a comprehensive modeling strategy is required in order to discriminate among alternative specifications for euro-area inflation dynamics and the Phillips curve—in particular, to account for the possible presence of various types of instabilities and nonlinearity. We start from a generalized form of the Phillips curve estimated by O'Reilly and Whelan (2005):

$$\pi_t = \alpha + \rho\pi_{t-1} + \sum_{j=1}^{p} \psi_j \Delta\pi_{t-j} + \gamma x_t + \sum_{j=1}^{k} \lambda_j \Delta x_{t-j} + \delta' z_t + \varepsilon_t, \quad (1)$$

where quarterly inflation π_t (measured in annualized percentage points) is a function of its own lags (Δ denotes the first-difference operator), the output gap x_t, and a vector of supply shocks z_t. For the latter we consider quarter-on-quarter growth rates of the oil price and of the nominal effective exchange rate of the euro, denoted as o_t and e_t, respectively.[7] These shocks are included in the same way as the output gap x_t; i.e., z_t consists of contemporaneous levels and first differences up to orders l and m, such that $z_t = (o_t, \Delta o_t, \ldots, \Delta o_{t-l}, e_t, \Delta e_t, \ldots, \Delta e_{t-m})'$. Both e_t and o_t are demeaned prior to inclusion and, given that the output-gap measure has mean zero by construction, the long-run mean of inflation in (1) is given by $\alpha/(1-\rho)$. Following O'Reilly and Whelan (2005) and others, we interpret ρ as a measure of inflation persistence. Compared with O'Reilly and Whelan (2005), we allow for lags in the output-gap variable and include a number of additive price shocks. Thus, the relationship resembles the triangle model advocated by Gordon (1997).

We specify the linear Phillips curve in (1) for both the GDP deflator and HICP inflation, including quarterly dummies for the latter inflation measure in order to capture its seasonal behavior. Furthermore, we include an additive outlier dummy for 1976:Q2 to capture the spike in the GDP deflator in that quarter resulting from inflation spikes in some countries like Italy and Spain, largely associated with the consequences of the currency crises experienced in those countries over that period. For the output gap x_t, we use

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[7] Some studies, including Aguiar and Martins (2005) and Rudd and Whelan (2005), have used the imported goods deflator (in its deviations from overall inflation) as a proxy for supply-side shocks. However, for the euro area such a variable is not available from 1970. The series for the import deflator that are available from 1970 (such as from the AWM database) include intra-euro-area trade, while series for the extra-euro-area import deflator are available only from the 1990s.

the first principal component of six measures of economic slack, as described in the previous section. The maximum number of lags for all variables is four, with specific lag orders chosen by combining the information from the Akaike, Schwarz (or Bayesian), and Hannan-Quinn criteria, denoted as AIC, BIC, and HQ. All models are estimated using an effective sample period from 1971:Q4 through 2005:Q4 ($T = 137$ observations).

In the process of developing a linear Phillips-curve equation for the GDP deflator and HICP inflation, it turns out that the resulting specification for the former inflation measure is considerably simpler, in the sense that the supply shocks z_t do not enhance the explanatory power of the model, while they are important for HICP inflation. For that reason we proceed by first considering a Phillips-curve specification for the GDP deflator, excluding the additive price shocks, and subsequently modeling the relationship between the GDP deflator and HICP inflation using a bridge equation, which also takes into account the additive price shocks.

The appropriate lag orders are selected by varying $p \in \{0, \ldots, 4\}$ and $k \in \{-1, 0, \ldots, 4\}$, where $p = 0$ ($k = -1$) indicates that no first differences of inflation (the output gap) are included in the model. AIC selects $p = 3$ and $k = 3$, while both BIC and HQ select $p = 3$ and $k = -1$. Upon estimating both specifications, we find that the first differences of the output gap do not add substantially to the model fit, such that we settle for the more parsimonious model, which only includes its contemporaneous level. The resulting model is given by

$$\begin{aligned}\hat{\pi}_t = \underset{(0.151)}{0.053} + \underset{(0.029)}{0.978}\ \pi_{t-1} - \underset{(0.080)}{0.493}\ \Delta\pi_{t-1} - \underset{(0.090)}{0.314}\ \Delta\pi_{t-2} \\ - \underset{(0.100)}{0.370}\ \Delta\pi_{t-3} + \underset{(0.067)}{0.280}\ x_t, \end{aligned} \tag{2}$$

$\hat{\sigma}_\pi = 3.96$, $\hat{\sigma}_\varepsilon = 1.20$, SK $= 0.38$, EK $= 1.43$, LJB $= 15.1(5.0 \times 10^{-4})$, ARCH(1) $= 0.23(0.63)$, ARCH(4) $= 7.12(0.13)$, $\text{LM}_{\text{SI}}(1) = 0.29(0.59)$, $\text{LM}_{\text{SI}}(4) = 1.47(0.22)$, AIC $= 0.483$, BIC $= 0.654$,

where heteroskedasticity-consistent standard errors are given in parentheses below the parameter estimates; $\hat{\sigma}_\pi$ is the standard deviation of the dependent variable; $\hat{\sigma}_\varepsilon$ is the residual standard deviation; SK and EK are residual skewness and excess kurtosis, respectively; LJB is the Lomnicki-Jarque-Bera test of normality of the residuals; ARCH(q) is the LM test of no ARCH effects up to order q in the residuals; and $\mathrm{LM}_{\mathrm{SI}}(m)$ is the Breusch-Godfrey test for no residual autocorrelation up to and including lag m. The numbers in parentheses following the test statistics are p-values.

The linear model seems adequate in that the errors are serially uncorrelated and homoskedastic, whereas the skewness and excess kurtosis are caused entirely by large residuals in 1973:Q1 and 1992:Q1. From this linear specification, inflation appears to be highly persistent with $\hat{\rho} = 0.978$. The coefficient of the output-gap level has the expected positive sign with $\hat{\gamma} = 0.280$.

5. Instability and Nonlinearity

In this section we assess the stability and linearity of the Phillips-curve specification for the GDP deflator discussed above. A relevant issue in this analysis is that nonlinearity and time-varying parameters generally are difficult to distinguish. In addition, instability in one part of the model may spuriously suggest instability in other parts as well. For example, a structural change in the mean of inflation, when neglected, may give the impression that inflation persistence has changed. In sum, analyzing the linearity and stability of the Phillips curve requires a well-structured and comprehensive approach. For that purpose, we adopt the methodology underlying the time-varying smooth transition (TV-STR) models as developed in Lundbergh, Teräsvirta, and van Dijk (2003). TV-STR models allow for nonlinearity and time-varying parameters simultaneously, while a modeling procedure is available for arriving at the most appropriate empirical specification; see also van Dijk, Teräsvirta, and Franses (2002) for a detailed discussion. This involves the application of a battery of diagnostic tests to a given model specification, including tests for nonlinearity and time-varying parameters, and expanding the model in the direction for which the statistical evidence is most convincing.

We start from the linear specification for the GDP deflator as given in (2). Among other misspecification tests, we separately test the stability and linearity of the intercept α, the persistence parameter ρ, and the output-gap coefficient γ as follows.

Stability of a given coefficient θ for a given variable v_t in the model is tested against the alternative of a single, gradual structural change of the form

$$\theta_t = \theta_1(1 - G(t; \xi, \tau)) + \theta_2 G(t; \xi, \tau), \tag{3}$$

where $G(t; \xi, \tau)$ is the logistic function

$$G(t; \xi, \tau) = \frac{1}{1 + \exp(-\xi(t - \tau))}, \qquad \xi > 0, \tag{4}$$

which changes monotonically from 0 to 1 as t increases such that θ_t changes from θ_1 to θ_2. The restriction on the parameter ξ, which governs the smoothness of the parameter change, is for identification purposes only. The parameter τ determines the location of the shift in θ_t, in the sense that $G(t; \xi, \tau) = 0.5$ when $t = \tau$. The null hypothesis of stability can be formulated as either $\xi = 0$ or $\theta_1 = \theta_2$. In both cases, the testing problem is nonstandard due to the presence of unidentified nuisance parameters under the null hypothesis. This can be remedied by approximating the logistic function $G(t; \xi, \tau)$ by means of a low-order Taylor approximation around the point $\xi = 0$, giving rise to an auxiliary regression including terms $v_t t$, $v_t t^2$, $v_t t^3, \ldots$. This can be estimated using least squares, and a standard F-test for the joint significance of the coefficients of the auxiliary regressors provides a test for stability.

Linearity of the relationship between π_t and v_t is tested against the same alternative (3), except that in the logistic function $G(\cdot)$ in (4), time t is replaced by another observable variable s_t, which then governs the switching of θ_t between its two extreme values, θ_1 and θ_2. Here we consider nonlinear specifications with the first lag of the level and first difference of inflation, and the current level and change of the slack measure as transition variables; i.e., $s_t \in \{\pi_{t-1}, \Delta\pi_{t-1}, x_t, \Delta x_t\}$. More details about the diagnostic tests for time-varying parameters and nonlinearity can be found in Eitrheim and Teräsvirta (1996). Medeiros and Veiga (2003) develop analogous test statistics for examining the constancy and linearity of the residual variance σ_ε^2, which we also employ here.

Table 2 reports p-values of the diagnostic tests of stability and linearity applied to the different components in the linear specification for the GDP deflator. We observe that several null hypotheses are rejected—in particular, stability of the intercept α, the persistence parameter ρ, and the slope of the curve γ. The evidence for structural change in the conditional variance σ_ε^2 is less convincing. All three types of possible structural change signaled by the diagnostic tests seem plausible and have been documented in previous literature; see section 2. Given that the p-value of the stability tests for α are smallest, we proceed with estimating a model that incorporates a change in the intercept, thereby allowing for a shift in the long-term mean of inflation. This appears plausible given the substantial changes in monetary policy regimes and, in particular, in the level of inflation targets experienced by euro-area countries over the course of the past three decades. The specification of the model thus is as follows:

$$\pi_t = \alpha_t + \rho\pi_{t-1} + \sum_{j=1}^{p} \psi_j \Delta\pi_{t-j} + \gamma x_t + \sum_{j=1}^{k} \lambda_j \Delta x_{t-j} + \varepsilon_t, \qquad (5)$$

where α_t is now time varying according to (3); i.e.,

$$\alpha_t = \alpha_1(1 - G(t;\xi,\tau)) + \alpha_2 G(t;\xi,\tau), \qquad (6)$$

with $G(t;\xi,\tau)$ given by (4), such that $\alpha_1/(1-\rho)$ and $\alpha_2/(1-\rho)$ are the long-run means of inflation before and after the change, respectively, and can be interpreted as the central bank inflation targets during those periods. The lag orders p and k are, once again, selected on the basis of the Akaike, Schwarz, and Hannan-Quinn information criteria, all of which indicate that $p = 3$ and $k = -1$ is the preferred specification. The model is estimated with nonlinear least squares, which yields the following results:

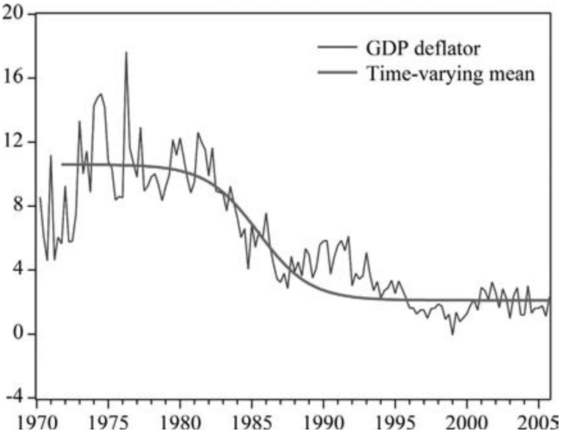
$$\begin{aligned}\hat{\pi}_t = {} & \underset{(0.950)}{3.247}\ (1 - G(t;\hat{\xi},\hat{\tau})) + \underset{(0.219)}{0.643}\ (G(t;\hat{\xi},\hat{\tau}) + \underset{(0.086)}{0.694}\ \pi_{t-1} \\ & - \underset{(0.101)}{0.330}\ \Delta\pi_{t-1} - \underset{(0.097)}{0.176}\ \Delta\pi_{t-2} - \underset{(0.085)}{0.291}\ \Delta\pi_{t-3} + \underset{(0.065)}{0.275}\ x_t, \end{aligned} \qquad (7)$$

Table 2. LM-Type Tests for Nonlinearity and Time-Varying Parameters in Phillips-Curve Specifications for GDP Deflator

Transition Variable s_t	$k =$	Linear Model			Model with Change in Mean			Model with Change in Mean and Slope		
		1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Intercept α										
π_{t-1}		—	0.599	0.790	—	0.200	0.174	—	0.242	0.163
$\Delta\pi_{t-1}$		—	0.953	0.772	—	0.431	0.408	—	0.194	0.355
x_t		—	0.355	0.190	—	0.998	0.823	—	0.385	0.245
Δx_t		0.266	0.433	0.299	0.510	0.667	0.295	0.688	0.667	0.239
t		0.000	0.000	0.000	0.860	0.928	0.607	0.982	0.909	0.983
Persistence ρ										
π_{t-1}		0.175	0.307	0.026	0.173	0.063	0.097	0.133	0.072	0.064
$\Delta\pi_{t-1}$		0.586	0.790	0.162	0.417	0.239	0.176	0.396	0.386	0.179
x_t		0.008	0.008	0.019	0.052	0.095	0.196	0.369	0.156	0.083
Δx_t		0.289	0.445	0.336	0.462	0.704	0.630	0.195	0.366	0.444
t		0.001	0.001	0.003	0.525	0.393	0.602	0.734	0.548	0.731
Slope γ										
π_{t-1}		0.007	0.023	0.057	0.047	0.141	0.167	0.625	0.051	0.032
$\Delta\pi_{t-1}$		0.008	0.028	0.067	0.052	0.149	0.217	0.560	0.090	0.090
x_t		0.355	0.190	0.340	0.998	0.823	0.823	0.385	0.245	0.459
Δx_t		0.851	0.091	0.110	0.903	0.468	0.437	0.748	0.662	0.238
t		0.001	0.002	0.001	0.004	0.011	0.028	0.993	0.994	0.914
Residual Variance σ^2_ε										
π_{t-1}		0.100	0.103	0.160	0.047	0.026	0.025	0.142	0.115	0.117
$\Delta\pi_{t-1}$		0.119	0.171	0.111	0.049	0.018	0.025	0.147	0.115	0.117
x_t		0.213	0.164	0.304	0.466	0.302	0.304	0.249	0.300	0.176
Δx_t		0.964	0.026	0.038	0.368	0.036	0.060	0.588	0.137	0.244
t		0.106	0.127	0.080	0.067	0.074	0.027	0.178	0.164	0.119

Note: The table presents p-values of F-tests for (remaining) nonlinearity and instability in Phillips-curve specifications for quarterly inflation based on the euro-area GDP deflator for the period 1971:Q4–2005:Q4. The headings "Linear Model," "Model with Change in Mean," and "Model with Change in Mean and Slope" refer to the specifications in (2), (7), and (11), respectively. Tests are conducted for the intercept α (first panel), the persistence parameter ρ (second panel), the slope coefficient γ (third panel), and the residual variance σ^2_ε (fourth panel). Tests are based on auxiliary regressions involving terms $v_t s_t$, $v_t s_t^2, \ldots, v_t s_t^k$, where v_t is a constant, lagged inflation π_{t-1} or the output gap x_t and s_t is the transition variable in the logistic function (4) under the alternative.

Figure 5. GDP Deflator and Time-Varying Mean



Note: The graph shows annualized quarter-on-quarter inflation rates for the euro-area GDP deflator and the time-varying mean in the Phillips-curve specification (7).

with

$$G(t;\hat{\xi},\hat{\tau}) = (1+\exp(-\underset{(0.061)}{0.138}(t-\underset{(3.72)}{53.8})))^{-1}, \tag{8}$$

$\hat{\sigma}_\pi = 3.96$, $\hat{\sigma}_\varepsilon = 1.12$, SK $= 0.34$, EK $= 0.55$, LJB $= 4.34(0.11)$, ARCH(1) $= 0.55(0.46)$, ARCH(4) $= 14.9(0.01)$, $\mathrm{LM}_{\mathrm{SI}}(1) = 0.12(0.73)$, $\mathrm{LM}_{\mathrm{SI}}(4) = 1.62(0.17)$, AIC $= 0.344$, BIC $= 0.514$.

The reduction in the intercept α_t is large from $\alpha_1 = 3.247$ to $\alpha_2 = 0.643$, implying a decline in the long-run mean of annualized inflation from 10.6 percent before the change to 2.1 percent thereafter. The time-varying inflation mean is plotted in figure 5, showing that the decline occurred rather gradually during the 1980s. This is broadly in line with existing literature, which dates the Great Disinflation in the early 1980s; see Cecchetti et al. (2007), among others. The second prominent feature of this specification is that allowing for a time-varying mean substantially reduces inflation persistence. The estimate of ρ in (5) is 0.694 compared with 0.978 in the specification with constant mean in (2), implying a reduction in the half-life of shocks to inflation from thirty-one to just two quarters. Finally, note that the estimated coefficient of the slack measure, $\hat{\gamma} = 0.275$, is essentially unchanged compared with the linear specification.

Table 2 reports diagnostic tests for the model with time-varying inflation mean, including tests for remaining nonlinearity and time-varying parameters. Several interesting results emerge. First, the previous evidence for time variation in inflation persistence has disappeared completely, which is in line with results of the IPN (see Altissimo, Ehrmann, and Smets 2006). Second, the single monotonic change in the intercept appears sufficient to capture the changes in the mean of inflation, as we find no statistical evidence for additional instability in the intercept. This result is somewhat surprising, as figure 5 suggests that after the large decline during the 1980s, inflation increased again during a short period around 1990, which was followed by a further downward shift to the current level of around 2 percent due to the implementation of the Maastricht Treaty and the convergence toward EMU. Third, the null hypothesis of stability of the slope parameter γ continues to be strongly rejected. This is in line with theoretical priors indicating a possible link between the level of inflation and the frequency of price adjustment, which affects the slope of the Phillips curve (Dotsey, King, and Wolman 1999). Based on the results from the various diagnostic tests, we proceed with estimating the following model, which allows for a change in slope in addition to the change in intercept:

$$\pi_t = \alpha_t + \rho\pi_{t-1} + \sum_{j=1}^{p} \psi_j \Delta\pi_{t-j} + \gamma_t x_t + \sum_{j=1}^{k} \lambda_j \Delta x_{t-j} + \varepsilon_t, \qquad (9)$$

where α_t evolves according to (6), and the slope coefficient γ_t is now time varying and follows

$$\gamma_t = \gamma_1(1 - G(t; \zeta, \kappa)) + \gamma_2 G(t; \zeta, \kappa). \qquad (10)$$

We obtain the following estimation results for this model:

$$
\begin{aligned}
\hat{\pi}_t = {} & \underset{(0.916)}{2.742}\,(1 - G(t;\hat{\xi},\hat{\tau})) + \underset{(0.207)}{0.454}\,G(t;\hat{\xi},\hat{\tau}) + \underset{(0.084)}{0.748}\pi_{t-1} \\
& - \underset{(0.099)}{0.408}\,\Delta\pi_{t-1} - \underset{(0.107)}{0.259}\,\Delta\pi_{t-2} - \underset{(0.080)}{0.327}\,\Delta\pi_{t-3} \\
& + [\underset{(0.109)}{0.466}\,(1 - G(t;\hat{\zeta},\hat{\kappa})) + \underset{(0.060)}{0.134}\,G(t;\hat{\zeta},\hat{\kappa})]x_t, \qquad (11)
\end{aligned}
$$

with

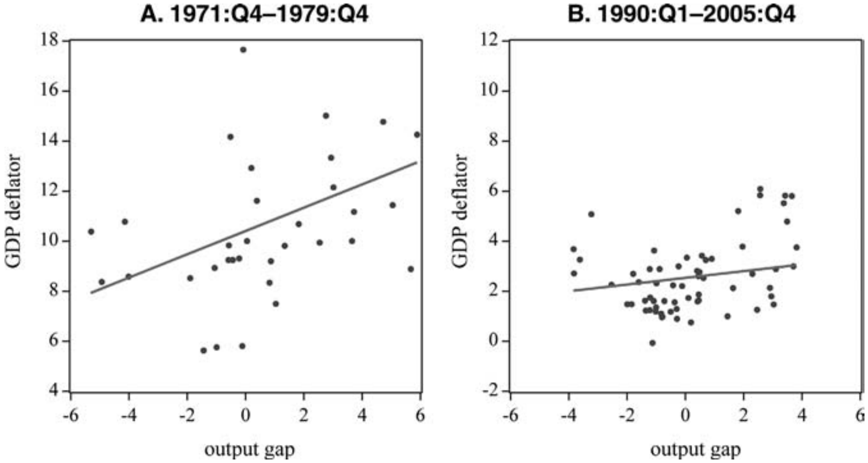
$$
G(t;\hat{\xi},\hat{\tau}) = (1 + \exp(-\underset{(0.042)}{0.081}\,(t - \underset{(0.69)}{50.1})))^{-1}, \qquad (12)
$$

$$
G(t;\hat{\zeta},\hat{\kappa}) = (1 + \exp(-\underset{(0.048)}{4.20}\,(t - \underset{(0.050)}{32.6})))^{-1}, \qquad (13)
$$

$\hat{\sigma}_\pi = 3.96$, $\hat{\sigma}_\varepsilon = 1.07$, SK $= 0.19$, EK $= 0.79$, LJB $= 4.44(0.11)$, ARCH(1) $= 0.39(0.53)$, ARCH(4) $= 13.6(0.01)$, $\text{LM}_{\text{SI}}(1) = 0.20(0.65)$, $\text{LM}_{\text{SI}}(4) = 6.37(0.17)$, AIC $= 0.272$, BIC $= 0.464$.

Two features of the model are striking. First, the reduction in the output-gap coefficient is substantial, with the slope after the break being approximately one-third of the slope before the break ($\hat{\gamma}_2 = 0.134$ compared with $\hat{\gamma}_1 = 0.466$). Second, the change in slope occurs rather abruptly, as indicated by the large estimate of ζ, and in 1979:Q4, prior to the change in the mean of inflation. Note that the timing and speed of the change in the intercept α_t are comparable to the estimates found before in (7), as shown in figure 5. The restriction that the timing and speed of the transitions of the intercept and slope are in fact identical is convincingly rejected on the basis of a likelihood ratio test. We believe that both the shift in the constant term and in the slope of the equation are related to the *change in monetary policy regime* in the first part of the 1980s and in particular to the transition from a regime of high and volatile inflation to a regime of low and stable inflation. One might conjecture that the transition in the frequency of price adjustment may have taken place as soon as the shift in monetary policy regime, already evident in 1980, was introduced, well before actual inflation started to fall

Figure 6. GDP Deflator and the Output Gap



Note: The graphs show scatter plots of the quarterly output gap against the annualized quarter-on-quarter inflation rate for the euro-area GDP deflator for the periods 1971:Q4–1979:Q4 and 1990:Q1–2005:Q4. The solid line shows the relationship $\hat{\pi}_t = \bar{\pi} + \hat{\gamma}_i x_t$ for $i = 1, 2$ where $\hat{\gamma}_i$ are the nonlinear least-squares estimates from (11) and $\bar{\pi}$ is the sample mean inflation rate over the respective subperiods.

and converge to lower levels as from the mid-1980s.[8] As a result of the shift in the slope, the Phillips curve has become significantly flatter from 1990 onward (i.e., after the adjustment of both the persistence and slope levels appears to be completed) compared with the 1970s (i.e., before these changes took place), as suggested by figure 6.

Table 2 reports diagnostic tests for remaining instability and nonlinearity for this model with time-varying intercept and slope. For most tests, the p-values are well above conventional significance levels. As regards nonlinearity, we find statistically insignificant test statistics when the transition variable is the level or first difference of the output gap; i.e., $s_t = x_t$ or Δx_t. Note that a nonlinear relationship between the inflation rate π_t and the output gap x_t with

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[8] This may imply that a model in which the change in the slope of the curve is driven by the level of (trend) inflation, as in De Veirman (2007) for Japan, may not be very appropriate in the euro area.

x_t itself as the transition variable would correspond to a concave or convex functional form of the Phillips curve. Hence, we find no evidence of these commonly studied types of nonlinearity for the euro area. However, we do find some indications for the presence of nonlinearity in the relationship between inflation and the output gap, as the p-values of the linearity tests with $s_t = \pi_{t-1}$ are below 10 percent. We attempted to estimate a smooth transition regression model accordingly, but this did not give meaningful results. Hence, we accept the specification in (11) as an adequate representation of the Phillips-curve dynamics over the period 1970–2005.

5.1 Sensitivity Analysis

We perform two types of sensitivity analysis to examine the robustness of our results. First, we include the price shocks z_t in the Phillips-curve specification as in (1). The information criteria suggest to include only the contemporaneous level of the oil price shock o_t and the contemporaneous level and one lagged first difference of the exchange rate shock e_t. As already noted in section 4, we find very little role for these additive price shocks in the equation for the GDP deflator and, not surprisingly, the main results concerning the changes in mean and slope of the Phillips curve remain practically unchanged.[9]

Second, we reestimate the model in (11) by substituting each of the six individual measures of the output gap discussed in section 3 as well as their arithmetic average for the summary measure based on the first principal component used before. Table 3 presents estimates of the parameters determining the time-varying slope γ_t as defined in (10) for the different choices of the output-gap measure x_t. To account for the different amplitude of the slack measures, we report scaled coefficients $\gamma_i^* = \gamma_i \times \sigma_x$, $i = 1, 2$, where σ_x denotes the sample standard deviation of x_t. The table shows that the coefficient estimates for the principal component and the arithmetic average are very close, both for the timing and speed of the structural change of the slope coefficient as well as its magnitude before and after the change. The same holds for the three gap measures

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[9] Results are not reported for brevity but are available from the authors upon request.

Table 3. Output-Gap Measures—Sensitivity Analysis

	PC	AVG	CC	PIC	BIV	BK	HP	UC
γ_1^*	1.042	1.115	1.384	1.495	1.546	0.855	0.830	0.833
γ_2^*	0.300	0.304	0.311	0.179	0.369	0.222	0.154	0.102
ζ	4.200	3.750	4.200	20.00	0.207	20.00	0.526	20.00
κ	39.60	39.60	39.30	42.80	34.00	80.40	79.60	40.10

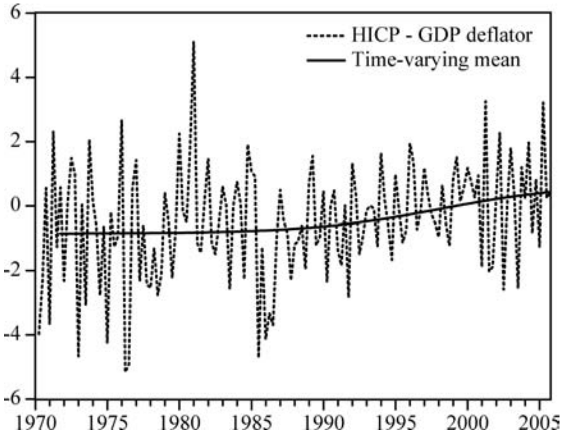
Note: The table presents estimates of the parameters in the time-varying slope γ_t defined in (10), which is used in the Phillips-curve specification given in (9) for different choices of the output-gap measure x_t. $\gamma_i^* = \gamma_i \times \sigma_x$, $i = 1, 2$, where σ_x denotes the sample standard deviation of x_t. CC, PIC, and BIV are obtained from the common cycles, the pseudo-integrated cycles, and the bivariate versions, respectively, of the multivariate unobserved-components model of Proietti, Musso, and Westermann (2007). BK denotes the Baxter-King band-pass filter, HP the Hodrick-Prescott filter, and UC a univariate unobserved-components model applied to quarterly real GDP. PC denotes the first principal component of these six measures, while AVG denotes their simple average.

based on the multivariate unobserved-components model of Proietti, Musso, and Westermann (2007). Larger differences are observed for the univariate measures based on statistical filters applied to real GDP. In particular, when using the Baxter-King band-pass filter or the Hodrick-Prescott filter, the timing of the change is dated a full decade later compared with the univariate unobserved-components model or any of the other gap measures ($\hat{\kappa} \approx 80$ as opposed to 40).

6. Modeling HICP Inflation

Although the rate of inflation derived from the GDP deflator is of great interest, the ECB's monetary policy objective of price stability is defined in terms of HICP inflation. For that reason, in this section we develop a model for HICP inflation, linking it to the GDP deflator using a so-called bridge equation, which has the difference between the HICP and GDP deflator inflation measures as the dependent variable. As discussed in sections 3 and 4, HICP inflation moves closely together with the GDP deflator inflation, but with two important differences. First, while GDP deflator inflation appears not to be affected by our measures of additive price shocks, HICP inflation

Figure 7. Difference between HICP and GDP Deflator Inflation



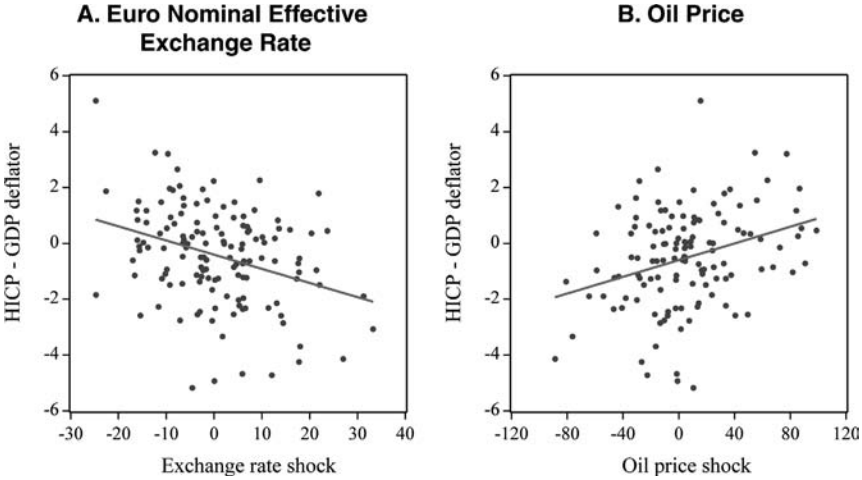
Note: The graph shows the difference between the annualized quarter-on-quarter inflation rates for the euro-area HICP and GDP deflator for the period 1970:Q2–2005:Q4. The horizontal line is the time-varying mean in the specification (14).

is. Second, while the GDP deflator is seasonally adjusted, the HICP is not.

Figure 7 plots the difference between the annualized quarter-on-quarter rate of change in the HICP and in the GDP deflator, denoted d_t. The difference between the two inflation measures appears to be stationary over the sample period that we cover, although an increase in the level seems to have occurred since 1990, approximately. Some seasonality also appears to be present in the series. The effects of price shocks become clear from figure 8, which shows scatter plots of the quarterly changes in the euro nominal effective exchange rate and in the oil price against d_t. As expected, the inflation differential is negatively related to exchange rate shocks and positively related to oil price shocks.

An appropriate model for d_t is developed using the same procedure applied to the Phillips-curve specification for the GDP deflator as discussed in sections 4 and 5. That is, we start with a linear specification of the form (1), but for d_t instead of π_t, and not including the

Figure 8. Price Shocks: Euro Nominal Effective Exchange Rate and Oil Price



Note: The graphs show scatter plots of the quarterly change in the euro nominal effective exchange rate and oil price against the difference between the annualized quarter-on-quarter inflation rates for the euro-area HICP and GDP deflator for the period 1970:Q2–2005:Q4. The solid line shows the least-squares fit of the inflation differential on a constant and the price shock.

terms involving the output gap x_t.[10] We do include the price shocks $z_t = (o_t, \Delta o_t, \ldots, \Delta o_{t-l}, e_t, \Delta e_t, \ldots, \Delta e_{t-m})'$ and, in addition, a set of centered seasonal dummies $D_t = (D^*_{1,t}, D^*_{2,t}, D^*_{3,t})' \equiv (D_{1,t} - D_{4,t}, D_{2,t} - D_{4,t}, D_{3,t} - D_{4,t})'$, where $D_{s,t}$, $s = 1, \ldots, 4$ are quarterly dummy variables, with $D_{s,t} = 1$ when time t corresponds with quarter s and $D_{s,t} = 0$ otherwise. Finally, additive outlier dummies are included for 1976:Q2 as before, as well as for 1974:Q1 to handle the extremely large oil price shocks that occurred at that time.

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[10] By definition, the difference between HICP and GDP inflation is the inflation rate on imports weighted by their share in the consumers' basket. As Galí and Gertler (1999) point out, the output gap x_t acts as a proxy for marginal costs in the determination of prices by monopolistically competitive firms producing value added (GDP), whereas imported inflation is taken as given by these firms. Hence, x_t does not necessarily cancel in the differential inflation d_t. We did attempt to include the output-gap measure in the model for d_t, but it turned out to be insignificant.

Based on the information criteria, the lag orders are set equal to $p = 4$, $l = 0$, and $m = -1$; i.e., we include the contemporaneous level and first difference of the oil price shock o_t and only the contemporaneous level of the exchange rate shock e_t. The estimated model is subjected to the usual misspecification tests for nonlinearity and parameter instability.[11] The test results indicate instability in the intercept of the model, reflecting the change in level of d_t, as well as instability in the coefficients of the quarterly dummies D_t, suggesting that the seasonal pattern also may have changed. No signs for instability or nonlinearity in the effects of the shocks o_t and e_t are found. (Sequentially) Incorporating the change in intercept and seasonality into the model, we finally arrive at the following estimated model:

$$\begin{aligned}
\hat{d}_t = {} & \underset{(0.317)}{-0.812}(1 - G(t;\hat{\xi},\hat{\tau})) + \underset{(1.397)}{0.637}\, G(t;\hat{\xi},\hat{\tau}) + \underset{(0.158)}{0.047}\, d_{t-1} \\
& - \underset{(0.143)}{0.075}\, \Delta d_{t-1} - \underset{(0.129)}{0.029}\, \Delta d_{t-2} + \underset{(0.117)}{0.074}\, \Delta d_{t-3} + \underset{(0.082)}{0.224}\, \Delta d_{t-4} \\
& + \underset{(0.0012)}{0.0045}\, o_t + \underset{(1.5 \times 10^{-4})}{9.4 \times 10^{-5}}\, \Delta o_t - \underset{(0.011)}{0.042}\, e_t \\
& + \left[\underset{(1.268)}{-2.362}\, D^*_{1,t} - \underset{(0.866)}{1.019}\, D^*_{2,t} + \underset{(0.835)}{2.412}\, D^*_{3,t}\right](1 - G(t;\hat{\zeta},\hat{\kappa})) \\
& + \left[\underset{(0.262)}{0.679}\, D^*_{1,t} + \underset{(0.229)}{0.499}\, D^*_{2,t} - \underset{(0.193)}{0.868}\, D^*_{3,t}\right] G(t;\hat{\zeta},\hat{\kappa}), \qquad (14)
\end{aligned}$$

with

$$G(t;\hat{\xi},\hat{\tau}) = (1 + \exp(-\underset{(0.075)}{0.055}\,(t - \underset{(1.99)}{107.6})))^{-1}, \qquad (15)$$

$$G(t;\hat{\zeta},\hat{\kappa}) = (1 + \exp(-\underset{(0.039)}{20.00}(t - \underset{(0.005)}{6.9})))^{-1}, \qquad (16)$$

$\hat{\sigma}_d = 1.73$, $\hat{\sigma}_\varepsilon = 1.17$, SK $= -0.19$, EK $= 0.35$, LJB $= 1.49(0.47)$, ARCH(1) $= 0.72(0.40)$, ARCH(4) $= 5.16(0.27)$,

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[11] Results are not reported for brevity but are available from the authors upon request.

$\mathrm{LM_{SI}}(1) = 1.12(0.29)$, $\mathrm{LM_{SI}}(4) = 0.67(0.61)$, $\mathrm{AIC} = 0.583$, $\mathrm{BIC} = 0.966$.

Several features of the model are noteworthy. First, the model explains more than half of the variation in the inflation differential and appears adequate, as the usual diagnostic tests do not indicate any obvious misspecification. Second, the change in mean occurs gradually and is centered around 1997; see also figure 7. The mean inflation differential changes from -0.85 percentage points before the change to 0.67 percentage points after. The latter should be interpreted with caution, however, as the function $G(t; \hat{\xi}, \hat{\tau})$ only takes the value 0.85 at the end of our sample period such that the change is not completed. Third, the estimates of the parameters in the second logistic function $G(t; \hat{\zeta}, \hat{\kappa})$ indicate that the change in seasonality occurs rapidly during the first half of 1973. Hence, the instability in the seasonal pattern appears to be due to a few erratic observations early in the sample period. Fourth, the oil price shock o_t has a significant positive effect on the inflation differential, consistent with the idea that an oil price increase leads to higher consumer prices but does not affect the GDP deflator. Similarly, the significantly negative coefficient for the exchange rate shock e_t suggests that consumer prices are influenced by changes in the euro exchange rate.

It is worth mentioning that the finding of no evidence of a *direct* asymmetric impact of oil price shocks *on inflation* is not necessarily inconsistent with an *overall* asymmetric impact once the transmission channel through the output gap is taken into account, if oil prices do have an asymmetric impact on demand conditions.

7. Conclusions

This paper has aimed at providing a comprehensive analysis of the stability and linearity of the euro-area Phillips curve, a question that is of obvious policy relevance in Europe, where a stable rate of inflation appears to coexist with a seemingly high level of spare capacity. The main results of the study are three. First, there is strong evidence, quite unsurprisingly, of a shift in the mean of euro-area inflation, with the change occurring quite gradually toward the middle of the 1980s. Second, there is also strong evidence of a shift in the slope of the curve, again occurring in the 1980s but somewhat earlier and much more abruptly. As a result of this shift, the curve becomes significantly flatter, consistent with the idea that the frequency of price adjustment is negatively related to the mean of inflation. Third, once we correct for this time variation in the parameters, we find no significant evidence of nonlinearity in the curve—in particular, in relation to the output gap. Hence, we conclude that the Phillips "curve" is, at least in the euro area, indeed a "line." The main policy implication of our study is, therefore, that there is at least no convincing evidence of the existence of a "free lunch" for monetary policy, whereby the central bank is able to stimulate economic activity without creating inflationary pressure.

Further analysis at the level of the individual countries in the euro area could be useful in order to ascertain whether there is any interesting heterogeneity in the stability and functional form of the Phillips curve. In particular, it appears interesting to compare low-inflation (e.g., Germany) and high-inflation (e.g., Italy) countries over a longer sample period, before the start of the monetary union. This appears to be an interesting avenue for future research.

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