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The analyses, opinions and fi ndings of these papers represent the views of the authors, they are not necessarily those of the Banco de Portugal or the Eurosystem

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Trends and cycles under changing economic conditions

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Abstract
The identification of trends and cycles is often a challenging task under sizeable changes in economic conditions. We solve this problem with a flexible unobserved components model, featuring an (unobserved) evolving trend inflation drift to cope with distinct inflationary periods and data-driven low frequency movements to partly influence *ex ante* key trend components. In the long run the model displays a balanced growth path, in addition to other standard restrictions (*e.g.* nil output and labour market slacks). We estimate the model with Bayesian techniques using two datasets, one for the euro area and another for Portugal, two economies displaying distinct macroeconomic environments over the last four decades, and conclude that Portugal witnessed (i) a steeper deceleration of potential output, since the 1990s; (ii) a pervasively higher volatility in labour and product markets; and (iii) a long-lived interruption in convergence trends after the 2000s. Results are robust to sensitivity analyses. Parameter uncertainty is, nevertheless, significant.

JEL: C11, C30, E32

Keywords: Potential output, simultaneous equation models, trends and cycles, bayesian estimation.

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1. Introduction

The economic position and outlook assessment of a particular country is often incomplete without an overview of latent variables, notably potential output. This unobserved variable is, however, a controversial and diffuse theoretical object hindered by model and data uncertainty. Some authors neglect the link between potential output and inflation; some are only interested in investigating the outcome of univariate filters, in particular the Hodrick-Prescott (HP) filter; others claim that this filtering method should never be used. In structural models, potential output is often defined as the level of output that would prevail if nominal frictions were absent, a concept sometimes not easily mapped into traditional views based on reduced-form Phillips curves.[1]

Herein we go back to the theoretical concept laid down by Arthur Okun in his Presidential Address of 1962: it is the maximum level of production, with full employment, that does not trigger inflationary pressures above the "social desire for price stability and free markets". More precisely, it represents a point of balance between "more output" and "greater price stability", which is distinct from the maximum output level that could be generated with any amount of aggregate demand. Output may therefore be above or below potential output, in the short run, signalling scenarios of over- or under-utilization of resources and thus providing information that may be relevant to derive policy prescriptions. We also borrow Okun's famous "law," which establishes that output and unemployment gaps are mirror images, and thus if output is above potential (positive output gap), then unemployment is below its underlying level (negative unemployment gap).[2] In the long run over- or under-utilization should be absent and both gaps should be nil.

Our main goal is to decompose observed variables into unobserved trends and cycles under significant time-varying economic conditions, *i.e.* in economies that witness important transformations over time, both in nominal and real terms—a need that emerges naturally in long sample periods. The Portuguese economy is a paradigmatic example. A major change was brought about in 1999 when Portugal became a founding member of the euro area—a monetary union with which the country has been establishing deeper and more complex economic bonds. Prior to 1999, Portugal witnessed a sharp

1. Alternative methods to estimate potential output have been reviewed in Banco de Portugal (2017) and Álvarez and Gómez-Loscos (2018). See Hamilton (2017) for a critique on the use of HP filters. A comparison between Dynamic Stochastic General Equilibrium and reduced-form approaches is available in Vetlov *et al.* (2011). Friedman (1964) suggested a "plucking model" where the business cycle is basically a cyclical contraction from the maximum feasible output.

2. See Okun (1962). Okun's law, which remains a valid relationship according to a variety of empirical methods, has been evaluated by Ball, Leigh, and Loungani (2013) or Lafourcade *et al.* (2016). An evaluation of the Portuguese business cycle, with policy implications, is available in Blanchard and Portugal (2017).

disinflation period, followed by relative price stabilization. Real growth also varied substantially, from high levels in the late 80s to relatively low growth after 1999 and to a severe contraction during the 2007-09 financial turmoil and the euro area sovereign debt crisis period. Data compiled by Fagan *et al.* (2001) suggests that the disinflation was much more pronounced than in the euro area, and growth clearly more volatile.

We evaluate the relative performance of the Portuguese and euro area economies over more than four decades in terms of underlying, not observed, variables such as potential output or the Non-Accelerating Wage Rate of Unemployment (NAWRU), *i.e.* the unobserved unemployment rate that does not trigger excessive wage pressure. For this purpose, we offer an unobserved components model—named hereafter, for simplicity, the *U* Model—that is sufficiently flexible to cope with distinct macroeconomic environments, but does not overlook standard long-run restrictions.

Our starting point is the multivariate model suggested by Tóth (2019), which features standard long-run properties, *e.g.* nil output and unemployment gaps.[3] Potential output is the outcome of a Cobb-Douglas production function where the underlying inputs are unobserved variables jointly estimated with the remaining unknowns, including the trend in Solow's residual. This approach contrasts with common practices of using production functions outside the model (Félix and Almeida 2006; D'Auria *et al.* 2010), and is qualitatively different from positing simple statistical laws of motion driving potential output. Price and wage inflation equations co-exist and respond to the output and unemployment gaps, respectively, against a background where real wages grow in line with labour productivity in the long run. The rest of the model is relatively more standard, also featuring a version of Okun's law. The model suggested in Tóth (2019) is estimated with Bayesian techniques using data after 1995 for the euro area and does not require any calibration to cope with excess volatility in latent variables, be it by fixing standard deviations or signal-to-noise ratios (Centeno *et al.* 2009; Hristov *et al.* 2017). Expectations take an adaptive form. Monetary policy reactions and international spillovers are absent.[4]

Notwithstanding, our approach makes a number of novel contributions. Firstly, we introduce a high degree of nominal flexibility in the model by assuming that the trend price inflation equation, in particular, features a time-varying unobserved drift. This allows us to easily cope with distinct

3. See also Szörfi and Tóth (2018).

4. See Maria (2016) for a model featuring common inflation targets, international spillovers and rational expectations. This model requires, however, a well-defined monetary union, including a central bank with pre-defined inflation targets, and therefore cannot be estimated with pre-1999 data. See Jarociński and Lenza (2018) for a recent alternative model where deviations of output from trend are consistent with inflation developments.

inflationary periods, and include for instance Portuguese pre- and post-1999 data.

Secondly, we rely on low frequency movements driven by observed data, computed with (double-sided) HP filters, to partially influence trend estimates. This assumption sets adequate starting points prior to estimation and facilitates the use of long time series. Such movements, however, do not determine final trend estimates, due to the co-existence of pure unobserved elements. For instance, NAWRU levels are influenced by the relative dynamics of long- and short-term unemployment in a way that, to our knowledge, is a novelty in the literature. This is in contrast with some authors, *e.g.* Rusticelli (2014), who assume that changes in NAWRU are directly influenced by changes in the observed long-term unemployment rate—an assumption that, we claim, introduces a systematic cyclical component into trend estimates. Another example is the total factor productivity trend component, which also reflects, in part, the outcome of an HP-filtered Solow residual .

Thirdly, the labour input is defined as a function of only two components—labour force (measured in hours) and unemployment rate—, as in Andrle *et al.* (2015). This contrasts with the traditional approach that decomposes the labour input into four components—working-age population, participation rate, unemployment rate and average hours worked per worker. The main advantage of our framework is that we are able to directly estimate meaningful labour force and unemployment gaps within the model, conditioned by the business cycle. Moreover, by focusing on aggregate labour force, our approach abstracts from whether households and firms adjust hours or the number of workers in face of changing cyclical conditions, a decision that may be time-varying, different across countries and possibly subject to active ageing effects. Given that we consider two components of the labour input, the overall labour market tightness with impact on nominal developments is, therefore, defined as the total hours worked gap, and not just the unemployment gap.

Finally, we added a balanced growth path restriction to the long-run properties of the model. This option has limited impacts on the ability to cope with distinct economic conditions, but is particularly suited to produce sensible medium to long-term model-based assessments of the economy.

We offer model-based estimates for Portugal and the euro area using essentially the same model, which favours comparability. Our main results are threefold. Firstly, estimates suggest a steeper deceleration of potential output in Portugal since the 1990s, *vis-à-vis* the euro area, measured by relative developments in trend output.

Secondly, there has been a pervasively higher volatility in Portuguese labour and product markets. Economic cycles, measured by output and unemployment gaps, have higher amplitudes in Portugal. Moreover, wage and price dispersion have been substantially higher. In the mid-1980s and a large part of the 1990s Portugal experienced a substantial disinflationary period, both in terms of actual and trend inflation. There is some parallel with the euro area, except that the decrease was more pronounced. In the post-1999 period actual and trend inflation rates remained higher in Portugal. There are some signs that the Portuguese nominal response to the business cycle has been more aligned with the euro area in labour than in product markets. In a small open economy, such as Portugal, prices in the product market are highly conditioned by the external environment.

Thirdly, convergence trends between Portugal and the euro area were interrupted in the 2000s. While Portuguese potential output grew persistently above the euro area in the first part of the sample, this picture was reverted during the last 15 years. Annual potential output growth differentials are systematically negative since 2003—an outcome that should motivate some reflection. This situation deepened with the 2007–09 financial turmoil and the sovereign debt crisis. These extreme events had an impact on trend and slack components in both economies, but it was much more pronounced in the Portuguese case.

We evaluated the model extensively, addressing parameter and model uncertainty, and robustness checks lead us to conclude that the main results presented above are robust. However, a word of caution is needed. Highly specific and fine-tuned analyses are necessarily linked with high uncertainty. In particular, output gaps and, more importantly, their estimated signs are data and model dependent, being conditional on the law of motion of unobserved variables, for instance on alternative orders of integration for the NAWRU—a topic often neglected. Confirming the output gap sign, negative or positive, requires a comprehensive economic assessment and should not be based on a single model-dependent outcome. Changes in the output gap and, therefore, in potential output are less uncertain.

The remainder of this paper is organized as follows. Section 2 presents the model, and describes the database and data sources. Results are reported in Section 3, while several robustness checks are documented in Section 4. Section 5 concludes.

2. The *U* Model

The *U* Model is a quarterly unobserved components model (UCM) featuring a multivariate filter with a Cobb-Douglas production function and reduced-form theoretical equations, relating slack in the product market, i.e. the output gap, to the unemployment gap and changes in price and wage inflation.[5] An advantage in using a production function is that developments in potential

5. An early contribution linking Okun's law with a production function and applying a production function to the Portuguese case can be found in Prachowny (1993) and Marques and Botas (1997), respectively.

output can be interpreted in the light of changes in production factors and their productivity.

We apply the Kalman filter to a state space representation of our model, which allows us to decompose key variables—real GDP, unemployment rate, price and wage inflation rate—into trend and cycle components. This decomposition is often done with exogenous information from actual variables. All shocks driving the reduced-form equations are zero-mean iid normal shocks ε_t with standard deviation σ^ε, and referred to as iid $(0, \sigma^\varepsilon)$ shocks.

In terms of notation, bars ($^-$) on real variables denote the trend components that are necessary to produce potential output $\bar{Y}$, Δ represents first differences ($\Delta X_t = X_t - X_{t-1}$), and small-case letters represent variables in log terms, i.e. $x_t = ln(X_t)$. For example, the (log) level of potential output at time t is given by $\bar{y}_t$, the output gap by $(y_t - \bar{y}_t)$, and the unemployment gap by $(U_t - \bar{U}_t)$.

2.1. The theoretical structure

Regarding the production function, we assume that total labour services $\mathcal{L}$ and total capital services $\mathcal{K}$ are conditional on their utilization rates U_i and efficiency levels E_i, $i = \{L, K\}$, as in D'Auria *et al.* (2010). More exactly, output Y is produced using a Cobb-Douglas technology

$$\begin{aligned} Y &= \mathcal{A}\mathcal{L}^\iota \mathcal{K}^{1-\iota} \\ &= (TFP)\ L^\iota K^{1-\iota}, \end{aligned}$$

where $\mathcal{A}$ represents (disembodied) Hicks-neutral total factor productivity (TFP), $\mathcal{L} \equiv (U_L E_L)L$, where L is measured in hours worked, $\mathcal{K} \equiv (U_K E_K)K$, where K is the capital stock, and $0 \leqslant \iota \leqslant 1$ represents the elasticity of output to labour. We refer to $TFP \equiv \mathcal{A}(U_L E_L)^\iota (U_K E_K)^{1-\iota}$ as the *adjusted* TFP, *i.e.* adjusted for unobserved utilization rates and efficiency levels. Potential output $\bar{Y}$ follows an identical technology with all inputs at their trend levels.

The system of equations defining the growth rate of $\bar{y}_t$, after collecting all terms, is given by

$$\Delta\bar{y}_t = \Delta\overline{tfp}_t + \iota\Delta\bar{l}_t + (1-\iota)\Delta\bar{k}_t, \tag{1}$$

$$\Delta\overline{tfp}_t \equiv \Delta\bar{a}_t + \iota(\Delta\overline{u}_{Lt} + \Delta\overline{e}_{Lt}) + (1-\iota)(\Delta\overline{u}_{Kt} + \Delta\overline{e}_{Kt}), \tag{2}$$

$$\Delta\bar{l}_t = \Delta\bar{h}_t + \Delta ln(1 - \bar{U}_t), \tag{3}$$

$$\Delta\bar{k}_t = \Delta k_t, \tag{4}$$

where $\Delta\overline{tfp}_t$ is the growth rate of the adjusted trend TFP; $\Delta\bar{a}_t$ represents the growth rate of the trend Hicks-neutral TFP; $\Delta\bar{l}_t$ is the change of trend labour measured in hours; $\Delta\bar{k}_t$ is the change in the observed capital stock; $\Delta\bar{h}_t$ is the change in trend labour force (measured in hours) and $\bar{U}_t$ is the trend unemployment rate, i.e. the NAWRU.[6] As in Prachowny (1993), we assume that disembodied TFP, a_t, the degree of efficiency, e_i with $i = \{L, K\}$, and the capital stock, k_t, are always at their trend level, i.e., $a_t = \bar{a}_t$, $e_{i,t} = \bar{e}_{i,t}$ and $k_t = \bar{k}_t$. Abstracting from measurement issues, this implies that the adjusted TFP gap $(tfp_t - \overline{tfp}_t) = \iota(u_L - \bar{u}_L) + (1-\iota)(u_K - \bar{u}_K)$ measures the deviation of utilization rates from their trend levels—an "utilization gap". This means that a positive adjusted TFP gap translates into a positive output gap and may lead to higher inflation. Note that we do not need to estimate each component of the adjusted TFP, only the aggregation of all components. Moreover, given that equation (1) is defined in terms of growth rates, we directly estimate the growth rate of adjusted TFP (the level is obtained as a residual from the production function).

Labour market tightness is given by the total hours worked gap $(l_t - \bar{l}_t) = (h_t - \bar{h}_t) - (U_t - \bar{U}_t)$, which includes the labour force gap $(h_t - \bar{h}_t)$, and the unemployment gap $(U_t - \bar{U}_t)$, and therefore is not solely the latter.

The growth rate of trend adjusted TFP, formally presented in equation (5), is informed by an observed low-frequency indicator ΔI_t^{tfp} and is subject to iid $(0, \sigma^{\varepsilon^{\Delta\overline{tfp}}})$ shocks. The response to such disturbances depends on the parameter $0 \leq \rho_1 \leq 1$. A higher ρ_1 is associated with higher information content of ΔI_t^{tfp} and with a faster adjustment towards this indicator in case a shock $\varepsilon_t^{\Delta\overline{tfp}}$ occurs. If $\rho_1 = 0$ then the growth rate of trend adjusted TFP would be a random walk, which corresponds to the working hypothesis of Tóth (2019).

$$\Delta\overline{tfp}_t = \rho_1 \Delta I_t^{tfp} + (1-\rho_1)\Delta\overline{tfp}_{t-1} + \varepsilon_t^{\Delta\overline{tfp}}. \tag{5}$$

We assume that the output gap follows an autoregressive process, as shown in equation (6),

$$A_1(L)(y_t - \bar{y}_t) = \varepsilon_{1,t}, \tag{6}$$

where $A_1(L)$ denotes a lag polynomial of order p_1 and $\varepsilon_{1,t}$ is an iid $(0, \sigma^{\varepsilon_1})$ shock.

The unemployment rate is decomposed into a trend $(\bar{U}_t)$ and a cyclical component, namely the unemployment gap $(U_t - \bar{U}_t)$. In order to have a

6. The production function is an important organising element of the model. In particular, developments in potential output can be seen in the light of production inputs and their productivity. It should be noted that the growth rate of potential output is given by the sum of three contributions: $\Delta\overline{tfp}_t$, which is the contribution from *adjusted* TFP; $\iota\Delta\bar{l}_t$, which is the contribution of labour; and, $(1-\iota)\Delta k_t$, which is the contribution of capital. It should also be mentioned a residual term omitted in equation (3) that ensures an exact decomposition of the labour input, namely to account for the differences between total employment in national accounts and total employment in the Labour Force Survey. See Appendix A for details.

flexible framework, we allow for a time-varying trend unemployment rate, which has the following form:

$$\bar{U}_t = \bar{U}_{t-1} + \Delta^{\bar{U}}_{t-1}, \tag{7}$$
$$\Delta^{\bar{U}}_t = \rho_2 \Delta I^U_t + (1-\rho_2)\Delta^{\bar{U}}_{t-1} + \varepsilon^{\bar{U}}_t, \tag{8}$$

where ΔI^U_t is an indicator that captures low-frequency movements in the duration of unemployment spells, $\varepsilon^{\bar{U}}_t$ is an iid $(0, \sigma^{\varepsilon^{\bar{U}}})$ shock, and $0 \leq \rho_2 \leq 1$. If $\rho_2 = 0$ then the NAWRU would be defined as a purely I(2) process. If $\rho_2 = 1$ changes in the NAWRU are basically determined by the indicator I^U_t.

Okun's law is specified as

$$A_2(L)(U_t - \bar{U}_t) = -B_2(L)(y_t - \bar{y}_t) + \varepsilon_{2,t}, \tag{9}$$

where $A_2(L)$ and $B_2(L)$ denote lag polynomials of order p_2 and q_2, respectively, and $\varepsilon_{2,t}$ is an iid $(0, \sigma^{\varepsilon_2})$ error term. In polynomial B we omit the contemporaneous term, reducing the degree of endogeneity of the model.

In addition to the unemployment gap, the underutilisation of available resources also accounts for the labour force gap, measured in hours. Hence, we consider that the labour force can be decomposed into the sum of trend labour force ($\bar{h}_t$) plus the cyclical component, or the labour force gap ($h_t - \bar{h}_t$). The degree of persistence of the unobserved trend labour force depends on $0 \leq \rho_3 \leq 1$, which has a direct influence on the importance of an indicator on trend developments ΔI^h_t, as follows

$$\bar{h}_t = \bar{h}_{t-1} + \Delta^{\bar{h}}_{t-1}, \tag{10}$$
$$\Delta^{\bar{h}}_t = \rho_3 \Delta I^h_t + (1-\rho_3)\Delta^{\bar{h}}_{t-1} + \varepsilon^{\bar{h}}_t, \tag{11}$$

where $\varepsilon^{\bar{h}}_t$ is an iid $(0, \sigma^{\varepsilon^{\bar{h}}})$ error term. Regarding the labour force gap, we postulate a negative relationship between the unemployment rate gap and the labour force gap,

$$A_3(L)(h_t - \bar{h}_t) = -B_3(L)(U_t - \bar{U}_t) + \varepsilon_{3,t}, \tag{12}$$

where $A_3(L)$ and $B_3(L)$ denote lag polynomials of order p_3 and q_3, respectively, and $\varepsilon_{3,t}$ is an iid $(0, \sigma^{\varepsilon_3})$ error term.

Price inflation is modelled, in annualized terms, as the sum of trend price inflation ($\bar{\pi}^p_t$) plus the cyclical component ($\pi^p_t - \bar{\pi}^p_t$). As clarified in equation (14), we inform changes in the trend component—which can be interpreted as a measure of price inflation expectations—with an indicator bearing information from actual data, namely $\Delta I^{\pi^p}_t$, plus an iid $(0, \sigma^{\varepsilon^{\bar{\pi}^p}})$ shock.

$$\bar{\pi}^p_t = \bar{\pi}^p_{t-1} + \Delta^{\bar{\pi}^p}_{t-1}, \tag{13}$$
$$\Delta^{\bar{\pi}^p}_t = \rho_4 \Delta I^{\pi^p}_t + (1-\rho_4)\Delta^{\bar{\pi}^p}_{t-1} + \varepsilon^{\bar{\pi}^p}_t. \tag{14}$$

The frequency movements of $\Delta I_t^{\pi^p}$ have a direct impact on the frequency of the trend component, *i.e.* the higher its frequency, the higher the volatility of inflation expectations.

The design of the price equation is standard in economics' textbooks, being quite parsimonious, flexible and easily tractable. It simply assumes a positive relationship with the output gap and an error term that can capture cost-push shocks, regularly associated with supply shocks, as follows,

$$A_4(L)(\pi_t^p - \bar{\pi}_t^p) = B_4(L)(y_t - \bar{y}_t) + \varepsilon_{4,t}, \tag{15}$$

where $A_4(L)$ and $B_4(L)$ denote lag polynomials of order p_4 and q_4, respectively, and $\varepsilon_{4,t}$ is an iid $(0, \sigma^{\varepsilon_4})$ error term.

A similar approach is used for wage inflation, which is modelled as the sum of annualized trend wage inflation ($\bar{\pi}_t^w$) plus a cyclical component ($\pi_t^w - \bar{\pi}_t^w$). The wage inflation trend is computed by assuming that real wages grow in line with labour productivity in the long run, but can diverge in the short run by a drift $\Delta_t^{\bar{\pi}^w}$, which is influenced by an indicator computed with observed data, namely $I_t^{\pi^w}$, plus an iid $(0, \sigma^{\varepsilon^{\bar{\pi}^w}})$ shock. More precisely, $\bar{\pi}_t^w$ is defined in the long run as the sum of price inflation expectations ($\bar{\pi}_t^p$) and trend labour productivity, in annualised terms. By using lagged trend productivity, namely $(\Delta\bar{y}_{t-1} - \Delta\bar{l}_{t-1})$, we reduce the degree of simultaneity in the model.

$$\bar{\pi}_t^w \quad = \bar{\pi}_t^p + 4 * (\Delta\bar{y}_{t-1} - \Delta\bar{l}_{t-1}) + \Delta_{t-1}^{\bar{\pi}^w}, \tag{16}$$

$$\Delta_t^{\bar{\pi}^w} \quad = \rho_5 \Delta I_t^{\pi^w} + (1 - \rho_5)\Delta_{t-1}^{\bar{\pi}^w} + \varepsilon_t^{\bar{\pi}^w}. \tag{17}$$

The wage equation posits a relationship between wage inflation gap $(\pi_t^w - \bar{\pi}_t^w)$, and labour market tightness $(l_t - \bar{l}_t)$. A positive relationship reflects standard short-run trade-offs between wages and underutilised resources in the labour market. The error term $\varepsilon_{5,t}$ aims to capture wage mark-up shocks, associated for example with changes in the bargaining power of workers.

$$A_5(L)(\pi_t^w - \bar{\pi}_t^w) = B_5(L)(l_t - \bar{l}_t) + \varepsilon_{5,t}, \tag{18}$$

where $l_t - \bar{l}_t = (h_t - \bar{h}_t) - (U_t - \bar{U}_t)$, $A_5(L)$ and $B_5(L)$ denote lag polynomials of order p_5 and q_5, respectively, and $\varepsilon_{5,t}$ is an iid $(0, \sigma^{\varepsilon_5})$ error term. Typically, the labour market slack is solely based on the unemployment gap. Under the current framework, unemployment rates below the NAWRU and a labour force above trend trigger a similar wage inflation reaction.

We impose a balanced growth path in the model with equation (19), which in its general form simply posits that capital and output growth will be equal in the long run, absent any shocks. More precisely,

$$\begin{aligned} A_6(L)\Delta k_t &= B_6(L)\Delta y_t + \varepsilon_t^k \\ A_6(1) &= B_6(1), \end{aligned} \tag{19}$$

where $A_6(L)$ and $B_6(L)$ denote lag polynomials of order p_6 and q_6, respectively, and ε_t^k is an iid $(0, \sigma^{\varepsilon^k})$ error term.

Finally, regarding indicators ΔI^i, $i = \{tfp, U, h, \pi^p, \pi^w\}$, their general form is given by standard zero mean processes, such as

$$A_i(L)\Delta I_t^i = \varepsilon_t^{I^i}, \tag{20}$$

where $A_i(L)$ denote lag polynomials of order p_i and $\varepsilon_t^{I^i}$ is an iid $(0, \sigma^{\varepsilon^{I^i}})$ shock.

The steady state of the model displays nil output and unemployment gaps—equations (6) and (9), respectively—; a nil labour force gap—equation (12)—; price and wage inflation are constant and equal to expectations—equations (15) and (18)—, the real wage grows in line with productivity, resulting in a constant labour share—equation (16); and capital grows in line with output—equation (19). Note that all low frequency indicator levels are also constant in the long run.

2.2. *The database*

The dataset is quarterly and relies on official national accounts data regarding employment, hours worked, compensation of employees, real GDP and the GDP deflator; and on Labour Force Survey data for the labour force and unemployment rates. Additionally, the model considers the gap between national accounts employment and the implied employment levels in the Labour Force Survey.[7]

Observed data range from 1980Q1 to 2018Q2. Portuguese data where retrieved from Statistics Portugal and Banco de Portugal databases, the latter including the capital stock and historical data prior to 1995. With the exception of the capital stock, euro area data were collected from Eurostat and backdated, whenever possible, with the Area-wide model database (Fagan *et al.* 2001) or alternatively with AMECO. The capital stock series for the euro area was retrieved from AMECO. Whenever necessary, annual data was converted to quarterly frequency through spline interpolation methods. Official euro area data corresponds to a 19 Member State aggregate, backdated with an equivalent euro area aggregate (or an aggregation of the largest countries). To reduce end-of-period biases these figures take into account an extension with projections up to 2021Q4 for Portugal (taken from Banco de Portugal) and 2020Q4 for the euro area (taken from AMECO).

The model draws partially on low-frequency indicators based on observed data (see equation 20 in section 2.1). Given that the final trend estimates are also the result of pure unobserved elements, a natural method to partly inform the model is to extract low-frequency movements in observed data using an

7. See Appendix A for the exact decomposition of the labour input and Appendix B for a more detailed description of all data.

HP filter. This is our option for ΔI_t^{tfp} and ΔI_t^h, *i.e.* the growth rate of trend adjusted TFP and the growth rate of trend labour force (equations (5) and (11)) are partly informed by the growth rates of the HP-filtered version of the *Solow residual* and of the labour force measured in hours, respectively. The smoothing parameter is $\lambda = 1600$ for the euro area, which is the standard value suggested by Hodrick and Prescott (1981) for quarterly data. For Portugal we set $\lambda = 7680$, following Félix and Almeida (2006).

In line with the backward-looking nature of the model, we set $\Delta I_t^{\pi^p} = \Delta \pi_t^p$ (equation (14)). Besides the simplicity, this option introduces a high degree of nominal flexibility in the model because any persistent inflationary process always ends up being captured by $\Delta I_t^{\pi^p}$.

Regarding indicator ΔI_t^U (equation (8)), we considered three options: (i) use long-term unemployment directly, as in Rusticelli (2014); (ii) use the HP-filtered long-term unemployment; and (iii) use the filtered gap between long and short-term unemployment, which to our knowledge is a novelty in the literature. Data since 1985 on the long-term unemployment share is taken from the OECD database. For estimation purposes, long- and short-term unemployment are backdated using average values of the first two available decades and prolonged after 2017 with average values of the last two decades. The resulting gap is smoothed with an HP-filter with $\lambda = 100$ and converted to quarterly frequency through spline interpolation methods.[8]

Figure 1 plots actual and filtered results for the three options. The *rationale* of the first option is based on *hysteresis* risks. Recession periods are frequently associated to high long-term unemployment, especially if they are prolonged, which can lead to a human capital deterioration and a decrease in the probability of being re-employed, therefore translating into structural unemployment. Notwithstanding, Figure 1 seems to suggest that cyclical shocks can increase long and short-term unemployment rather indistinctively. Similarly, there is a high correlation between long-term and overall unemployment, which leads us to conclude that, despite the merits, this first approach would mechanically bring along a systematic cyclical component into NAWRU estimates. The link with cyclical developments was highlighted by Katz (2010), who claims that most of the increase in long-term unemployment during the Great Recession in the US was due to the cyclical collapse of aggregate demand.

The second option would remove part of the business cycle effect contained in the first option. However, by filtering long-term unemployment we would still be importing some effects steaming from the clear positive correlation between long-term and overall unemployment dynamics—a feature that one may want to avoid.

8. For more details see Appendix B.

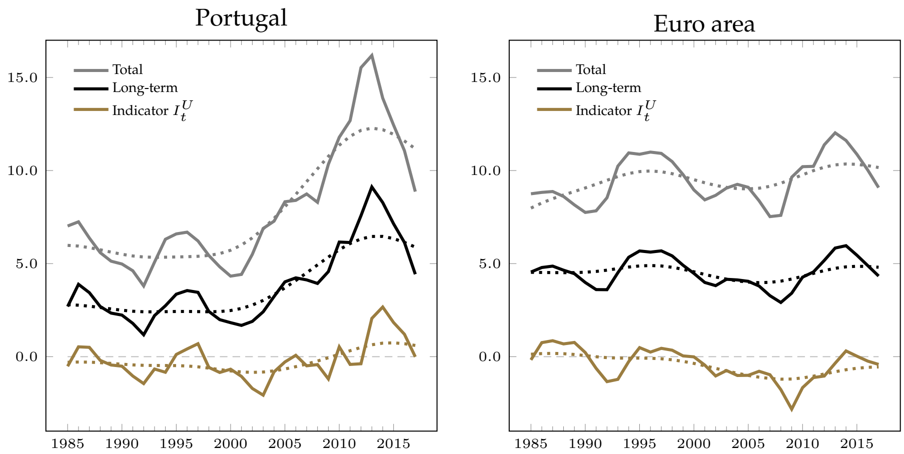

Figure 1: Unemployment, long-term unemployment and indicator I_t^U

Sources: Banco de Portugal, Eurostat, OECD, Statistics Portugal and authors' calculations.

Notes: Long–term unemployment (LT_t) and short-term unemployment (ST_t) depend on whether the worker has been less than or at least 12 months unemployed, in percentage of total labour force. Dashed lines correspond to HP-filtered series, computed with annual data and a smoothing parameter of 100. Indicator I_t^U corresponds to the HP-filtered version of $LT_t - ST_t$.

By filtering the difference between long- and short-term unemployment rates, the third option, it is clear that such indicator only leads to increases in NAWRU estimates if long-term unemployment increases *persistently* more than short-term unemployment, which seems more aligned with a low frequency decrease in the probability of being re-employed and more compatible with slow-moving and deep-rooted changes in the labour market. In contrast, workers may not lose their skills during short unemployment spells. With this option, $-1 \leq I_t^U \leq 1$, where a negative outcome indicates that a larger share of workers is unemployed by less than 12 months. Figure 1 shows that the sharp increase in Portuguese unemployment during the 2007-09 financial turmoil and the sovereign debt crisis was largely driven by both short- and long-term unemployment. This option limits the effects of the crisis in comparison with the sole use of long-term unemployment. There was clearly a less accentuated rise in the gap between long- and short-term unemployment. Similar conclusions can be drawn for the euro area.

Figure 2 plots the changes in trend versions of total unemployment, long-term unemployment and the gap between long- and short-term unemployment. Results illustrate that while changes in trend overall unemployment oscillate between -0.4 and +0.7 pp in Portugal and -0.2 and +0.4 pp in the euro area, these intervals are reduced to [-0.1, +0.2] and [-0.1, +0.1] in the case of the third indicator.

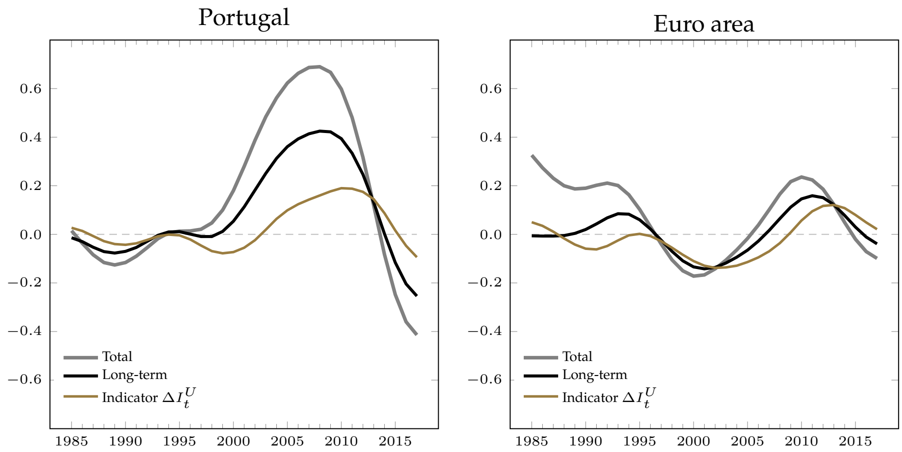

Figure 2: Changes in unemployment, long-term unemployment and indicator I_t^U

Sources: Banco de Portugal, Eurostat, OECD, Statistics Portugal and authors' calculations.

Note: The changes correspond to the first difference of the HP-filtered series ploted in Figure 1.

Section 4.2 evaluates the impact of all alternative indicators for I_t^U. Given that the final impact also depends on ρ_2 estimates (Equation 8), we also estimated the impact of excluding I_t^U, i.e. set $\rho_2 = 0$, both with I(1) and I(2) specifications.

2.3. *The parametrization*

Portuguese and euro area models are parametrized with Bayesian techniques. We kept both structure as identical and parsimonious as possible, to favour comparability, subject to the restrictions that initial prior moments are acceptable starting points, and posterior moments are compatible with sensible interpretations. In line with economic theory we impose sign restrictions, as clarified below.

The polynominal lag structure, presented in Table 1, is identical for both economies, except in equation (6). For Portugal we consider that the output gap follows an autoregressive process of order 2, whereas for the euro area we assume an order 1. Without loss of generality, we refrained from estimating the autoregressive parameters of equations (19) and (20), the former by setting $A_6(1) = 1$, and the latter by assuming random walk processes. For parsimonious reasons we also set $\rho_5 = 1$ and $I_t^{\pi^w} = 0$ in equation (16), as a high level of nominal flexibility is already achieved by estimating ρ_4 in equation (14).[9]

9. Results using $AR(1)$ processes in equations (19) and (20) are available upon request, as well as ρ_5 estimates assuming that $I_t^{\pi^w} = \pi_t^w$.

	Equations	Parameters	**Portugal**	**Euro area**
A polynomial				
p_1	(6)	α_1, α_2	2	1
p_2	(9)	γ_1	1	1
p_3	(12)	η_1	1	1
p_4	(15)	β_1	1	1
p_5	(18)	β_3	1	1
p_6	(19)	–	–	–
p_i	(20)	–	–	–
B polynomial				
q_2	(9)	γ_2, γ_3	2	2
q_3	(12)	η_2	1	1
q_4	(15)	β_2	1	1
q_5	(18)	β_4	1	1
q_6	(19)	–	–	–

Table 1. The model's lag structure

Note: Polynominals of type B omit the contemporaneous term, reducing the degree of endogeneity of the model. Identifiers p_i consider $i = \{tfp, U, h, \pi^p, \pi^w\}$.

Prior distributions are identical, as reported in Table 2. The autoregressive components in all economic relationships assume a Beta distribution (which avoids an explosive behaviour), while Gamma distributions guarantee parameters' signs that are in line with economic theory. All standard errors of innovations have inverse-Gamma prior distributions.

Some coefficients feature sign restrictions, namely $-\gamma_2 < 0$ and $-\gamma_3 < 0$ in equation (9). The unemployment gap implicit in equation (18) has also a negative coefficient given by $-\beta_4 < 0$, whereas the labour force gap has a positive coefficient given by $\beta_4 > 0$. Posterior parameters are median values of posterior distributions, as in Jarociński and Lenza (2018) or Tóth (2019). Differences compared with mean values are, however, negligible.

Results show that direct shocks on output and unemployment gaps tend to disseminate over time throughout the Portuguese economy, subject to higher autoregressive responses than in the euro area ($\alpha_1 + \alpha_2 = 0.93$, which compares with 0.85, while $\gamma_1 = 0.78$, which compares with 0.67). In contrast, autoregressive parameters of labour force, price and wage equations are lower in Portugal. The unemployment gap sensitivity to changes in output gap is lower in Portugal ($-\gamma_2 - \gamma_3 = -0.16$, which compares with -0.24 for the euro area). Long-term Okun's coefficient, defined as $(-\gamma_2 - \gamma_3)/(1 - \gamma_1)$, is relatively large, standing at -0.7 in both Portugal and the euro area.[10]

Low-frequency movements in observed data are, in general, less relevant to inform the Portuguese underlying variables, as depicted by lower ρ_i estimates ($i = 1, ..., 4$). Parameter ρ_3, however, is relatively close in both economies.

10. Maria (2016) also computed similar Okun's coefficient in both regions (close to -0.6 in 2015).

Model structure	Param.	Prior Dist. Mean	Dist.	s.d.	Posterior Dist. - Portugal 5%	50%	95%	Mean	Posterior Dist. - Euro area 5%	50%	95%	Mean
Economic relationships												
Output gap equation: $y_t - \bar{y}_t$												
$(y_{t-1} - \bar{y}_{t-1})$	α_1	0.50	β	0.15	0.58	**0.72**	0.84	0.72	0.76	**0.85**	0.92	0.85
$(y_{t-2} - \bar{y}_{t-2})$	α_2	0.40	β	0.20	0.09	**0.21**	0.36	0.22	-	-	-	-
Output elasticity of labour	ι	0.63	β	0.05	0.59	**0.65**	0.71	0.65	0.58	**0.64**	0.69	0.64
Okun's law: $U_t - \bar{U}_t$												
$(U_{t-1} - \bar{U}_{t-1})$	γ_1	0.50	β	0.15	0.64	**0.78**	0.88	0.77	0.48	**0.67**	0.82	0.67
$(y_{t-1} - \bar{y}_{t-1})$	γ_2	0.50	Γ	0.30	0.04	**0.10**	0.19	0.10	0.05	**0.14**	0.26	0.15
$(y_{t-2} - \bar{y}_{t-2})$	γ_3	0.50	Γ	0.30	0.02	**0.06**	0.14	0.07	0.03	**0.10**	0.21	0.11
Price equation: $\pi_t^p - \bar{\pi}_t^p$												
$(\pi_{t-1}^p - \bar{\pi}_{t-1}^p)$	β_1	0.50	β	0.10	0.13	**0.20**	0.29	0.20	0.28	**0.41**	0.56	0.41
$(y_{t-1} - \bar{y}_{t-1})$	β_2	0.50	Γ	0.30	0.08	**0.23**	0.48	0.25	0.07	**0.19**	0.34	0.20
Wage equation: $\pi_t^w - \bar{\pi}_t^w$												
$(\pi_{t-1}^w - \bar{\pi}_{t-1}^w)$	β_3	0.50	β	0.15	0.05	**0.11**	0.20	0.12	0.12	**0.25**	0.41	0.26
$(l_{t-1} - \bar{l}_{t-1})$	β_4	0.50	Γ	0.15	0.35	**0.56**	0.85	0.58	0.24	**0.38**	0.56	0.39
Labour force equation: $h_t - \bar{h}_t$												
$(h_{t-1} - \bar{h}_{t-1})$	η_1	0.50	β	0.20	0.20	**0.40**	0.62	0.41	0.60	**0.82**	0.95	0.80
$(U_{t-1} - \bar{U}_{t-1})$	η_2	0.20	Γ	0.10	0.06	**0.14**	0.27	0.15	0.04	**0.11**	0.20	0.11
Unobserved components' law of motion												
Trend TFP $(I_t^{t\bar{f}p})$	ρ_1	0.50	Γ	0.20	0.29	**0.53**	0.94	0.56	0.41	**0.70**	1.10	0.72
NAWRU $(I_t^{\bar{U}})$	ρ_2	0.50	Γ	0.20	0.24	**0.46**	0.81	0.49	0.34	**0.61**	0.99	0.63
Trend labour force $(I_t^{\bar{h}})$	ρ_3	0.50	Γ	0.20	0.26	**0.44**	0.70	0.45	0.25	**0.43**	0.67	0.44
Trend inflation $(I_t^{\bar{\pi}^p})$	ρ_4	0.50	Γ	0.20	0.07	**0.12**	0.19	0.12	0.14	**0.24**	0.36	0.24
Standard errors of innovations: economic relationships												
Output gap: $y_t - \bar{y}_t$	σ^{ε_1}	1.00	Inv-Γ	∞	0.0104	**0.0117**	0.0132	0.0118	0.0089	**0.0101**	0.0115	0.0101
Okun's law: $U_t - \bar{U}_t$	σ^{ε_2}	1.00	Inv-Γ	∞	0.0072	**0.0082**	0.0093	0.0082	0.0072	**0.0083**	0.0096	0.0083
Price equation: $\pi_t^p - \bar{\pi}_t^p$	σ^{ε_4}	1.00	Inv-Γ	∞	0.0488	**0.0540**	0.0601	0.0542	0.0116	**0.0131**	0.0150	0.0132
Wage equation: $\pi_t^w - \bar{\pi}_t^w$	σ^{ε_5}	1.00	Inv-Γ	∞	0.0545	**0.0608**	0.0678	0.0609	0.0151	**0.0172**	0.0196	0.0172
Lab. force equation: $h_t - \bar{h}_t$	σ^{ε_3}	1.00	Inv-Γ	∞	0.0114	**0.0128**	0.0145	0.0129	0.0078	**0.0089**	0.0102	0.0090
Standard errors of innovations: unobserved components												
TFP growth: $\Delta t\bar{f}p$	$\varepsilon_t^{\Delta \overline{tfp}}$	0.01	Inv-Γ	∞	0.0012	**0.0020**	0.0031	0.0021	0.0008	**0.0011**	0.0015	0.0011
NAWRU: $\bar{U}$	$\sigma^{\varepsilon^{\bar{U}}}$	0.01	Inv-Γ	∞	0.0010	**0.0016**	0.0023	0.0016	0.0009	**0.0013**	0.0019	0.0013
Expected price inflation: $\bar{\pi}^p$	$\sigma^{\varepsilon^{\bar{\pi}^p}}$	0.01	Inv-Γ	∞	0.0008	**0.0013**	0.0022	0.0014	0.0008	**0.0012**	0.0018	0.0012
Expected wage inflation: $\bar{\pi}^w$	$\sigma^{\varepsilon^{\bar{\pi}^w}}$	0.01	Inv-Γ	∞	0.0020	**0.0053**	0.0171	0.0069	0.0015	**0.0028**	0.0051	0.0030
Trend labour force: $\bar{h}$	$\sigma^{\varepsilon^{\bar{h}}}$	0.01	Inv-Γ	∞	0.0013	**0.0020**	0.0030	0.0021	0.0011	**0.0016**	0.0023	0.0016

Table 2. Estimated parameters

Source: Authors' calculations.

Notes: Economic relationships and unobserved components include in parenthesis the variable that is being affected by the associated parameter (Param.), *e.g.*, α_1 affects $(y_{t-1} - \bar{y}_{t-1})$ in the output gap equation. Prior distributions are identical for both Portugal and the euro area. Identifiers β, Γ and Inv-Γ refer to Beta, Gamma and Inverse-gamma distributions, respectively. Identifier "s.d." refers to standard deviations. Posterior distributions are computed with 8 million draws, from which we discard 40%. The estimation period is 1980Q1-2018Q2 for Portugal and 1985Q1-2018Q2 for the euro area. Percentages 5%, 50% and 95% refer to percentiles of posterior distribution and the benchmark parametrization is in bold. Parameters γ_2, γ_3 and η_2 are positive in this table but are subject to sign restrictions (and thus enter in the model as $-\gamma_2$, $-\gamma_3$ and $-\eta_2$). Results are based on IRIS, a Matlab toolbox available at `http://www.iris-toolbox.com`.

In general, shocks hitting the Portuguese economy have higher standard deviations, both in terms of main economic relationships and of unobserved components' law of motion. This is consistent with more volatile product and labour markets.

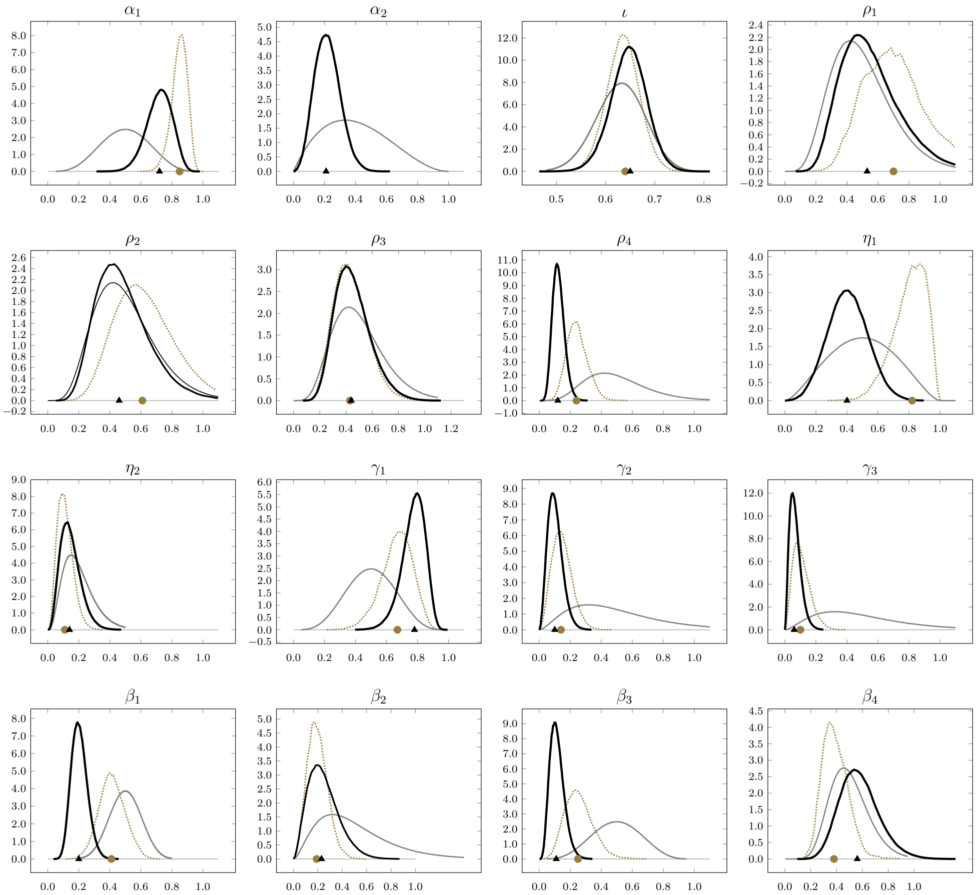

Figure 3: Priors and posteriors

Source: Authors' calculations.

Notes: Prior distributions for both Portugal and the euro area are in gray. Posterior distributions are in black for Portugal (posterior medians are highlighted in black triangles), and in ochre for the euro area (idem, ochre circles).

Posterior distributions associated with economic relationships and with unobserved component's law of motion are depicted in Figure 3.[11] For convenience, posterior medians are also reported, namely with black triangles for Portugal and ochre circles for the euro area.

Although prior distributions are identical, there is enough information in the data to distinguish the two economies. For instance, the autoregressive dynamics in the wage inflation gap (β_3) is estimated with less uncertainty in

11. Posterior distributions of standard errors are omitted but available from the authors upon request.

Portugal, and the posterior median is lower. In some cases priors take a highly informative nature. The most striking case is the elasticity of output to labour (ι), which by design is not allowed to substantially deviate from typical values of the labour's share of income.[12]

In general, however, informative prior distributions in one economy do not necessarily remain informative in the other. An example is the parameter in the wage equation (β_4), in which the prior is only closer to the posterior distribution in the Portuguese case. Posterior distributions of parameters associated with the low-frequency indicator for trend adjusted TFP (ρ_1) and for the NAWRU (ρ_2) are also closer to prior distributions in Portugal. In turn, the posterior distributions of parameters associated with lagged inflation (ρ_4) is distant from priors, and also rather different across the two economies.

A final methodological note: posterior distributions were computed with 1980Q1–2018Q2 quarterly data for Portugal and 1985Q1–2018Q2 for the euro area. Posterior medians were afterwards selected to compute unobserved components over the 1980–2018 period for both Portugal and the euro area. Unobserved euro area components over 1980–1985 period were extrapolated by fixing all previously-computed unobserved components in the estimation sample. All unobserved time series are smoothed estimates computed with the Kalman filter. By extending the database to a period prior to the euro area creation, we enrich our analysis with a larger time span and avoid focusing on a sample highly conditioned by the 2007-13 period. Additionally, to reduce end-of-period biases, unobserved components take into account an extension of the sample period with projections up to 2021 for Portugal (taken from Banco de Portugal) and up to 2020 for the euro area (taken from AMECO).

3. Potential output in Portugal and in the euro area

Figure 4 (left) depicts annual changes in actual and potential output for the Portuguese economy and the euro area between 1981 and 2017. Despite the considerable transformations that have occurred over such a long period of time, results suggest that the model is able to cope with these significant time-varying economic conditions, in this case the higher volatility of the Portuguese product and labour markets *vis-à-vis* the euro area.

Model-based estimates for Portugal point to a strong deceleration path of potential output since the 90s, followed by negative rates of change in the aftermath of the international financial turmoil and sovereign debt crisis, implying an estimated reduction in the potential output level. Since 2013, however, potential output growth has inverted this trend, becoming positive

12. Assuming labour and output markets operate in perfect competition, this elasticity can be inferred by the wage share in value added.

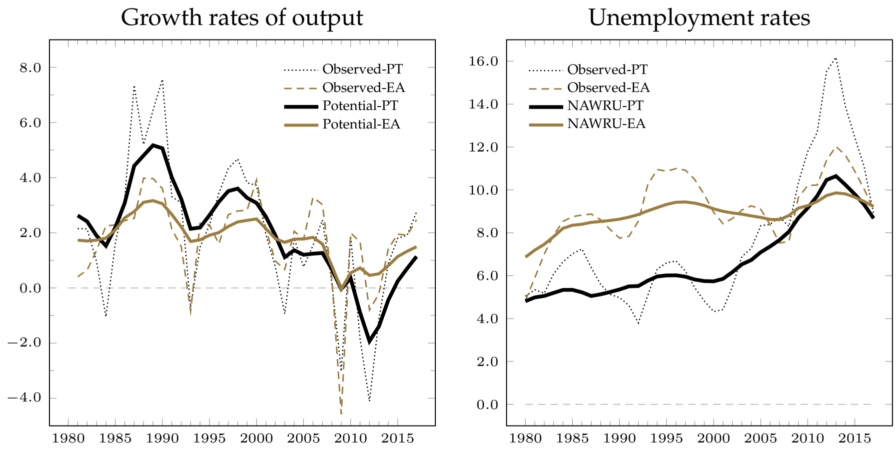

Figure 4: Potential output and the NAWRU

Sources: Area-wide model database, Banco de Portugal, Eurostat, Statistics Portugal and authors'calculations.

Notes: Indentifiers PT and EA refer to Portugal and the euro area; growth rates are in percentage and unemployment rates are expressed in percent of the labour force.

in 2015 and standing around 1% in 2017. The Portuguese economy has been growing above its potential since 2014, while potential growth remains considerably below the estimated rates for the 80s and 90s (more than 2 pp below).

The model points to more stable growth rates in the euro area, namely more modest growth rates during the first two decades and a less pronounced deceleration thereafter. In particular, potential output grew on average 2% during the 80s and 90s, almost 1 pp less than Portugal. At the trough of the crisis, potential growth decreased to close to 0%, but did not decline as in the Portuguese case. Potential output in the euro area has continuously accelerated since then, reaching growth rates of approximately 1.5% in 2017, still below the growth rates estimated for the pre-crisis period (but above Portuguese estimates).

Figure 4 (right) depicts the unemployment rate and the NAWRU. Over the 80s and the 90s, the estimated average level of Portuguese NAWRU is around 5.5%, which is in line with previous empirical literature (Centeno *et al.* 2009; Esteves *et al.* 2004). Since the beginning of the 2000s, model-based estimates point towards an increasing trend. After having peaked at 11% in 2013, the NAWRU is estimated to have declined, though remaining at a fairly high

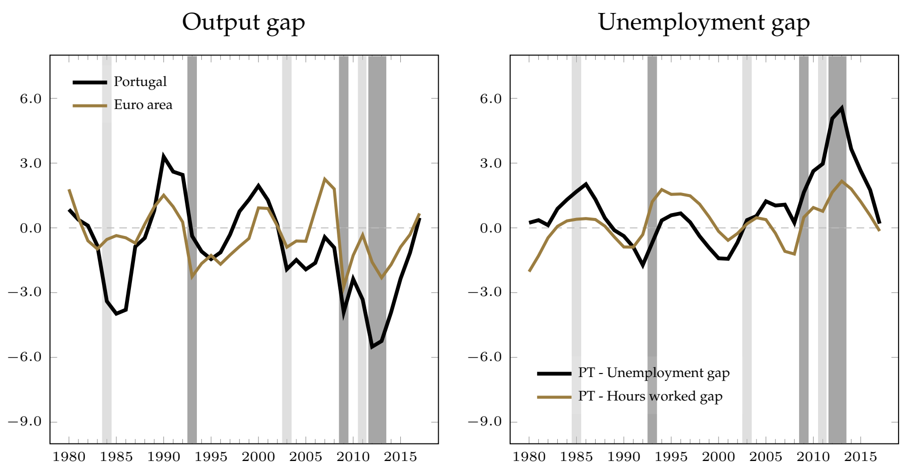

Figure 5: Okun's law

Source: Authors' calculations.

Notes: Darker shaded areas highlight periods where GDP fell simultaneously in Portugal and the euro area; lighter areas highlight periods where GDP fell in Portugal; labour slack measures include both the unemployment gap $(U_t - \bar{U}_t)$, and the total hours hourked gap $(l_t - \bar{l}_t) = (h_t - \bar{h}_t) - (U_t - \bar{U}_t)$.

rate in 2017 (8.5%).[13] In the context of the model it is important to highlight that long-term unemployment increased persistently more than short-term unemployment between 2003-15—an increase in the I_t^U—, which pushes upward NAWRU estimates. These figures compare to very modest increases in euro area estimates over the entire sample period, and to a smaller impact of the crisis. Notice, however, that the euro area presented persistently higher unemployment rates over the first three decades. Therefore, the developments observed in the Portuguese labour market imply that both observed and trend unemployment approached euro area levels.

Figure 5 presents the output and unemployment gaps. While business cycles seem relatively synchronized with the euro area, output gaps tend to be considerably larger in Portugal, ranging between -5.7% and 3.6%, while the euro area estimates range between -2.9% and 2.4%. Results show a negative output gap in the aftermath of the international financial crisis and the sovereign debt crisis—the largest over the entire sample in both economies—followed by a narrowing movement also in both economies until 2017. As expected, output gaps are mirrored by unemployment gaps.

13. NAWRU estimates are probably influenced, over this period, by persistent effects of the economic crisis, and possibly by labour market reforms, none of these specifically addressed in the model.

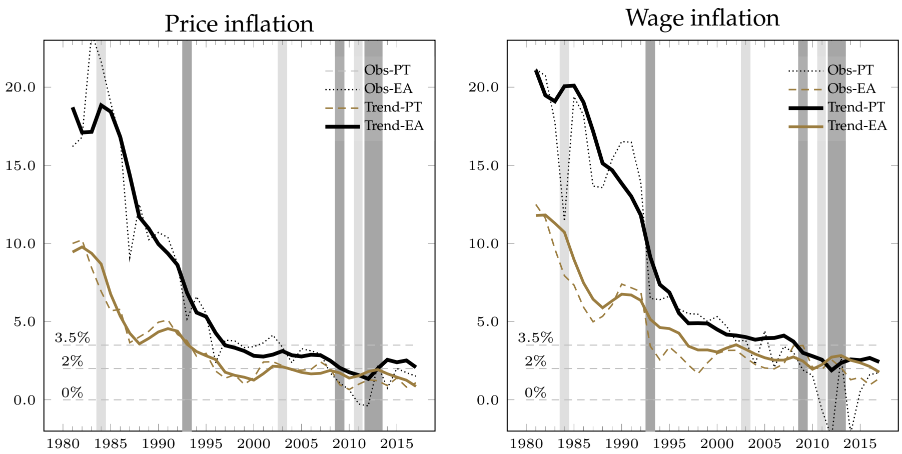

Figure 6: Price and wage inflation (actual and trend)

Sources: Area-wide model database, Banco de Portugal, Eurostat, Statistics Portugal and authors'calculations.

Note: See notes of Figure 5.

Figure 6 depicts developments in trend price and wage inflation alongside observed data. Results show that Portugal witnessed higher price and wage increases (both observed and trend) than the euro area during most of the sample. Despite noticeable disinflationary movements in both economies, the adjustment in Portugal was larger, narrowing the differential *vis-à-vis* the euro area. Notwithstanding, price and wage inflation in the early 90s had only reached euro area levels of the early 80s. In addition, trend price inflation remained above the euro area counterpart over almost the entire sample and above the reference value of 2% during most of the post-1999 period, while the euro area converged to *below but close to* 2% since the inception of the euro (both in terms of actual and trend values). Similarly, since the late 90s euro area actual and trend wage inflation evolved between 2 and 3.5%, while Portugal only reached values below 3.5% after 2009.

The most recent crisis period was the only exception, with actual Portuguese price and wage inflation falling both below their trends and below euro area levels, in line with large negative output gaps and slack in the labour market. Notice that during the recent crisis, slack in the labour market was greater than what the unemployment gap indicates, due to a negative labour force gap. Therefore, as clarified by equation (18), both the labour force slack and the unemployment gap matter.

Finally, despite the nominal instability observed in Portugal during the first two decades, results confirm that price and wage equations (equations (15) and (18), respectively) were able to cope with the distinct pre- and post 1999 developments. Indeed, these equations allow for distinct shocks, namely, larger estimated exogenous price shocks in Portugal than in the euro area; and more comparable exogenous wage shocks. Notice that the former may be partly related to the external environment of the Portuguese economy, namely, to external price shocks.

4. Model evaluation

Parameter, model and data uncertainty, evaluated in the next sections, are standard sources of concern that might have a significant impact on the estimates of unobserved variables.[14]

4.1. Parameter uncertainty

Figure 7 plots uncertainty bands using the 5th-95th percentile range of possible outcomes over the sample period, and superimposes the benchmark results computed with posterior medians.

Estimates suggest that output gap uncertainty is much higher in the Portuguese case, in comparison with the euro area, alongside noticeable time-varying effects, both in terms of symmetry and amplitude. On several occasions the estimated median is symmetrically enclosed by the confidence band, in contrast with occasions where asymmetries are clear. The time-varying amplitude is quite noticeable in the Portuguese case. The largest value has been reached over the 2009–2013 period. Finally, the plotted interval often contains the nil output gap when point estimates suggest positive or negative signs.

Regarding potential growth, the Portuguese economy also features higher volatility. However, in this case benchmark results are relatively more robust and none of the main qualitative messages of previous sections are challenged. The same is valid for the level and changes of the unemployment gap. The results suggest that policy makers should perhaps focus more on changes in unemployment gaps rather than on specific levels.[15]

Figure 8 collects annual median estimates of parameters using an expanding window between 2008–2017, *i.e.* the first sample period starts in 1980Q1 and ends in 2007Q4, the second ends in 2008Q1, etc. Results are mixed. This recursive exercise shows that, on the one hand, some parameters have been relatively stable in the Portuguese case since 2007Q4, for instance those associated with the labour force (ρ_3, or η_2). On the other hand, other parameters have upward or downward trends with different slopes. The autoregressive parameters linked with output gap and unemployment

14. Some results used in this section are only briefly highlighted, while others are omitted, but all are available from the authors upon request.

15. This result is in line with Druant *et al.* (2012).

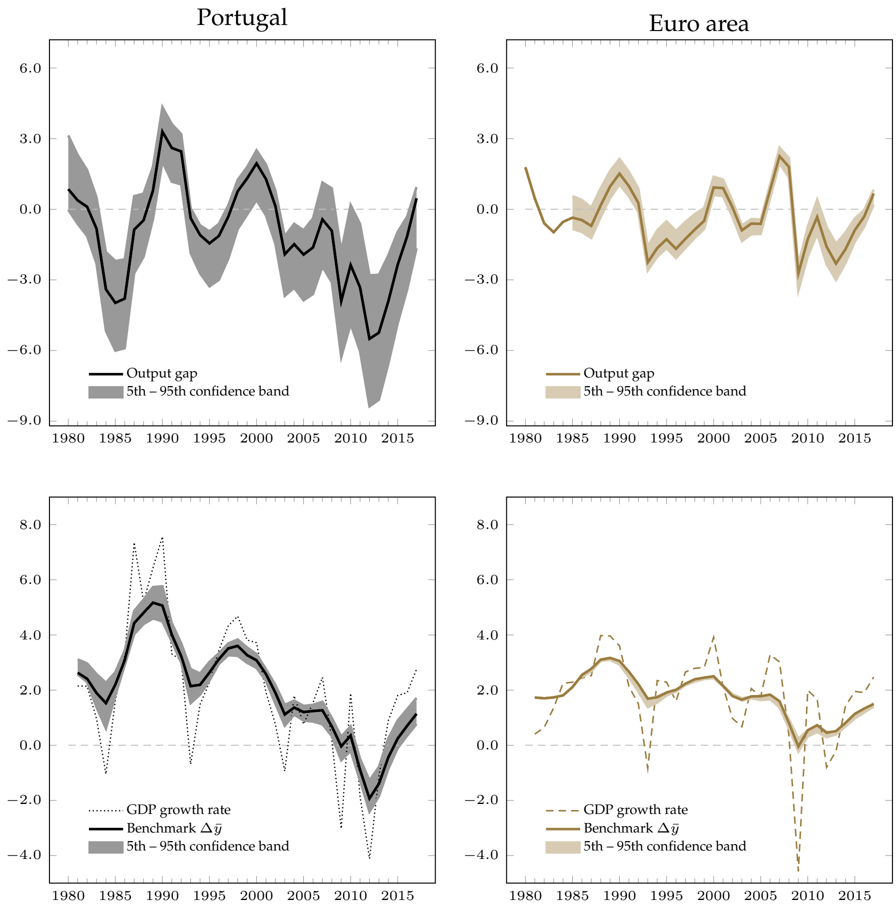

Figure 7: Parameter uncertainty

Sources: Area-wide model database, Banco de Portugal, Eurostat, Statistics Portugal and authors' calculations.

Note: The first row of graphs corresponds to output gaps; the second row to growth rates.

dynamics, namely α_1 and γ_1, increased over the period, while the parameters linked with nominal developments decreased, namely β_1 and β_3.

Coefficients affecting the importance of low-frequency movements in observed data depict some stability, with the exception of ρ_2, which shows a downward trend in the Portuguese case since 2008, from around 0.65 to 0.45. This result is conditioned by labour market developments over this period, characterized by systematic larger movements in the unemployment rate than in the chosen indicator. A question that we address in the next section is whether we should set $\rho_2 = 0$, and thus ignore the information content of $I_t^{\bar{U}}$, or simply assume an I(1) process for the NAWRU.

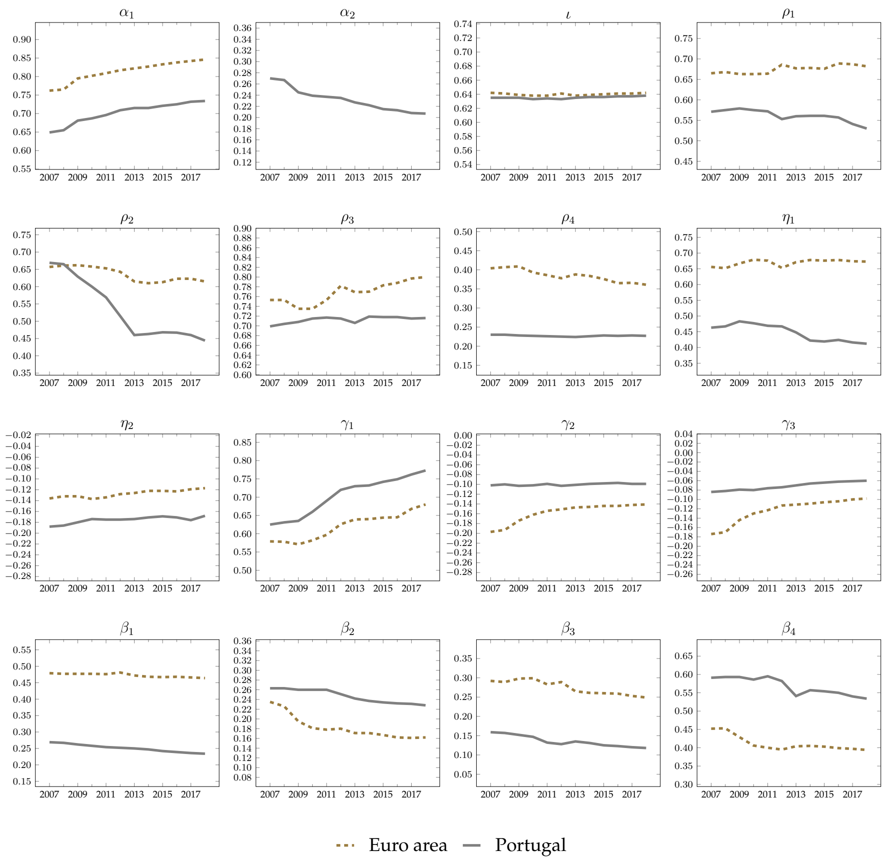

Figure 8: Recursive posterior median estimates

Source: Authors' calculations.

The first row of Figure 9 presents the output gap revisions brought about by the time-varying medians reported in Figure 8, in comparison with those brought about by an HP filter over equivalent expanding windows of the GDP database. These revisions are mean-squared deviations from output gaps computed with the full sample period. Values lower than 1 denote more stable output gap estimates of the U model compared to estimates obtained from an HP filter.

Results show that the U model is relatively more stable than the outcome of HP filters if one collects average deviations that occurred over the last 4, 8 or 12 quarters in each iteration (identified as [t; t-3], [t; t-7], and [t; t-11], respectively). If one collects mean-squared deviations that occurred for each single quarter, namely the latest (t), the one before ($t-1$), etc, the results are even more striking for Portugal (second row of Figure 9), suggesting a higher stability in all quarters. In the euro area results are, in

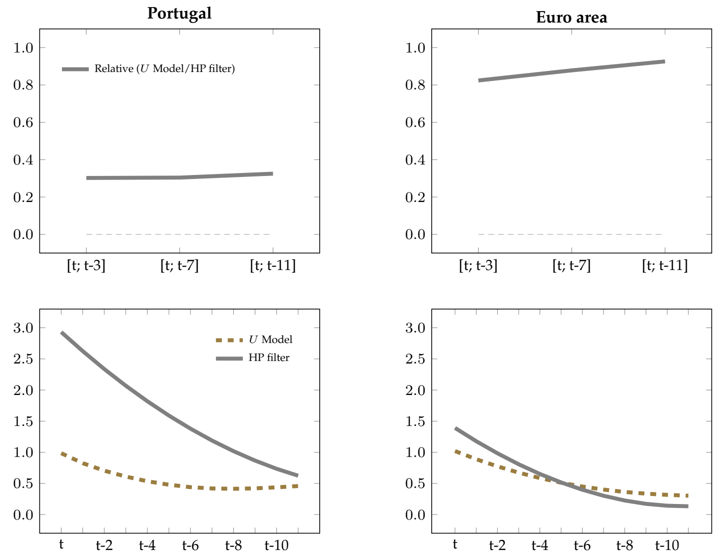

Figure 9: Output gap revisions

Source: Authors' calculations.

Note: All results are based on deviations against full sample estimates. The first row of graphs depicts the relative root-mean-squared deviation obtained with the U Model and (double-sided) HP filters; identifiers $t - i$, where $i = 0, 3, 7, 11$, refer to average deviations covering the period from the current quarter (t) to the last i quarter.

contrast, not distant from the outcome of an HP filter, though slightly more stable in the most recent quarters. In general, the U model seems suited to cope with time-varying conditions, as seen in the case of the Portuguese economy.

4.2. Model uncertainty

Figure 10 focuses on the impact of alternative laws of motion for the NAWRU. In addition to the benchmark parametrisation, we consider two alternative specifications. On the one hand, we consider the possibility of $\bar{U}_t$ being an I(1) variable in both Portugal and the euro area. This amounts to replacing equations (7) and (8) with

$$\bar{U}_t = \bar{U}_{t-1} + \varepsilon_t^{\bar{U}}. \tag{21}$$

On the other hand, we also consider the case in which $\bar{U}_t$ is I(2) but is not informed by low-frequency movements of observed data, which is equivalent to superimpose the restriction that $\rho_2 = 0$ in equation (8).

Clearly, choosing an I(1) or an I(2) specification changes the NAWRU's level and volatility. Impacts on the output gap coming from specifications

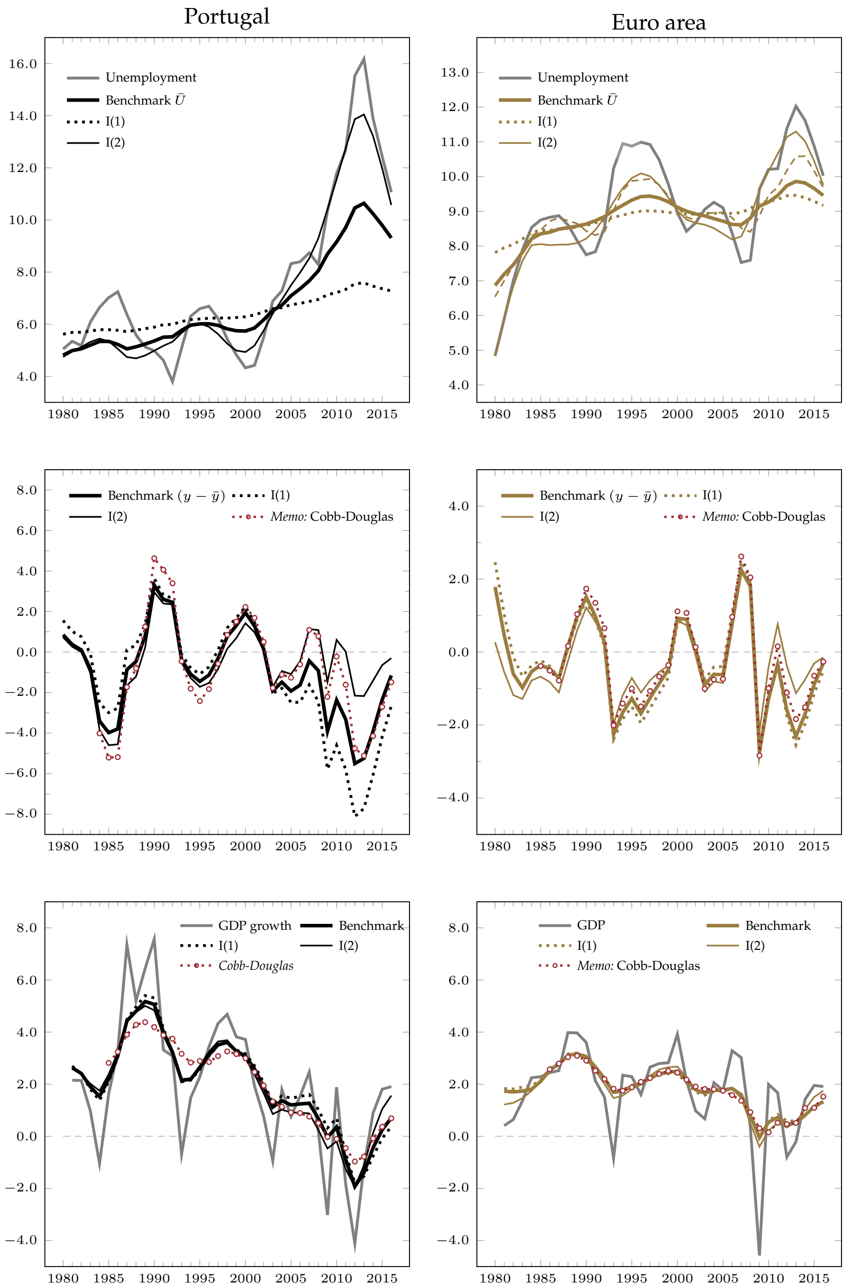

Figure 10: Model uncertainty

Source: Authors' calculations.

Notes: The first row of graphs corresponds to labour market outcomes of all models; the second and third rows to product markets, namely output gaps and growth rates. Dotted lines with markers denote a production function outside the model, using the benchmark NAWRU and an HP filter for all other inputs.

with alternative laws of motion for the NAWRU are reported in the second row of Figure 10.

The higher the NAWRU volatility the lower the unemployment gap and also, by design, the output gap. Results are again more striking in Portugal than in the euro area. Apparently, the information content in actual price and wage developments is not sufficient to restrict unobserved variables' estimates, particularly in the more volatile Portuguese economy. By using low frequency movements of observed data, the benchmark model represents a compromise between the two alternative options.

Posterior median estimates of all these alternative options, nevertheless, give a sense of constancy. With the exception of all those that are directly affected by the laws of motion for the NAWRU, all parameters remain relatively unchanged.[16]

When parameters are directly affected by the unemployment gap, the differences are somewhat larger, for instance γ_1. The same applies to standard deviations of unobserved components. When comparing all specifications, it is clear that shocks affecting the NAWRU equation need to be larger in the I(1) case.[17]

The second row of Figure 10 also reports an alternative output gap estimate in which potential output is derived from a Cobb-Douglas, using the benchmark NAWRU and an HP filter on all other inputs, as in Félix and Almeida (2006). This alternative methodology naturally leads to different results. In the Portuguese case, using a production function outside the model delivers results that are often close to the I(2) specification without information from observed data, but not during the entire sample. After 2010, for example, output gaps estimates are closer to the benchmark case.

The impact of model uncertainty on growth rates of potential output, presented on the third row of Figure 10, is smaller. The Portuguese economy features a higher volatility than the euro area but results remain relatively close to benchmark estimates. The Portuguese potential output growth estimates obtained solely from a Cobb-Douglas production function are not systematically different from the other options, except that the latter seem less procyclical.

In the euro area results are clustered around relatively tight intervals, both in terms of output gap and growth rates.

Finally, as discussed in section 2.2, we also assessed empirically the impact of using different indicators to inform NAWRU changes. In addition to the

16. For instance, the parameter associated with the autoregressive dynamics in the output gap (α_1) changes between 0.71 and 0.74 for Portugal and between 0.84 and 0.85 for the euro area. See Table C.1 in Appendix C for details.

17. As an example, parameter $\sigma^{\varepsilon^{\bar{U}}}$ increases marginally from 0.0016 to 0.0017 between the Portuguese benchmark and I(1) specifications, but decreases to 0.0011 in the I(2) case. Equivalent results for the euro area are 0.0013, 0.0014 and 0.0009, respectively.

indicator included in the benchmark model—filtered gap between long and short-term unemployment—we also analysed two additional indicators—long-term unemployment and HP-filtered long-term unemployment.

As shown in Figure 11, results suggest that, as before, level estimates are more affected, particularly NAWRU estimates, than growth rates of potential output. Moreover, changing the benchmark indicator I_t^U to the HP-filtered long-term unemployment causes relatively minor impacts. However, taking on board long-term unemployment directly results in a highly volatile NAWRU, which is associated with smaller cyclical components, both in terms of unemployment and output gaps.

4.3. Data uncertainty

Information uncertainty can take many forms. It may refer to the impact of alternative data in available databases. For instance, if we were to use distinct labour markets levels (available in AMECO, or labour force surveys), results would naturally change. In addition, there is information uncertainty regarding historical data vintages and data revisions.[18]

Instead of alternative datasets or data vintages, our analysis focuses exclusively on distinct sample periods, which may bring along different data moments. All outcomes presented in Section 3 are based on a unique sample period and a unique data vintage, both for Portugal and the euro area.

Figure 12 retrieves the benchmark results and reports the impact of ignoring data before 1995Q1. Conclusions have a similar flavour as before, namely that the *levels* of unobserved variables are more volatile, while *growth rates* tend to be more robust. We detect, in particular, a NAWRU upward shift both in Portugal and the euro area, particularly in the first part of this new sample. Part of this shift may be influenced by the increase in the average unemployment rate over the two samples.[19]

18. Blanchard and Portugal (2017) claim that the impact of data vintages is large for Portugal.

19. Parameter vectors are again median estimates. Appendix D show changes *vis-à-vis* the benchmark parametrization.

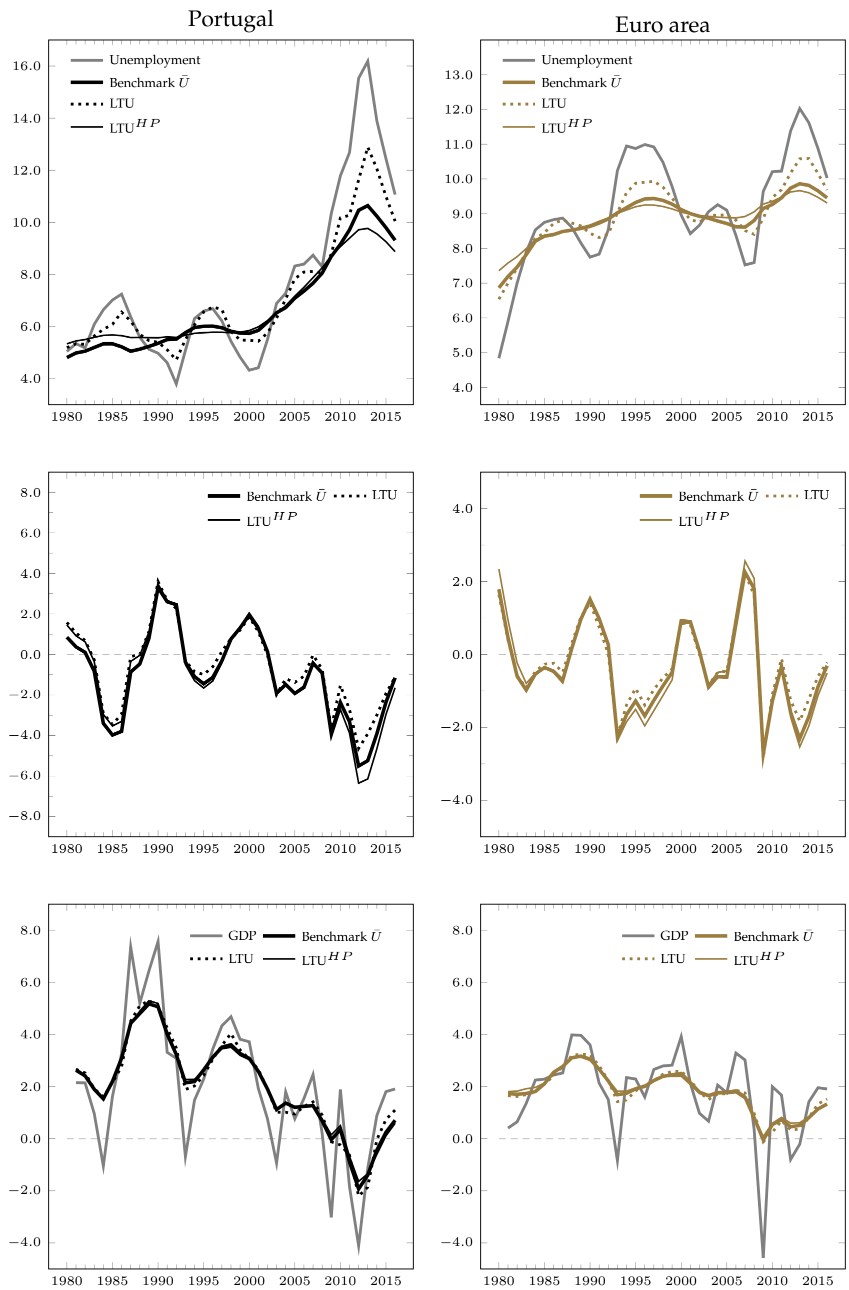

Figure 11: Actual long-term unemployment and the NAWRU

Source: Authors' calculations.

Notes: The first row of graphs corresponds to labour market outcomes of all models; the second and third rows to product markets, namely output gaps and potential output growth rates.

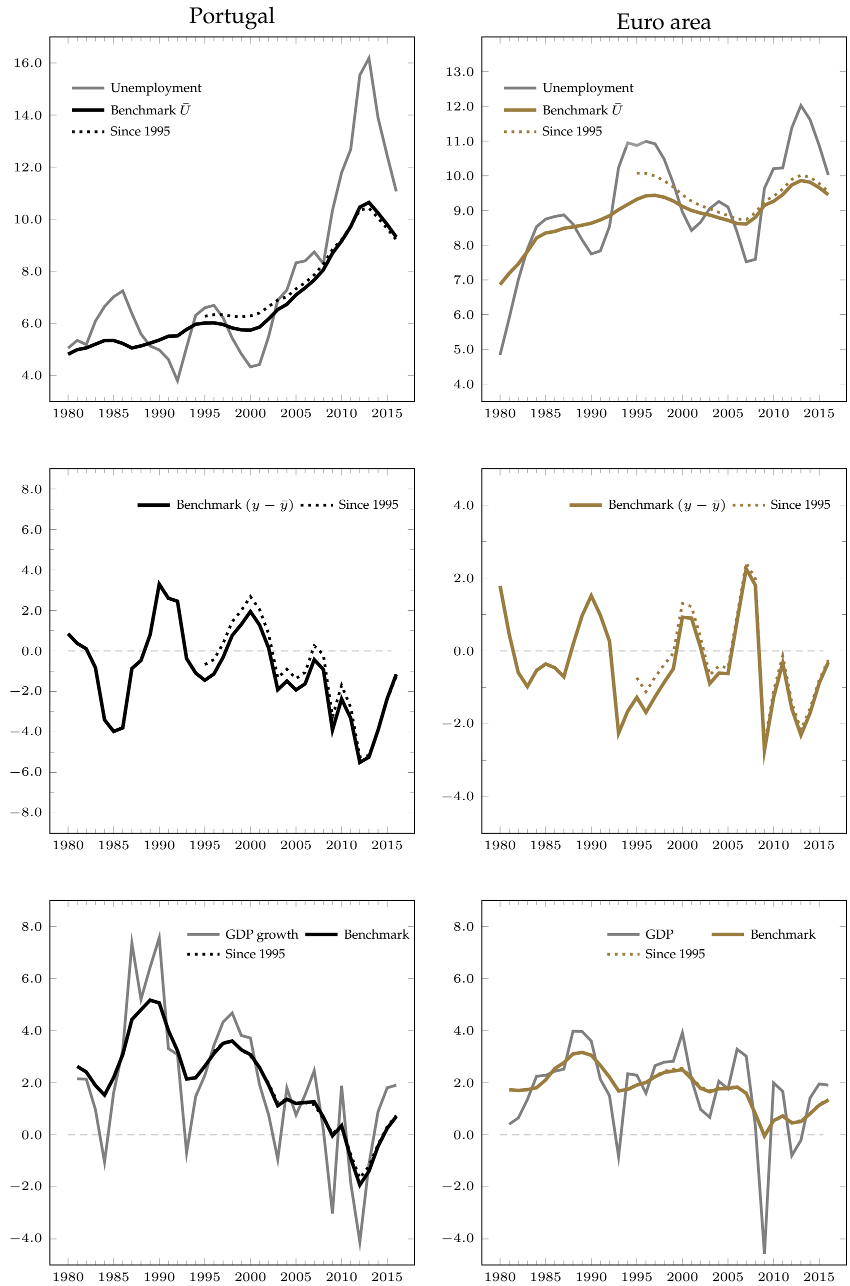

Figure 12: Information uncertainty

Source: Authors' calculations.

Notes: All graphs compare the same model with distinct sample periods, namelly the benchmark sample and and over 1995-2018.

5. Final Remarks

We used a flexible unobserved components model to successfully estimate relevant latent variables, such as potential output, under sizeable changes in economic conditions.

Introducing a time-varying unobserved drift in the price inflation trend equation of the model—briefly named *U* Model—was key to cope with distinct inflationary periods. Setting adequate starting points, prior to estimation, based on the information content of low frequency movements in observed data, was also relevant to partially influence final trend estimates. A special focus was placed, as a NAWRU driver, on low frequency relative dynamics of long- and short-term unemployment.

The model was estimated both for Portugal and the euro area, using data spanning four decades. To increase comparability we posit identical prior distributions and similar polynomial lag structures. Results suggest the failure of Portugal to interrupt a steeper deceleration of potential output *vis-à-vis* the euro area, or to avoid negative growth differentials for the most part of the last fifteen years, in a context of more volatile labour and product markets.

Following several sensitivity analyses, our main results proved robust. However, level estimates are more prone to parameter, model and data uncertainty than growth rates. Ignoring these uncertainty sources may lead to an economic assessment bias. Achieving a robust business cycle measurement requires, therefore, a comprehensive monitoring of the economy. Finally, given the importance of the time-varying unobserved drift in the price equation, the evaluation of alternative unobserved price dynamics will be considered in future work.

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Appendix A: An exact decomposition of labour input

Consider the following nomenclature:

LFN_t	$=$	Labour Force (+15 years old; Labour Force Survey (LFS))
U_t	$=$	Unemployment (15-74 years old; LFS), in per cent of LFN_t
L_t^{LFS}	$=$	Employment, heads (+15 years old; LFS)
L_t^{NA}	$=$	Employment, heads (all workers; National Accounts (NA))
AHN_t	$=$	Average hours worked, per head

Measured in total hours worked, labour input can be decomposed as $L_t^{LFS}.AHN_t = LFN_t\ (1 - U_t)AHN_t$. Given that we are interested in using L_t^{NA}, one needs to define, in logs:

$$l_t = h_t + log(1 - U_t) + \gamma_t \tag{A.1}$$

where $l_t = log(L_t^{NA}.AHN_t)$, $h_t = log(LFN_t.AHN_t)$, and the residual term $\gamma_t = log(L^{NA}/L_t^{LFS})$. The trend component of γ_t, defined as $\bar{\gamma}_t$ and omitted from equation (3), is jointly estimated in the model using the following set of equations

$$\begin{aligned}
\gamma_t &= \overline{\gamma}_t + (\gamma_t - \overline{\gamma}_t) && \text{(A.2)}\\
\overline{\gamma}_t &= \overline{\gamma}_{t-1} + \Delta_{t-1}^{\overline{\gamma}} && \text{(A.3)}\\
\Delta_t^{\overline{\gamma}} &= \rho \Delta I_t^{\overline{\gamma}} + (1-\rho)\Delta_{t-1}^{\overline{\gamma}} + \varepsilon_t^{\Delta\overline{\gamma}} && \text{(A.4)}\\
(\gamma_t - \overline{\gamma}_t) &= \varepsilon_t^{(\gamma-\overline{\gamma})} && \text{(A.5)}
\end{aligned}$$

where $\overline{\gamma}_t$ and $\Delta_t^{\overline{\gamma}}$ are unobservables, $\Delta I_t^{\overline{\gamma}}$ is a zero-mean indicator (computed with an HP filter on γ_t, with a smoothing parameter $\lambda = 30$), and $\varepsilon_t^{\Delta\overline{\gamma}}$ and $\varepsilon_t^{(\gamma-\overline{\gamma})}$ are error terms. Actual and trend components using the benchmark calibration are depicted in Figure A.1.

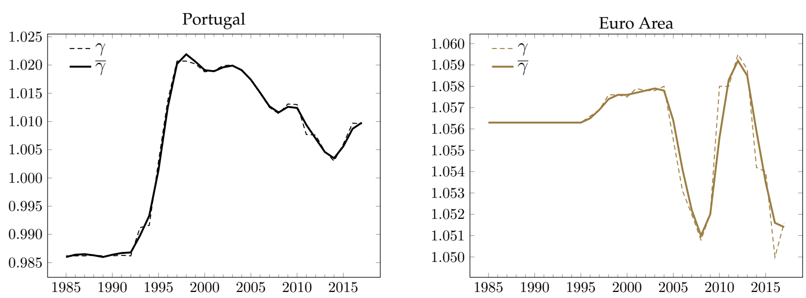

Figure A.1: Gap between NA and the LFS employment (γ)

Source: Authors' calculations.

Appendix B: Database details

Output
Quarterly seasonally adjusted Real Gross Domestic Product (logarithm).
Sources: Portugal - Statistics Portugal (1995Q1-2018Q2) and Banco de Portugal (used to backdate data to 1980Q1 and to project data until 2021Q4). Euro area - Eurostat (1995Q1-2018Q2); Area-wide model database (quarterly growth rates used to backdate data to 1980Q1); AMECO (yearly growth rates used to project data until 2020Q4).

Labour input
Level of labour supply measured in hours: sum of quarterly seasonally adjusted labour force (logarithm) and average hours worked (logarithm) adjusted by the number of unemployed and by the difference between employment in national accounts and in the Labour Force Survey.

Labour force
Quarterly seasonally adjusted labour force, which comprises all employed and unemployed persons (logarithm).
Sources: Portugal - Statistics Portugal (Labour Force Survey) and Banco de Portugal. Euro area - Eurostat, Labour Force Survey (2005Q1Q2-2018Q2); Area-wide model database (quarterly growth rates used to backdate data to 1980Q1); AMECO (yearly growth rates used to project data until 2020Q4).

Unemployment
Quarterly seasonally adjusted number of unemployed in percentage of the labour force.
Sources: Portugal - Statistics Portugal (Labour Force Survey) and Banco de Portugal. Euro area - Eurostat, Labour Force Survey (1998Q2-2018Q2); Area-wide model database (quarterly growth rates used to backdate data to 1980Q1); AMECO (yearly growth rates used to project data until 2020Q4).

Average hours worked
Number of hours worked per worker: difference between the total hours worked (logarithm) and the number of workers (logarithm).

Total hours worked
Quarterly seasonally adjusted total number of hours worked by all workers (logarithm). For Portugal, we assume that average hours worked before 1995Q1 were constant at the average value between 1995Q1-1998Q4.
Sources: Portugal - Statistics Portugal (national accounts) and Banco de Portugal. Euro area - Eurostat, national accounts (1995Q1-2018Q2); AMECO (yearly growth rates used to backdate data to 1980Q1 and project data until 2020Q4).

Labour input (Cont.)

Employment
Quarterly seasonally adjusted number of employed workers, including employees and self-employed workers (logarithm).
Sources: Portugal - Statistics Portugal and Banco de Portugal. Euro area - Eurostat (1995Q1-2018Q2); Area-wide model database (quarterly growth rates used to backdate data to 1980Q1); AMECO (yearly growth rates used to project data until 2020Q4).

Capital input
In the case of the euro area, annual capital stock is converted to quarterly frequency (logarithm).
Sources: Portugal - Banco de Portugal. Euro area - AMECO.

Total Factor Productivity (TFP)
TFP is computed as the Solow residual of a Cobb-Douglas production function.

Price inflation
Annualized quarter-on-quarter changes of GDP deflator (logarithm).
Sources: Portugal - Statistics Portugal and Banco de Portugal. Euro area - Eurostat (1995Q1-2018Q2); Area-wide model database (quarterly growth rates used to backdate data to 1980Q1); AMECO (yearly growth rates used to project data until 2020Q4).

Wage inflation
Annualized quarter-on-quarter changes of compensation of employees per hour worked (logarithm).

Compensation of employees
Quarterly seasonally adjusted compensation of employees.
Sources: Portugal - Statistics Portugal and Banco de Portugal. Euro area - Eurostat (1999Q1-2018Q2); Area-wide model database (quarterly growth rates used to backdate data to 1980Q1); AMECO (yearly growth rates used to project data until 2020Q4).

Hours worked by employees
Quarterly seasonally adjusted total number of hours worked by employees. For Portugal, we assume that average hours worked by employees before 1995Q1 were constant at the average value between 1995Q1-1998Q4.
Sources: Portugal - Statistics Portugal and Banco de Portugal. Euro area - Eurostat (1995Q1-2018Q2); AMECO (yearly growth rates of total average hours worked per worker used to backdate data to 1980Q1 and project data until 2020Q4).

Gap between long and short-term unemployment
The difference between annual long-term and short-term unemployment. The percentage of long-term unemployed over the unemployed for Germany, France, Italy and Spain is used as a proxy for the euro area. The gap is backdated to 1980 and projected until 2020, using the average value of the first and last two decades with available data, respectively.

Long-term unemployment
The annual number of long-term unemployed in percentage of the labour force.
Sources: OECD labour force statistics (Long-term unemployed in percentage of the unemployed, 1986-2017).

Short-term unemployment
The difference between the annual unemployment and the long-term unemployment, as defined above.

Appendix C: Model uncertainty

Model structure	Param.	Posterior Dist. - Portugal (1)	(2)	(3)	Posterior Dist. - Euro area (4)	(5)	(6)
Economic relationships							
Output gap equation: $y_t - \bar{y}_t$							
$(y_{t-1} - \bar{y}_{t-1})$	α_1	0.74	0.71	**0.72**	0.85	0.84	**0.85**
$(y_{t-2} - \bar{y}_{t-2})$	α_2	0.21	0.22	**0.21**	-	-	**-**
Output elasticity of labour	ι	0.64	0.66	**0.65**	0.64	0.64	**0.64**
Okun's law: $U_t - \bar{U}_t$							
$(U_{t-1} - \bar{U}_{t-1})$	γ_1	0.79	0.75	**0.78**	0.68	0.70	**0.67**
$(y_{t-1} - \bar{y}_{t-1})$	γ_2	0.11	0.09	**0.10**	0.15	0.13	**0.14**
$(y_{t-2} - \bar{y}_{t-2})$	γ_3	0.07	0.05	**0.06**	0.12	0.09	**0.10**
Price equation: $\pi_t^p - \bar{\pi}_t^p$							
$(\pi_{t-1}^p - \bar{\pi}_{t-1}^p)$	β_1	0.20	0.20	**0.20**	0.41	0.41	**0.41**
$(y_{t-1} - \bar{y}_{t-1})$	β_2	0.25	0.23	**0.23**	0.18	0.19	**0.19**
Wage equation: $\pi_t^w - \bar{\pi}_t^w$							
$(\pi_{t-1}^w - \bar{\pi}_{t-1}^w)$	β_3	0.11	0.11	**0.11**	0.25	0.24	**0.25**
$(l_{t-1} - \bar{l}_{t-1})$	β_4	0.51	0.59	**0.56**	0.37	0.40	**0.38**
Labour force equation: $h_t - \bar{h}_t$							
$(h_{t-1} - \bar{h}_{t-1})$	η_1	0.39	0.42	**0.40**	0.71	0.82	**0.82**
$(U_{t-1} - \bar{U}_{t-1})$	η_2	0.12	0.14	**0.14**	0.10	0.11	**0.11**
Unobserved components' law of motion							
Trend TFP $(I_t^{t\bar{f}p})$	ρ_1	0.47	0.59	**0.53**	0.72	0.68	**0.70**
NAWRU $(I_t^{\bar{U}})$	ρ_2	-	-	**0.46**	-	-	**0.61**
Trend labour force $(I_t^{\bar{h}})$	ρ_3	0.43	0.44	**0.44**	0.38	0.43	**0.43**
Trend inflation $(I_t^{\bar{\pi}^p})$	ρ_4	0.12	0.12	**0.12**	0.24	0.24	**0.24**
Standard errors of innovations: economic relationships							
Output gap: $y_t - \bar{y}_t$	σ^{ε_1}	0.0118	0.0117	**0.0117**	0.0101	0.0099	**0.0101**
Okun's law: $U_t - \bar{U}_t$	σ^{ε_2}	0.0083	0.0079	**0.0082**	0.0084	0.0082	**0.0083**
Price equation: $\pi_t^p - \bar{\pi}_t^p$	σ^{ε_4}	0.0542	0.0544	**0.0540**	0.0131	0.0131	**0.0131**
Wage equation: $\pi_t^w - \bar{\pi}_t^w$	σ^{ε_5}	0.0609	0.0610	**0.0608**	0.0171	0.0172	**0.0172**
Lab. force equation: $h_t - \bar{h}_t$	σ^{ε_3}	0.0128	0.0128	**0.0128**	0.0089	0.0089	**0.0089**
Standard errors of innovations: unobserved components							
TFP growth: $\Delta t\bar{f}p$	$\varepsilon_t^{\Delta \overline{tfp}}$	0.0021	0.0019	**0.0020**	0.0011	0.0011	**0.0011**
NAWRU: $\bar{U}$	$\sigma^{\varepsilon^{\bar{U}}}$	0.0017	0.0011	**0.0016**	0.0014	0.0009	**0.0013**
Expected price inflation: $\bar{\pi}^p$	$\sigma^{\varepsilon^{\bar{\pi}^p}}$	0.0013	0.0013	**0.0013**	0.0012	0.0012	**0.0012**
Expected wage inflation: $\bar{\pi}^w$	$\sigma^{\varepsilon^{\bar{\pi}^w}}$	0.0054	0.0059	**0.0053**	0.0028	0.0028	**0.0028**
Trend labour force: $\bar{h}$	$\sigma^{\varepsilon^{\bar{h}}}$	0.0020	0.0020	**0.0020**	0.0015	0.0016	**0.0016**
Log-likelihood		-6918.9	-6929.3	**-8267.1**	-7072.8	-7076.2	**-8259.5**

Table C.1. Estimated parameters: robustness checks

Source: Authors' calculations.

Notes: Columns (1) and (4) consider that the NAWRU is an I(1) variable, columns (2) and (5) consider that the NAWRU is an I(2) variable and columns (3) and (6) retrieve the benchamrk results; all results are obtained following the same approach of the benchmark model, *e.g.* all parameters are median of posterior distributions; the number of draws are the same, as well as the discharged percentages, etc. See Table 2 for details.

Appendix D: Information uncertainty

Model structure	Param.	Portugal (1)	Portugal (2)	Euro area (3)	Euro area (4)
Economic relationships					
Output gap equation: $y_t - \bar{y}_t$					
$(y_{t-1} - \bar{y}_{t-1})$	α_1	0.67	**0.72**	0.80	**0.85**
$(y_{t-2} - \bar{y}_{t-2})$	α_2	0.24	**0.21**	**-**	**-**
Output elasticity of labour	ι	0.63	**0.65**	0.64	**0.64**
Okun's law: $U_t - \bar{U}_t$					
$(U_{t-1} - \bar{U}_{t-1})$	γ_1	0.64	**0.78**	0.57	**0.67**
$(y_{t-1} - \bar{y}_{t-1})$	γ_2	0.19	**0.10**	0.17	**0.14**
$(y_{t-2} - \bar{y}_{t-2})$	γ_3	0.14	**0.06**	0.14	**0.10**
Price equation: $\pi_t^p - \bar{\pi}_t^p$					
$(\pi_{t-1}^p - \bar{\pi}_{t-1}^p)$	β_1	0.30	**0.20**	0.44	**0.41**
$(y_{t-1} - \bar{y}_{t-1})$	β_2	0.26	**0.23**	0.22	**0.19**
Wage equation: $\pi_t^w - \bar{\pi}_t^w$					
$(\pi_{t-1}^w - \bar{\pi}_{t-1}^w)$	β_3	0.11	**0.11**	0.35	**0.25**
$(l_{t-1} - \bar{l}_{t-1})$	β_4	0.52	**0.56**	0.35	**0.38**
Labour force equation: $h_t - \bar{h}_t$					
$(h_{t-1} - \bar{h}_{t-1})$	η_1	0.34	**0.40**	0.72	**0.82**
$(U_{t-1} - \bar{U}_{t-1})$	η_2	0.15	**0.14**	0.14	**0.11**
Unobserved components' law of motion					
Trend TFP $(I_t^{t\bar{f}p})$	ρ_1	0.64	**0.53**	0.63	**0.70**
NAWRU $(I_t^{\bar{U}})$	ρ_2	0.51	**0.46**	0.60	**0.61**
Trend labour force $(I_t^{\bar{h}})$	ρ_3	0.47	**0.44**	0.47	**0.43**
Trend inflation $(I_t^{\bar{\pi}^p})$	ρ_4	0.24	**0.12**	0.32	**0.24**
Standard errors of innovations: economic relationships					
Output gap: $y_t - \bar{y}_t$	σ^{ε_1}	0.0140	**0.0117**	0.0126	**0.0101**
Okun's law: $U_t - \bar{U}_t$	σ^{ε_2}	0.0124	**0.0082**	0.0115	**0.0083**
Price equation: $\pi_t^p - \bar{\pi}_t^p$	σ^{ε_4}	0.0308	**0.0540**	0.0153	**0.0131**
Wage equation: $\pi_t^w - \bar{\pi}_t^w$	σ^{ε_5}	0.0696	**0.0608**	0.0180	**0.0172**
Lab. force equation: $h_t - \bar{h}_t$	σ^{ε_3}	0.0172	**0.0128**	0.0120	**0.0089**
Standard errors of innovations: unobserved components					
TFP growth: $\Delta t\bar{f}p$	$\varepsilon_t^{\Delta \overline{tfp}}$	0.0019	**0.0020**	0.0012	**0.0011**
NAWRU: $\bar{U}$	$\sigma^{\varepsilon^{\bar{U}}}$	0.0020	**0.0016**	0.0015	**0.0013**
Expected price inflation: $\bar{\pi}^p$	$\sigma^{\varepsilon^{\bar{\pi}^p}}$	0.0018	**0.0013**	0.0015	**0.0012**
Expected wage inflation: $\bar{\pi}^w$	$\sigma^{\varepsilon^{\bar{\pi}^w}}$	0.0055	**0.0053**	0.0029	**0.0028**
Trend labour force: $\bar{h}$	$\sigma^{\varepsilon^{\bar{h}}}$	0.0023	**0.0020**	0.0018	**0.0016**

Table D.1. Information uncertainty

Source: Authors' calculations.

Notes: Columns (1) and (3) are computed with information over 1995Q1–2018Q2. The other columns retrieve the benchmark calibration. All results are obtained following the same approach of the benchmark model, *e.g.* all parameters are median of posterior distributions; the number of draws are the same, as well as the discharged percentages, etc. See Table 2 for details.

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