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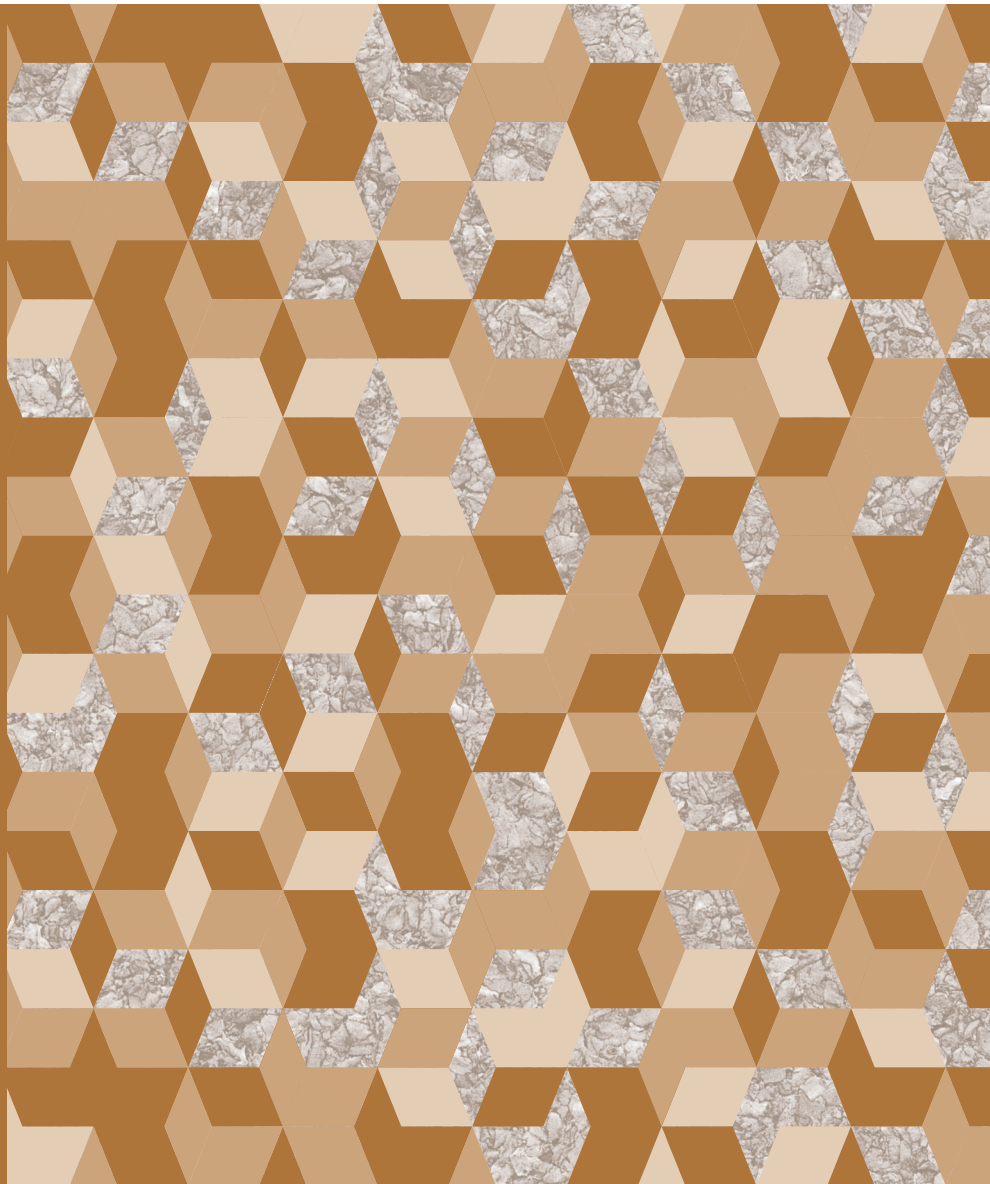

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Modelling currency demand in a small open economy within a monetary union

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Abstract
Currency management is a core business function of a central bank. Understanding the factors driving cash demand and its denomination structure are vital for the smooth functioning of the economy. We pursue an analytical framework which allows to model the demand for each denomination individually as well as to capture the interactions between them, both over the short- and long-run. The approach builds on the DSUR estimator for the long-run relationships coupled with a SUR ECM for modelling the short-run dynamics. The focus is on a small open economy within the euro area monetary union. Such a context adds dimensions which go beyond the traditional drivers considered in the previous literature. In particular, the importance of currency migration through tourism flows is highlighted. Furthermore, the interconnections between demand for different denominations are found to be quite significant and the heterogeneous role of the determinants across denominations is documented.

JEL: C32, E41, E50

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1. Introduction

The deepening of the Economic and Monetary Union led to the adoption of a single currency, the euro. Although the euro was launched on 1 January 1999, the introduction of euro banknotes and coins only took place on 1 January 2002. It was the largest-ever currency changeover with the euro becoming the currency of more than 300 million people in Europe.

Naturally, a key operational task of the Eurosystem is to ensure an adequate supply of euro currency to meet demand conditions. In fact, euro banknotes in circulation are one of the largest autonomous factors in the context of the Eurosystem liquidity management. In practice, euro banknotes are produced jointly by the national central banks of the euro area and each one is in charge of, and bears the costs of, a share of the total production. This issuance activity impacts on seigniorage revenues and its developments affect the need to invest in cash printing, storage, and distribution facilities. Within the Eurosystem, each central bank contributes to the decision making process regarding the production plans through national expertise concerning the currency demand evolution for the corresponding country.[1] Hence, it is crucial to understand the determinants of cash demand in each country to avoid disruptions to the functioning of the economy through shortfalls in the supply of currency and to avoid running unnecessary costs due to overproduction. Furthermore, the evolution of the demand for cash may also impact on the conduct of monetary policy (see, for example, Friedman (1999), Freedman (2000), Goodhart (2000) and Woodford (2000)).

As the determinants of currency demand may differ or have a different impact depending on the cash denomination, it is important to consider the breakdown in terms of value. For instance, large-value banknotes demand is more prone to be influenced by store of value purposes whereas low-value denominations demand is typically driven by the transactions motive. From a central bank point of view, it is also vital to sustain a proper mix of denominations in the currency supply. In this respect, Sargent and Velde (1999, 2002) discuss several historic episodes where the disruption of such a mix had a considerable economic impact.

1. In the case of euro coins, although the national governments of the euro area countries are responsible for minting coins, the overall value of the coins to be put into circulation has also to be approved by the Governing Council of the European Central Bank.

Recent work focusing on the modelling of cash demand by denomination includes, for example, Doyle (2000) who estimates currency demand equations for the United States, Germany, Switzerland, Canada, Netherlands and Austria and considers a breakdown of currency into large and small-value denominations for some of these countries. Judson and Porter (2004) focus on the United States and consider three groups of U.S. dollar bills. Amromin and Chakravorti (2009) study a panel of thirteen advanced economies and split cash into three denomination categories to investigate its store of value and payment functions. Nachane *et al.* (2013) and Cusbert and Rohling (2013) consider small, medium, and large denominations for India and Australia, respectively. Concerning the euro area, Fischer *et al.* (2004) consider small- and large-value denominations for the euro area countries drawing on euro legacy banknotes. More recently, Bartzsch *et al.* (2015) consider demand for small (€5, €10 and €20), medium (€50 and €100) and large (€200 and €500) banknotes issued by Deutsche Bundesbank since 2002. The results obtained in the above mentioned studies suggest a heterogeneous behavior across denominations.

The current study goes beyond the previous work by considering a larger disaggregation level of currency demand. In particular, all euro banknote denominations are taken individually, namely €500, €200, €100, €50, €20, €10, €5, besides coins. Such a high disaggregation level allows to unveil more markedly the heterogeneous behavior across denominations and enables a deeper assessment of the importance of the several determinants of currency demand.

Besides taking on board the heterogeneity across denominations, a key feature that one should also account for when modelling currency demand is the interaction between demands for different denominations. As denominations are substitutable at the margin, the interconnections cannot be disregarded. To address this issue, we consider an analytical framework which allows one to model the demand for each denomination as well as to capture the interactions between them, both over the short- and long-run. As standard in the literature on modelling currency demand, and more generally on the estimation of money demand functions, we consider an Error Correction Model (ECM) framework. However, we depart econometrically from previous work in the following way. By pursuing a two-step approach, we first focus on the estimation of a system of heterogeneous long-run relationships. In particular, we resort to the Dynamic Seemingly Unrelated Regression (DSUR) estimator proposed by Mark *et al.* (2005) which allows the efficient estimation of multiple-equation cointegration

regressions. In the second step, we proceed with the estimation of a SUR ECM for modelling the short-run dynamics. In this way, one is able to model the demand for each denomination while tackling the interconnections among demands over both the long-run relationships and short-run dynamics.

The current study focus on the Portuguese case which is an interesting one by nature. On the one hand, the impact of financial innovation on currency demand has been given an increasingly attention in the literature (see Snellman *et al.* (2001), Dutta and Weale (2001), Attanasio *et al.* (2002), Alvarez and Lippi (2009), Lippi and Secchi (2009) among others). As Portugal has been characterized by a strong penetration of financial technology, it constitutes a natural case study to assess the role of financial innovation on the demand for cash. On the other hand, the currency put into circulation may differ substantially from the domestic cash holdings. For instance, in countries like the United States, Japan, Germany and Switzerland, the currency issued by the central bank is strongly affected by foreign demand with a sizeable fraction of their currencies held outside their countries' borders (see, for example, Porter and Judson (1996), Rogoff (1998) and Bartzsch *et al.* (2011, 2013a, 2013b)). The currency demand by non-residents puts an upward pressure on the net cumulated issuance by the central bank. In contrast, the opposite evolution has been observed for Portugal. Such evidence raises the need to bring forth an additional driver of cash demand evolution. In particular, in a small open economy like Portugal, where tourism plays a noteworthy role, one should consider this channel when modelling cash demand. Since each national central bank is not the sole issuer of currency within the monetary union, tourism flows involving the inflow of euro currency may translate into a significant negative effect on the currency issued by the national central bank. Hence, such a determinant, which has not yet been considered in the literature, should be taken into account when modelling cash demand.

The paper is organised as follows. In section 2, the challenging nature of the Portuguese case for modelling currency demand is underlined. The econometric framework is outlined in section 3 and the empirical results are presented in the section 4. Finally, section 5 concludes.

2. Why is the Portuguese case a special one?

Since the physical introduction of the euro at the beginning of 2002, each central bank within the Eurosystem has been in charge of issuing euro currency. In Figure 1, the total euro currency in circulation as well as the cumulated net issuance in Portugal are displayed (end of year figures as percentage of the euro area and Portuguese nominal GDP, respectively).[2] Despite a similar starting point (at around 3 per cent of nominal GDP at the beginning of 2002), the cumulated net issuance in Portugal has presented a quite different pattern as against of the Eurosystem as a whole. While there has been a relatively steady increase over time of the euro currency in circulation, the cumulated net issuance in Portugal has been decreasing, becoming negative since 2011 and attaining -6.2 per cent of nominal GDP at the end of 2016. Among the 19 countries that belong to the euro area, this is by far the lowest figure with Portugal being the only country recording a negative cumulated net issuance value at the end of 2016. Hence, the Portuguese case is in sharp contrast with the euro area as whole where the cumulated net issuance stands above 10 per cent of nominal GDP.

At the other end, we find, for instance, Germany with a cumulated net issuance of more than 19 per cent of nominal GDP at the end of 2016 and accounting for more than half of the euro currency issued by the Eurosystem (whereas in 2002 it was only around one third). Contrarily to the Portuguese case, in Germany there has been a strong increase of euro cash demand throughout time. In particular, the development of the cumulated net issuance of euro banknotes by the Bundesbank reflects, to a large extent, foreign demand, that is, German-issued euro banknotes in circulation abroad. According to Bartzsch *et al.* (2015), at the end of 2013, over 70 per cent of the cumulated net issuance of banknotes by the Deutsche Bundesbank ended up in circulation abroad, namely 50 per cent outside the euro area and 20 per cent in the rest of the euro area.

The breakdown by denomination of cumulated euro currency issued by Banco de Portugal is displayed in Figure 2. One can see that the above discussed pattern of decrease over time of the cumulated net issuance reflects the developments of the larger banknotes, with particular emphasis on €50,

2. The net issuance corresponds to the difference between the withdrawals and lodgements at the central bank.

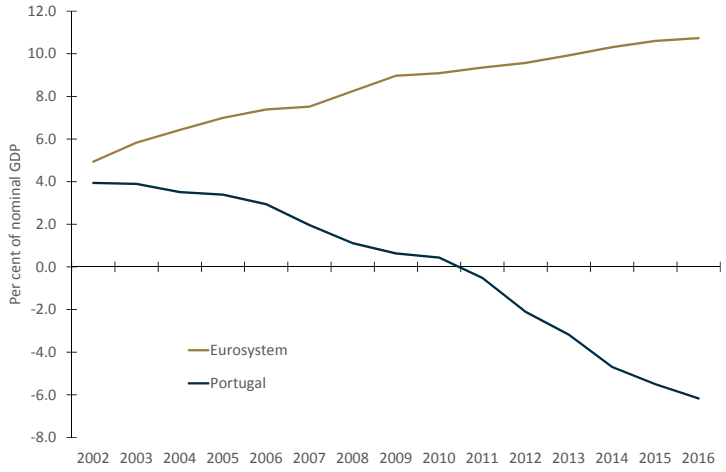

FIGURE 1: Cumulated net issuance of euro currency

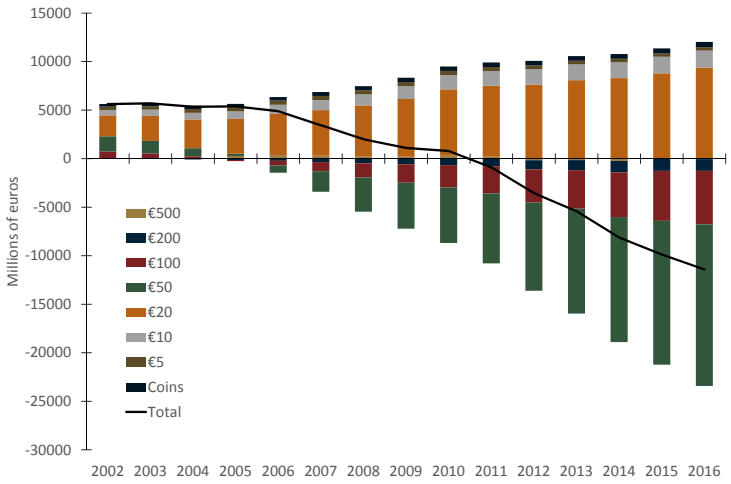

FIGURE 2: Breakdown by denomination of the cumulated net issuance in Portugal

€100 and €200 banknotes. The traditional determinants of currency demand are unable to explain such a marked behavior. In fact, being Portugal a small

open economy within a monetary union it faces an additional source of supply of euro currency besides the national central bank, as all the other countries belonging to the euro area also issue euro currency, which physically enters in Portugal via the inflow of tourists. For instance, German tourists travelling to Portugal take euro currency issued by the Deutsche Bundesbank with them to Portugal, which ends up lodged at the Banco de Portugal. This issue highlights the importance of such a channel in determining currency demand in a country within a monetary union where tourism is relatively important and getting larger (see Figure 3). At the end of 2016, non-residents expenditure accounted for 6.6 per cent of nominal GDP. Hence, besides the usual motives for holding cash, one has to take into account the migration of euro currency which is notably spurred by tourism flows.

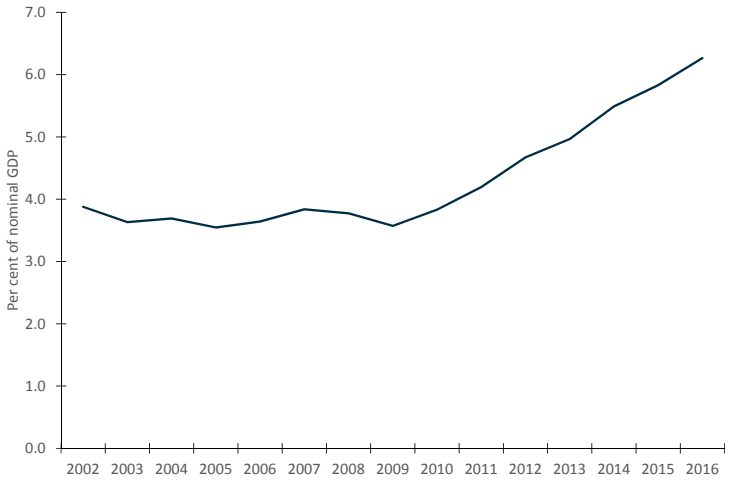

FIGURE 3: Non-residents expenditure in Portugal

The ongoing process of financial innovation may also influence currency demand. In fact, the growing use of alternative means of payment, such as credit and debit cards, may result in all goods becoming less likely to be purchased with cash. Another feature of the financial innovation process has been the widespread availability of Automated Teller Machines (ATM) from which is possible to conveniently withdraw money. Hence, while electronic card payments reduce the use of cash, bank cards can also be used to withdraw

money easily from widespread ATMs which may increase currency in circulation (as found by, for instance, Virén (1992)).[3] Therefore, the overall effect of financial innovation may be ambiguous.

In this respect, Portugal is also a noteworthy case study as it is one of the countries where there has been a higher penetration of financial technology and consumer sophistication. For instance, since the beginning of the current decade, Portugal has ranked first in terms of the value of card payments (as a ratio to nominal GDP) among all the European Union countries (see Figure 4). At the same time, as depicted in Figure 5, it is also the country which records the highest number of ATM terminals per million inhabitants. Hence, it seems particularly interesting to investigate the influence of these financial innovations on the demand for currency in Portugal.

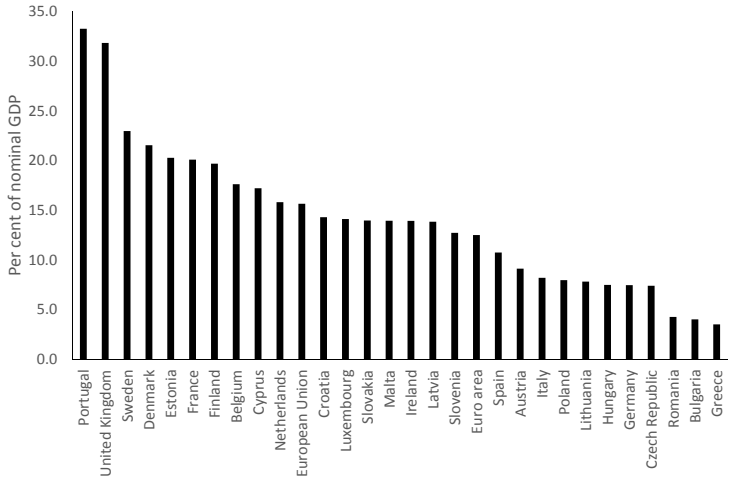

FIGURE 4: Value of card payments as a ratio to GDP

3. Note that the availability of ATMs also allows to enhance the efficiency of cash holdings. As it implies a lower transaction cost to consumers compared to the traditional over-the-counter withdrawal at a branch office, it can also result in a decrease of cash balances.

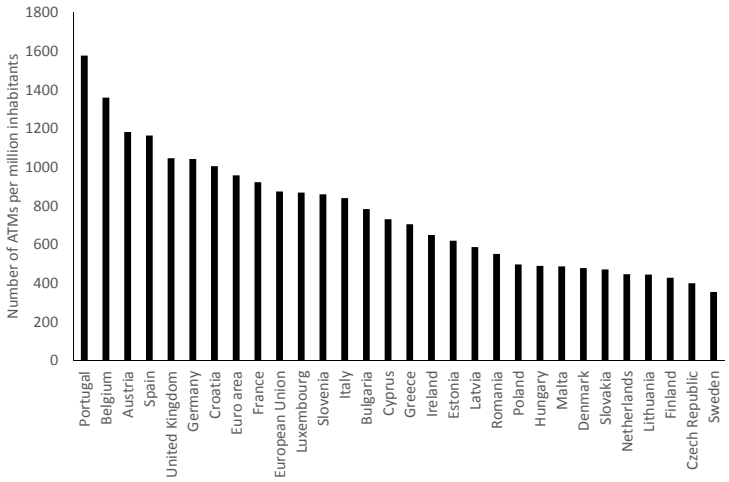

FIGURE 5: Number of ATM terminals per million inhabitants

3. Econometric framework

Typically, currency demand models, and more generally money demand functions, are estimated resorting to an ECM framework following the seminal work of Engle and Granger (1987). Such a modelling procedure allows to address both the short-run dynamics and the long-run relationship. In particular, the approach developed by Engle and Granger comprises two steps. In the first step, the parameters of the cointegrating relationship are estimated while in the second step these are fed into the error correction form with the short-run dynamics being estimated subsequently. As advocated by Engle and Granger, the least squares estimator can be used in both steps.

Although, ordinary least squares may be used to consistently estimate the cointegrating relationship, the least squares estimator may be substantially biased in small samples and it is not efficient (see Stock (1987) and Phillips (1991)). In fact, despite of being super consistent, as it converges to the true value at rate T instead of the usual rate $T^{\frac{1}{2}}$, the least squares estimator may not perform well when working with a relatively small sample size, as in our case. Phillips and Loretan (1991) and Stock and Watson (1993) suggested an improved estimator to cope with the above issues. It consists in augmenting the cointegrating regression with leads and lags of the first-differenced regressors

and then estimate the augmented regression by least squares. The resulting estimator is called the Dynamic OLS (DOLS). It is consistent, asymptotically normally distributed and efficient (equivalent to maximum likelihood) under certain assumptions.

This single-equation cointegration estimator has been extended by Mark *et al.* (2005) to the case of multiple-equation cointegration regressions. The proposed Dynamic Seemingly Unrelated Regression (DSUR) estimator is shown to deliver noteworthy efficiency gains over single equation methods such as DOLS namely in the case of heterogeneous cointegrating vectors and when equilibrium errors are correlated across cointegrating regressions. These features make DSUR estimator particularly suitable in the current context.

Following Mark *et al.* (2005), we consider N cointegrating regressions each with T observations. Each equation $i = 1, ..., N$ has a triangular representation

$$y_{it} = x'_{it}\beta_i + u_{it} \tag{1}$$

$$\Delta x_{it} = e_{it} \tag{2}$$

where x_{it} and e_{it} are $k \times 1$ dimensional vectors. An endogeneity problem can arise if there exists correlation between the equilibrium error of equation i and leads and lags of the first-differenced regressors from all of the equations in the system. Hence, to purge endogeneity, one has to include leads and lags not only of Δx_{it} but leads and lags of Δx_{1t} through Δx_{Nt}. For a finite number of p leads and lags, let $z'_{it} = \left(\Delta x'_{i,t-p}, ..., \Delta x'_{i,t+p}\right)$ and $z'_t = (z'_{1t}, ..., z'_{Nt})$. Mark *et al.* (2005) suggest projecting u_{it} onto z'_t, that is

$$u_{it} = z'_t\delta_i + \varepsilon_{it} \tag{3}$$

The resulting projection error ε_{it} is, by construction, orthogonal to all leads and lags of Δx_{it}, $i = 1, ..., N$. Substituting (3) into (1) yields the following regression

$$y_{it} = x'_{it}\beta_i + z'_t\delta_i + \varepsilon_{it} \tag{4}$$

The N equations like (4) can be stacked together in a system as

$$Y_t = \begin{bmatrix} X_t \\ Z_t \end{bmatrix}' \begin{bmatrix} \beta \\ \delta \end{bmatrix} + \varepsilon_t \tag{5}$$

with $Y_t = (y_{1t}, ..., y_{Nt})'$, $X_t = diag\,(x_{1t}, ..., x_{Nt})$, $Z_t = (I_N \otimes z_t)$, $\beta = (\beta_1, ..., \beta_N)'$, $\delta = (\delta_1, ..., \delta_N)'$ and $\varepsilon_t = (\varepsilon_{1t}, ..., \varepsilon_{Nt})'$.

The DSUR estimator is given by

$$\begin{bmatrix} \beta^{DSUR} \\ \delta^{DSUR} \end{bmatrix} = \left(\sum_{t=1+p}^{T-p} \begin{bmatrix} X_t \\ Z_t \end{bmatrix} \Omega_{\varepsilon\varepsilon}^{-1} \begin{bmatrix} X_t & Z_t \end{bmatrix} \right)^{-1} \left(\sum_{t=1+p}^{T-p} \begin{bmatrix} X_t \\ Z_t \end{bmatrix} \Omega_{\varepsilon\varepsilon}^{-1} Y_t \right) \tag{6}$$

where $\Omega_{\varepsilon\varepsilon}$ is the long-run covariance matrix of ε_t. Note that the DSUR differs from DOLS estimator in that endogeneity in equation i is corrected by incorporating leads and lags of the first difference not only of the regressors of equation i but also of the regressors of all other equations in the system. Moreover, the DSUR estimator achieves asymptotic efficiency gains over DOLS by incorporating the long-run cross sectional dependence in the equilibrium errors in estimation.

Once obtained a DSUR estimate of β_i for equation i, denoted by $\widehat{\beta}_i^{DSUR}$, one can proceed to the second step of Engle and Granger procedure by modelling an ECM for y_{it} as usual

$$\Delta y_{it} = \varphi_{i0} + \sum_{j=1} \varphi_{ij} \Delta y_{i,t-j} + \sum_{h=0} x'_{i,t-h} \theta_{ih} + \gamma_i \left(y_{i,t-1} - x'_{i,t-1} \widehat{\beta}_i^{DSUR} \right) + \xi_{it} \tag{7}$$

By stacking equation (7) for $i = 1, ..., N$, one can apply the standard SUR estimator to the resulting system. In this way, one can also take on board the correlation across equations when modelling the short-run dynamics.

4. Empirical analysis

4.1. Data and variables for modelling currency demand

As mentioned earlier, one of the purposes of this study is to consider a higher level of disaggregation than previous work so as to enhance the modelling and understanding of the drivers of currency demand. In particular, we consider the cumulated net issuance by the Banco de Portugal of the different euro banknote denominations namely €500, €200, €100, €50, €20, €10 and €5, as well as total amount of coins. The data has been provided by the Issue and Treasury Department of Banco de Portugal.

Regarding the determinants of currency demand, the classical motive for holding money is for transactions purposes. The medium of exchange function has led to the development of models where the transaction role is emphasized

such as the inventory-theoretic models of Baumol (1952) and Tobin (1956) and cash-in-advance models. In the former, money is basically seen as an inventory held for transactions purposes whereas in the latter there is the constraint that purchases in a given period have to be paid for by currency held over from the previous period (see also the seminal contribution of Lucas (1980)). To take on board the transactions motive, one has to consider a measure of transactions. Although broad economic measures can be used, such as GNP or GDP, not all the transactions are equally money-intensive (see Goldfeld and Sichel (1990)). In this respect, Mankiw and Summers (1986) argue that consumer expenditure is a more appropriate choice. Taking beyond such a reasoning, one may argue that the cash-intensity and more specifically the denomination-intensity is likely to vary according to the type of consumer expenditure. For example, expenditures typically associated with small (large) value transactions most probably are paid with lower (higher) denominations. Hence, we consider a disaggregation of private consumption into durables, food and non-durables excluding food. Note that by considering disaggregated consumer expenditure one also copes with changes across spending categories allowing to tackle potential composition effects. In the Portuguese case, the data concerning nominal private consumption components are taken from the Quarterly National Accounts released by INE, the National Statistical Institute of Portugal.

Besides serving as medium of exchange, cash has also a store of value function. Naturally, one would expect such a role to be stronger for higher denomination banknotes (see, for instance, Boeschoten and Fase (1992)). At the same time, these banknotes would be more adversely affected by the opportunity cost (as found by, for example, Amromin and Chakravorti (2009) for a panel of countries). Since cash carries no interest return, one can use the prevailing level of interest rate as an opportunity cost measure for holding cash. In particular, we consider a short-term interest rate corresponding to the three-month Euribor and a long-term interest rate corresponding to the 10-year Treasury bond yield.

As discussed earlier, the process of financial innovation may affect cash holdings. On the one hand, the introduction and more widespread use of alternative means of payment such as cheques and credit and debit cards, can impact negatively on currency demand. In particular, cash is less convenient for large transactions than alternative means of payment. On the other hand, the increasingly number of ATM terminals can spur the use of currency. To

capture the former effect, we consider the value of payments with cards issued by domestic banks as well as payments resorting to cheques. We also consider the number of available Point-of-Sale (POS) terminals as it influences the use of debit and credit cards. To assess the latter effect, we collected data on the number of ATM terminals located within the Portuguese territory throughout time. This data is provided by the Payment Systems Department of Banco de Portugal.

A feature that distinguishes cash from close substitutes as a means of payment is its anonymity. This makes cash a particularly attractive way for pursuing transactions in the shadow economy as it leaves no traces (see, for example, Schneider and Enste (2000)). Given the unavailability of reliable high frequency estimates of the shadow economy for Portugal, we consider the level of unemployment. As argued by Bartzsch *et al.* (2015), a high unemployment encourages people to work underground having a positive impact on the underground economy. Furthermore, there is empirical evidence suggesting that unemployed people tend to have larger cash holdings and use cash more intensively (see, for example, Duca and Whitesell (1995) and Liu (2009)). The data regarding the number of unemployed is from the Quarterly Labour Force Survey which is released by INE.

The net issuance of a central bank can also be affected by the inflows and outflows of currency between countries. In this respect, the typical studied determinant relates to foreign demand, that is, currency demand by non-residents. This foreign demand influences strongly the net issuance of currency in countries such as the United States, Japan, Switzerland and Germany. Whereas in those countries the cumulated net issuance is higher than one would expect it to be if it was driven solely by domestic holdings, it seems to be the opposite case in Portugal. As mentioned previously, tourism flows might account for such a phenomenon. To capture this factor, we consider the nominal expenditures of non-residents in Portugal which are also compiled by INE. As tourists may also resort to alternative means of payment, namely debit and credit cards, we consider the value of payments within Portuguese territory with cards issued by foreign banks. The data is provided by the Payment Systems Department of Banco de Portugal.

All data are available on a quarterly basis and considered on a seasonally adjusted form (with the exception of interest rates and the number of ATM and POS terminals). Whenever deemed necessary, we use the same seasonal adjustment procedure used by INE, namely the X-13 ARIMA with calendar

effects adjustment resorting to JDemetra+ software provided by the Eurostat. Since the cumulated net issuance records negative values in the case of several denominations, as discussed earlier, we do not take any logs. The sample period runs from the introduction of the euro at the beginning of 2002 up to the end of 2016.

4.2. Unit roots

We begin by addressing the non-stationarity issue of the series resorting to a standard battery of unit root tests. In particular, we consider the Augmented Dickey-Fuller (ADF) test, the Dickey-Fuller test with GLS detrending (DF-GLS), the Phillips-Perron (PP) test, the Kwiatkowski, Phillips, Schmidt, and Shin (KPSS) test and the Elliot, Rothenberg and Stock point optimal (ERS) test. One should mention that only the KPSS test postulates stationarity as the null hypothesis whereas the remaining consider a unit root in the null hypothesis. The results are reported in Table 1. As expected, we find that most series have a unit root. The null of stationarity is rejected in the case of the KPSS whereas the presence of a unit root is not rejected in the remaining tests. Only in the case of interest rates the results are less clear cut. In fact, the stationarity is not rejected by the KPSS test but neither is the hypothesis of a unit root in most of the other tests. Despite the latter evidence, we proceed by considering the interest rates as stationary as usual. For the series presenting evidence of a unit root, we check if the first difference is stationary which turns out to be the case for all series.

Variable	Abbreviation	ADF	DF-GLS	PP	ERS	KPSS
500 euro banknotes	€500	-1.85	-1.87	-1.48	3.10	0.83**
200 euro banknotes	€200	-2.67	-1.53	0.23	17.36	0.95**
100 euro banknotes	€100	-0.08	-1.76	2.96	998.74	0.95**
50 euro banknotes	€50	1.94	-0.92	5.60	1481.16	0.94**
20 euro banknotes	€20	0.02	0.64	-0.05	956.74	0.96**
10 euro banknotes	€10	-1.15	-0.15	0.08	574.83	0.94**
5 euro banknotes	€5	-1.40	-1.37	-0.88	6.53	0.52*
Coins	Coins	-0.57	2.10	-2.15	555.21	0.97**
Private consumption of durables	PCDur	-1.48	-1.46	-1.66	6.00	0.53*
Private consumption of non-durables	PCNDur	-1.32	0.41	-1.24	145.29	0.93**
Private consumption of food	PCFood	-1.88	0.28	-2.23	114.69	0.75**
Short-term interest rate	STIR	-1.85	-1.43	-1.28	6.67	0.45
Long-term interest rate	LTIR	-2.55	-2.57*	-1.83	1.77**	0.14
National card payments	NCardPay	-0.38	0.69	-0.60	92.32	0.92**
Cheques	Cheques	-0.42	0.72	-1.06	271.25	0.95**
POS terminals	POS	-0.85	0.05	-0.67	58.91	0.91**
ATM terminals	ATM	-2.27	-1.65	-2.30	32.01	0.67*
Unemployment	Unemp	-1.58	-0.94	-1.91	24.97	0.73*
Expenditures by non-residents	Tourism	3.79	1.40	3.87	204.63	0.87**
Foreign card payments	FCardPay	2.29	3.33	2.83	154.26	0.90**

TABLE 1. Unit root test statistics

Note: *,** denote rejection of the null hypothesis at 5 and 1 per cent significance levels, respectively.

4.3. DSUR estimation

Drawing on the above unit root tests results and guided by the previously discussed economic theory, a search for the variables to be included in the long-run relationship for each type of currency is conducted. Basically, we drop the variables that do not reveal to be statistically significant as well as those presenting the wrong expected sign according to economic theory.

The DSUR estimation is performed using the feasible two-step DSUR estimator as described in Mark *et al.* (2005). Regarding the number of leads and lags, we consider $p = 1$ as $T = 60$ in our case.[4]

To check the adequacy of resorting to a SUR type estimator one should also assess the existence of cross-section dependence. In particular, we consider the Lagrange multiplier (LM) test of Breusch and Pagan (1980) which tests the null hypothesis that all pair-wise correlations are zero, that is $\rho_{ij} = 0$ for all $i \neq j$. The test statistic is given by

$$LM = T \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \widehat{\rho}_{ij}^2 \tag{8}$$

with the sample estimate of the pair-wise correlation $\widehat{\rho}_{ij}$ defined as

$$\widehat{\rho}_{ij} = \widehat{\rho}_{ji} = \frac{\sum \nu_{it} \nu_{jt}}{\left(\sum \nu_{it}^2\right)^{\frac{1}{2}} \left(\sum \nu_{jt}^2\right)^{\frac{1}{2}}} \tag{9}$$

where ν_{it} are the estimated residuals of the correspondig cointegrating equations. Under the null of no cross-section dependence, the LM statistic is asymptotically distributed as χ^2 with $N(N-1)/2$ degrees of freedom.

We also consider the alternative test statistic proposed by Pesaran (2004, 2015) defined as

$$CD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \widehat{\rho}_{ij} \right) \tag{10}$$

which is asymptotically distributed as $N(0,1)$ under the null.

4. As mentioned by Mark *et al.* (2005), the common practice in Monte Carlo and empirical studies, following the work of Stock and Watson (1993), is setting $p = 1$ for $T = 50$, $p = 2$ for $T = 100$ and $p = 3$ for $T = 300$. Nevertheless, we also conducted a sensitivity analysis by varying the number of leads and lags and the results remained qualitatively similar.

The DSUR estimation results are reported in Table 2 and the cross-section dependence tests are presented in Table 3.

Regressors	Dependent variable y_t							
	€500	€200	€100	€50	€20	€10	€5	Coins
PCDur_t	0.358	0.300	1.166	2.786				
	[0.050]	[0.013]	[0.044]	[0.089]				
PCNDur_t	0.043			0.315	0.262	0.055	0.019	0.008
	[0.010]			[0.027]	[0.025]	[0.007]	[0.001]	[0.003]
PCFood_t							0.036	0.093
							[0.005]	[0.015]
NCardPay_t		−0.198	−0.743	−2.135				
		[0.006]	[0.022]	[0.060]				
Unemp_t					5.151	1.068		
					[0.181]	[0.042]		
Tourism_t	−0.246	−0.354	−2.020	−6.862	2.520	0.364	−0.108	0.033
	[0.056]	[0.020]	[0.073]	[0.153]	[0.140]	[0.039]	[0.008]	[0.011]

TABLE 2. DSUR estimation results

Note: Standard deviations are reported within brackets.

	Test Statistic	$P-value$
LM	318.10	0.000
CD	10.19	0.000

TABLE 3. Tests for cross-section dependence of the cointegrating residuals

In Table 3, we strongly reject the null of no cross-section dependence with both test statistics. These results confirm the presence of significant interactions between the equilibrium errors of the long-run demand for different currency denominations.

	€500	€200	€100	€50	€20	€10	€5	Coins
Test Statistic	0.035	0.045	0.045	0.056	0.095	0.098	0.081	0.072

TABLE 4. Cointegration test

Naturally, one should also check for the presence of cointegration among the set of variables considered for each denomination. Resorting to the residual-based cointegration test proposed by Shin (1994) we do not reject the existence of cointegration for all denominations (see Table 4).[5]

Drawing on Table 2, we find that the transaction motive has a positive impact on the demand for currency for all denominations. However, we find that the relevant type of consumer expenditure changes across denominations. In particular, we find that private consumption of typically higher value goods, such as durable goods, influence the demand of higher banknote denominations (namely €500, €200, €100 and €50 banknotes) whereas low-price goods such as food are more important for the demand of €5 banknotes and coins.

The results also provide empirical evidence on the negative effect of the use of debit and credit cards on the demand of higher value banknotes, in particular, €200, €100 and €50 banknotes. As non-cash payment methods have attributes which make them particularly attractive as a means of payment for higher value transactions, its use ends up influencing more significantly the demand for larger denomination banknotes which are also typically associated with higher value transactions. We find a positive relationship between unemployment and the demand for €20 and €10 banknotes.

Regarding the impact of tourism on currency demand, we find the expenditures by non-residents to influence significantly the demand of all denominations. In most cases, the effect on demand is negative. As discussed earlier, tourists travelling to Portugal bring in euro currency issued by other central banks within the Eurosystem to Portugal which results in a lower demand for currency issued by the Portuguese central bank. However, in the cases of €20 and €10 banknotes and coins, we find a positive relationship. For the €20 and €10 banknotes, this can be due to the fact that tourists also withdraw cash at ATM terminals in Portugal. In fact, cash withdrawals at ATM terminals in Portuguese territory using foreign cards have been increasing accounting for more than 16 per cent of non-residents expenditures in 2016.

5. One should mention that this test allows to assess the cointegration hypothesis directly as it considers the null hypothesis of cointegration against the alternative of no cointegration. In fact, it is often argued that cointegration is a more natural choice of the null hypothesis rather than no cointegration. Furthermore, the limiting distribution of the test statistic holds for different types of efficient estimators of the cointegrating vector and therefore can also be applied in the current context.

Since ATM terminals in Portugal are basically loaded with €20 and €10 banknotes, this can contribute to the positive relationship between tourism and the demand for these denominations.[6] Regarding coins, a possible reasoning is that when tourists pay with banknotes, they receive coins as change.[7] Hence, tourism may lead to an increase in demand for coins.

4.4. SUR ECM estimation

Given the above estimated system of cointegrating relationships, we now proceed to the modelling of the short-run dynamics by estimating a system of ECM equations as described in section 3. In this respect, we consider a few number of time dummies to take into account special episodes that influenced currency demand over the period under analysis. In particular, there was an abrupt increase in currency demand following the collapse of Lehman Brothers in mid-September so a dummy variable for the fourth quarter of 2008 was included (D2008Q4). A spurt has been also recorded when the Portuguese government requested financial assistance to the International Monetary Fund and the European Financial Stability Facility in April 2011. Hence, a dummy variable for the second quarter of 2011 is considered (D2011Q2). We also included a dummy variable for the second quarter of 2013 (D2013Q2) following the announcement of the bail-in package for Cyprus at the end of March. Among other things, there was a limit on cash withdrawals and depositors with over €100 000 lost part of their money. This had a spillover effect for currency demand in Portugal, which was still under the Financial Assistance Program. Additionally, the resolution of the bank BANIF in December 2015 influenced currency demand in the fourth quarter of 2015 and first quarter of 2016 (D2015Q4 and D2016Q1, respectively). Naturally, given the type of episodes mentioned, one would expect the impact to be more visible for higher value banknotes due to its more marked store of value function. Finally, in May 2016, the ECB announced the end of production and issuance of the €500 banknote. This had an immediate negative impact on the demand for €500

6. For example, in 2016, the distribution by denomination of the quantity of banknotes loaded in the ATM terminals was the following: 4 per cent for €5; 42 per cent for €10; 53 per cent for €20; 1 per cent for €50.

7. Note that the same reasoning may also be applied to €20 and €10 banknotes. In fact, if tourists pay with higher value banknotes they may also end up receiving €20 and €10 banknotes as change, as these are the most commonly used denominations in Portugal.

banknotes and a positive impact on the other high value banknotes. Thereafter, albeit less strongly, such a substitution effect seems to have persisted. Hence, we consider a dummy variable for the second quarter of 2016 to capture the initial impact of the announcement and a step dummy starting in the third quarter of 2016 to account for the fact that such a re-composition effect has continued (D2016Q2 and SD2016Q3, respectively). For the sake of parsimony, in the final specification for each denomination, we only retain those variables that are statistically significant.

The estimated system of ECM equations, using the SUR estimator, is reported in Table 5. As usual, we checked for autocorrelation and heteroscedasticity and find all residuals to be well-behaved. Moreover, the cross-section dependence tests reinforce the importance of resorting to a SUR estimator (see Table 6). Hence, a SUR type approach is particularly adequate for the estimation of both long- and short-run dynamics in the current context.

From Table 5, one can see that in all equations the one-period lagged term of the dependent variable is statistically significant. Only in the case of the €5 banknotes, one has to consider two lags. Furthermore, the estimated coefficients are all positive denoting habit persistence. We also find that changes in private consumption components, namely durables and non-durables excluding food, have a positive impact on the changes of higher value banknotes demand.

Regarding the opportunity cost of holding currency, we find that the dynamics of €500 banknote demand is adversely affected by the level of the interest rate. In particular, the evolution of the short-term interest rate influences with a noteworthy advance the behaviour of the €500 banknote demand. This seems to suggest that early considerations concerning the opportunity cost are relevant for determining changes in the demand of such high value banknotes which are more prone to be used as store of value. We also find that the short-term interest rate impacts negatively the demand for €20 and €10 banknotes. However, in this case, the link is contemporaneous. This may be due to the fact that, as these banknotes are readily accessible through ATM terminals, agents can adjust more quickly their cash holdings to current interest rates.

Concerning financial innovation, we find short-run movements of national card payments to have a negative effect on the behaviour of cash demand, in particular, €200 and €100 banknotes. In contrast, the availability of ATMs has a positive impact on the demand for €20 and €10 banknotes. This reflects

Regressors	Dependent variable Δy_t							
	€500	€200	€100	€50	€20	€10	€5	Coins
Constant	−186.8	39.1	149.6	135.8	−316.3	−64.1	0.6	−15.8
	[24.9]	[7.1]	[30.5]	[60.1]	[126.2]	[32.3]	[0.7]	[7.2]
Δy_{t-1}	0.635	0.714	0.768	0.845	0.423	0.186	0.549	0.547
	[0.044]	[0.041]	[0.027]	[0.026]	[0.061]	[0.083]	[0.093]	[0.102]
Δy_{t-2}							0.327	
							[0.092]	
ΔPCDur$_t$	0.048	0.016	0.033	0.084				
	[0.015]	[0.003]	[0.010]	[0.025]				
ΔPCNDur$_t$	0.050	0.005	0.016					
	[0.011]	[0.002]	[0.007]					
STIR$_t$					−33.0	−8.0		
					[5.9]	[1.9]		
STIR$_{t-4}$	−6.6							
	[1.5]							
ΔNCardPay$_t$		−0.024	−0.044					
		[0.006]	[0.017]					
ΔATM$_{t-2}$					0.134	0.059		
					[0.057]	[0.019]		
ΔATM$_{t-3}$					0.199	0.056		
					[0.058]	[0.019]		
ΔUnemp$_{t-1}$	0.533	0.106	0.297	0.586				
	[0.100]	[0.018]	[0.055]	[0.164]				
Coint$_{t-1}^{DSUR}$	−0.158	−0.084	−0.052	−0.026	−0.059	−0.071	−0.025	−0.074
	[0.021]	[0.012]	[0.009]	[0.008]	[0.018]	[0.027]	[0.021]	[0.030]
D2008Q4	142.6	14.8	30.3	121.2	114.6	14.6		
	[18.6]	[3.2]	[10.2]	[34.2]	[32.9]	[10.5]		
D2011Q2	90.3	8.9	21.6	92.5	178.4	30.3		
	[16.7]	[2.9]	[9.6]	[33.2]	[32.5]	[10.5]		
D2013Q2	107.8	12.1	24.5					
	[13.6]	[2.4]	[6.7]					
D2015Q4	39.1	9.4	18.3					
	[13.8]	[2.4]	[6.7]					
D2016Q1	82.9	14.1	24.9					
	[14.3]	[2.4]	[6.7]					
D2016Q2	−67.8	16.6	12.8					
	[15.2]	[2.6]	[7.0]					
SD2016Q3	−23.1	36.0	39.1					
	[10.6]	[2.8]	[5.6]					
R^2	0.90	0.95	0.93	0.93	0.94	0.69	0.53	0.32

TABLE 5. SUR ECM estimation results

Note: Coint$_{i,t-1}^{DSUR} = y_{i,t-1} - x'_{i,t-1}\widehat{\beta}_i^{DSUR}$. Standard deviations are reported within brackets.

the fact that these denominations account for most of the banknotes loaded at ATM terminals.

We also find that one-period lagged changes in unemployment affect positively currency demand, in particular, higher value banknotes. Regarding

	Test Statistic	$P-value$
LM	180.10	0.000
CD	7.53	0.000

TABLE 6. Tests for cross-section dependence of the SUR ECM residuals

the error correction term, its coefficient represents the size of adjustment towards the long-run equilibrium. As expected, the adjustment coefficient is negative and very significant in all equations, though weaker for the €5 banknotes.

With respect to the time dummy variables, we find that the dummies for 2008 Q4 and 2011 Q2 are statistically relevant for most denominations. The surge of the global financial crisis and the Portuguese bailout led to an increase in currency demand. Only for very low value denominations, namely €5 banknotes and coins, this is not the case. Concerning the events captured by the dummies for 2013 Q2, 2015 Q4 and 2016 Q1, we find that they had a significant positive impact on the demand for high value banknotes (€500, €200 and €100). The announcement by the ECB of the end of production and issuance of the €500 banknote is estimated to have had a strong negative impact on the demand for this denomination in the second quarter of 2016 which persisted thereafter albeit with a lower magnitude. In contrast, we find that it had a noteworthy positive effect on the demand for €200 and €100 banknotes. As these denominations are closest to €500, it is natural that these banknotes operate as substitutes to the €500 banknote.

The estimated system delivers a quite impressive fit for most denominations. In fact, for denominations ranging from €20 up to €500, the R^2 exceeds 90 per cent. For the €10 banknotes, the R^2 is close to 70 per cent. For low value currency, the dynamics seem to be harder to model. For the €5 banknotes the R^2 is slightly above 50 per cent and for coins it stands close to 30 per cent. Overall, the systemwide R^2, as proposed by McElroy (1977), is 91 per cent. Hence, the estimated system is able to replicate the data quite well.

5. Conclusions

Currency management by the central bank requires the understanding of the determinants of cash demand. The assessment of the factors influencing the short- and long-term demand for currency and issues relating to its

denomination structure are crucial for promoting a normal functioning of the economy. Despite this importance, the literature on modelling currency demand accounts only for a small share of the literature on estimating money demand functions. The current study aims at contributing to this topic by considering currency demand in a small open economy within a monetary union. Such a context adds some challenges which make Portugal an interesting case study on its own.

Besides the traditional motives for holding cash typically considered in the literature, we considered the influence of financial innovation as well as the role of tourism. These two potential explanatory factors are particularly relevant in the Portuguese case. In the former case, there is a striking penetration of financial technology with the widespread adoption of electronic card payments and the extensive availability of ATM terminals. Regarding the latter, the cumulated net issuance of euro banknotes put into circulation by the national central bank differs considerably from the domestic cash holdings. In contrast with other countries, such as Germany, where the net cumulated issuance has been growing strongly being positively influenced by non-residents demand, Portugal has been recording the opposite evolution. This seems to reflect the significant role that tourism plays in the Portuguese economy. In particular, as the Portuguese central bank is not the sole issuer of euro currency, the sizeable inflow of tourists generate an overall negative effect on euro currency demand within the Portuguese territory.

Furthermore, besides taking into account that factors behind demand affect currency in circulation in different ways, one should also allow for the impact to differ across denominations. Such a deeper analysis enhances the assessment of the several driving forces of cash demand. In this respect, and in contrast with the previous literature, we consider the highest possible disaggregation level for euro banknotes (€500, €200, €100, €50, €20, €10, €5) besides coins. Naturally, such a disaggregation, raises some methodological challenges namely associated with the fact that denominations are substitutable at the margin. To take on board the interconnections between denominations both in the short- and long-run, which we find to be empirically quite significant, we rely on the DSUR estimator for the estimation of heterogeneous cointegrating relationships while estimating a SUR ECM for modelling short-run dynamics.

Focusing on the period since the physical introduction of the euro, we find that the transactions motive is relevant for the demand of all denominations. However, by considering different types of consumer expenditures and

denominations, we also find that expenditures commonly associated with higher (lower) value transactions are more linked to the demand of higher (lower) value denominations. As expected, the opportunity cost of holding money affects negatively the demand for highest denomination but also the most commonly used banknotes in the economy. We also find that unemployment influences positively the demand for almost all banknotes. Regarding the impact of alternative means of payment on cash demand, we find that card payments affect negatively the demand for relatively high denominations as cash is less convenient for larger transactions. In contrast, the widespread availability of ATM terminals impacts positively, in the short-run, the demand for the denominations that account for most of the banknotes loaded in these cash dispensers. Concerning the effect of tourism, we find that it influences negatively most of the denominations as the expenditure by tourists constitutes an additional source of supply of euro currency.

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