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Demystifying Consumers' Adoption of a Digital Euro in the Euro Area [1]

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Abstract. *A central bank digital currency is a step forward for central banks in the context of technological advancements in the financial world. This study examines households' digital euro adoption process in the euro area. It adopts a novel and simple approach to estimate the upper bounds of the short-term adoption rate in the euro area. Among the quantitative methods employed, the most significant are unsupervised machine learning algorithms (clustering techniques), non-parametric statistical methods, and an econometric vector autoregressive model. The results show that this process may be slower and less extensive than may be expected, and it is unlikely to considerably impact the economy and society immediately after its introduction. The model indicates that, in the best-case scenario, the maximum retail digital euro's adoption rate at the euro-area level is less than 5% of the euro area banks' total liabilities and approximately 20% of its quarterly gross domestic product. The findings are critical for the domain as policymakers could use them to adjust their impact studies over the banking sector and real economy. Additionally, this study proposes a new hypothesis regarding the parity of funding sources for digital euro accounts (cash reserves-to-deposits ratio).*

Keywords: digital euro demand, behaviour finance, households' structural finance.

Introduction

Although the concept of a central bank-issued digital currency is relatively new, it has sparked intense interest among central banks and researchers. According to Auer et al. (2023), this digital asset issued by a central bank is at least in the exploration and research phase for numerous central banks, including the European Central Bank (ECB, 2023a). However, these processes are challenging, and the issuing of this currency by a central bank entails potential advantages and risks. According to the Bank for International Settlements (Kosse and Mattei, 2023), among a central bank's motives for issuing a central bank digital currency (CBDC) and the potential advantages of this action could be the streamlining and increased security of the payment methods available to European households, enhancement of digital financial inclusion (Auer, Frost, et al., 2022), reduction of the informal economy, and beneficial macroeconomic and monetary effects (Das et al., 2023). The most significant risk is the potential shift in bank deposits from commercial banks to digital-currency holdings (Ahnert et al., 2022), which could reduce bank liquidity. Reduced liquidity in the banking sector could lead to financial disintermediation and a scenario in which banks might be compelled to resort to riskier and costlier funding sources (Hoffmann et al., 2023).

Throughout this study, I refer only to the retail digital euro, in which case only households can hold digital euros.

According to the latest ECB communications, to preserve and safeguard the euro area's financial stability, holdings of the digital euro will be capped, and the digital euro will not bear interest (ECB, 2023b, 2023c). The issuance of the digital currency in the euro area may have a

[1] Abbreviations: European Central Bank (ECB); central-bank digital currency (CBDC); standard vector autoregressive (VAR); fuzzy K-means (FKM); Gaussian mixture model (GMM); Partitioning around medoids (PAM).

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limited effect on term deposits in a scenario in which remuneration is equal to or near zero, especially in an environment characterised by high interest rates. Moreover, a bank run toward holdings of the digital euro is unlikely, even in a crisis such as the sovereign debt crisis of 2009–2012 (Azzone and Barucci, 2023). In addition, I find that a random economic downturn or upturn does not change household saving behaviour in Germany, France, Italy, and Spain. However, stress in the banking sector could lead to bank runs or flights for safety episodes (as in the United States (US) in March 2023). In the event of a migration of deposits to digital euro holdings, financial intermediation decreases by a percentage lower than that associated with transferred deposits, as customers remaining in the commercial banking sector are more optimistic about this sector's stability (Muñoz and Soons, 2023).

The scenario used in the present study involves the cumulative fulfilment of the following highly plausible conditions: i) the digital euro will not be remunerated; ii) the holding limit will be no more than € 3000; iii) negligible stress in the banking sector; and iv) the adoption will be such that at least one of the two functionalities (payments to merchants and money transfer) is used, with the store-of-value function being implicit.

In the following lines, remarks are provided regarding the remuneration associated with the holdings of digital euros and the limits that may or will be imposed. Establishing a limit on holdings can be considered a macroprudential measure aimed at maintaining liquidity in the banking sector at comfortable levels, especially in a crisis and in its aftermath. It can demonstrate its benefits during periods of stress in the banking sector, primarily by preventing the outflow of overnight deposits as term deposits are guaranteed up to an amount that significantly exceeds the potential limit of digital euro holdings. Potential remuneration, which could positively contribute to the efficiency of monetary policy transmission (Das et al., 2023), may lead to both the migration of deposits (both term and overnight) to holdings of digital euros (in regular and crisis periods) and a loss of incentive for banks to participate in the distribution of digital euros, as the withdrawal of deposits harms their interests. Two essential factors would alter the dynamics of a bank run: remuneration and holding limits (Adalid et al., 2022).

This study calculated the estimated maximum adoption rate for the short term. Medium- and long-term numbers largely depend on herding effects and the signs of the network effects created among consumers, credit institutions, and merchants (Martens, 2021). The estimation is a point-in-time figure because CBDC issuance and adoption have no history. Approaches based on the probable profile of a digital euro holder and their digital financial behaviour were adopted. Individuals with the profile necessary to adopt the digital euro for transfers between individuals and payments to merchants were considered. Given that digital euro holdings will not bear interest, and, as shown below in this study, a key determinant of household deposit creation in three of the largest European economies is the interest, it can be concluded that banked individuals from these countries, in the absence of a financial crisis, will not turn to digital euro holdings solely to benefit from the store-of-value function, with some exceptions, to a small extent. National-level surveys support the results above for some euro-area member states. My research results are valid for 2022, as all data were collected during this timeframe (2021 being the reference year). However, it is important to mention that these numbers could and will be recalculated as newer data becomes available.

From the perspective of the adoption level of the digital euro for payments or money-transfer purposes, the euro-area countries were clustered as follows, from the highest to the lowest take-up level: 1. North and Northwest; 2. Western and Baltic states; 3. Central and East; and 4. South.

One of this study's primary hypotheses is that the capacity to adopt the digital euro is more important than the intention (measured through various surveys), particularly the maximum amount, which represents the holding limit calculated by Adalid et al. (2022) or Meller et al. (2023). All the surveys conducted thus far at the level of euro area countries have shown that the level of adoption intention is lower than that calculated in this study through the measurement of adoption capacity, primarily based on people's habits. The adoption capacity itself was measured using specific parameters of digital financial inclusion and digital behavioural finance. This study will show that the results obtained overestimate the real level of population adoption of the digital euro, which is conducive to financial stability. If the study's results underestimated the real level of adoption, the calculated holding limit would exceed the banking sector's capacity to cope with a high level of digital euro adoption.

The second part of the study focuses on the potential funding sources for digital euro accounts within the euro area. To find a realistic ratio, I examined the variation in the share of cash reserves and cash in circulation within the total of the population's most essential and liquid financial assets. Additionally, I graphically and statistically argued, using non-parametric methods, the hypothesis that regardless of geopolitical events, the presence or absence of economic and financial crises, phases of business and financial cycles, financial digital revolution, level of inflation, and interest rates on term deposits, people's propensity to hold cash reserves had not decreased, and the fluctuation of overnight or term deposits had predominantly occurred between these two types of assets. According to Adalid et al. (2022) and Petracco Giudici and Di Girolamo (2023), the ratio of cash reserves to deposits as funding sources for digital euro accounts is approximately 47:53 (using 2022 data; the authors used 2021 data and estimated that half of the cash reserves would be used to open digital euro accounts). More specifically, the authors estimate that individuals in the euro area will adopt the retail digital euro (amounting to approximately € 1 trillion) by withdrawing 50% from their cash reserves (approximately € 380 billion), with the remaining € 620 billion coming from deposits, thus creating a ratio of approximately 40:60 (cash reserves: deposits). I show below that this ratio tends more toward 10:90.

These two variables—the maximum potential adoption level and number of deposits that would be transformed into digital euro holdings—represent the two focal elements based on which the holding limit can be quantified so that the euro area's financial stability remains unaffected.

Literature review

According to a survey conducted by the Official Monetary and Financial Institutions Forum (OMFIF, 2023), for two-thirds of the respondents (central banks from developed countries), the most significant concern regarding digital currencies is households' possible lack of interest in this type of asset. A series of surveys were conducted at the national level within euro-area member states, such as the Netherlands (2023), Austria (2023), Germany (Deutsche Bundesbank, 2021), Spain (Bank of Spain, 2023), and at the euro-area level (Eurobarometer). However, only two studies have attempted to estimate the boundaries of the potential demand for the digital euro at the euro area level (Gross and Letizia, 2023; Lambert et al., 2024). Another study assessed the take-up of the digital euro, but only in Spain (León et al., 2023). The central assumption in Gross and Letizia's (2023) study was that no limit on holdings was imposed. They use an agent-based model, employing a utility function and Nash-equilibrium model to estimate potential demand and calculate an adoption interval from cash-like take-up to deposit-like take-up edges. Gross and Letizia split the holdings into deposit-like (used primarily for the store-of-value function, in which case the digital euro will bear interest close to or equal to the ECB's policy rate) and cash-like

(used to pay merchants or for P2P transfers). They estimate an upper bound of 20% of the broad money in the euro area if the take-ups were more deposit-like. If the digital euro were perceived only as a cash-like instrument, the lower boundary of demand would be 1% of the broad money in the euro area. Also, Lambert et al. (2024) find that the maximum demand, in a capped scenario, would be no more than 0.38 trillion euros. Furthermore, Nocciola and Zamora-Perez (2024) try to quantify transactional demand for CBDC; however, they do not estimate any minimum or maximum boundaries but find what could drive the transactional demand for the digital euro.

The digital euro serves three fundamental functions: i) payment to merchants, ii) fund transfers between individuals, and iii) store of value. It is essential to distinguish between the public's interest at regular times (the absence of financial turmoil/stress) and appetite for the digital euro during and in the aftermath of turbulence in the banking sector.

Considering that the digital euro is unlikely to bear interest, the public is unlikely to perceive this asset as an investment. Therefore, those who adopt the digital euro are presumed to do so to benefit from all three fundamental functions, or at least not solely from the value-storage function in a period that is not characterised by financial stress. However, the upper-boundary interval was estimated to range from a level associated with the absence of a financial crisis to one associated with turmoil in the banking sector.

Meller and Soons (2023) estimate a generally applicable limit for digital euro holdings at € 3000. Imposing this limit would not affect the euro area's financial stability, and liquidity outflows from the banking sector would be manageable. The scenario used in this study (as well as in the study of Adalid et al. (2022)) involves the entire population of the euro area adopting the digital euro, with each person reaching this holding limit. However, even the authors acknowledge that it is doubtful for the adoption rate to reach 100%.

One of the central ideas underpinning this study is that repetitive habits exhibit a strong predictive power for future behaviour. Aarts et al. (1998) assert that frequently performed actions are often habitual in nature, thereby defining a boundary condition for the applicability of attitude-behaviour models. Additionally, Limayem et al. (2007) conclude that satisfaction, the frequency of past behaviour, and the comprehensiveness of usage are key factors in habit formation, making them particularly relevant in the context of continuance behaviour. However, while those most inclined to adopt a digital euro tend to have established habits concerning the frequent use of modern payment or transfer methods, certain motivations or intentions, when sufficiently strong, can reshape these habits. Gardner et al. (2020) argue that intentions contrary to habitual tendencies can override the influence of established habits. These findings are significant as they shed light on the potential adoption of digital euro. Moreover, this paper introduces a new and sound ratio between sources that could fuel the digital euro account, further enriching our understanding of digital currency adoption.

Data and methodologies

The primary data sources used in this study were the World Bank (WB, FINDEX) and Eurostat (ES) indicators, ECB (deposits and interest data), World Economics (WE) public databases, and the European Commission's (2022) Eurobarometer (E). Several critical indicators for this study were disseminated for the first time starting in 2022 (for the reference year 2021 by Eurostat), while others were published at a frequency of three years (WB indicators). To ensure the consistency and comparability of the results, data primarily from 2021 were extensively used, most of which were collected in 2022. The lack of data for some indicators from the WB for Luxembourg led to its exclusion from all samples.

Only in the case of data not included in calculating and validating the digital euro adoption rate are 2022 and 2023 the last years with data (e.g., the VAR model used to identify whether the random interest-rate change was an essential determinant of the creation of household term deposits). Based on point-in-time data, this analysis likely represents the status quo as of mid-2022. To identify the ratio between cash and deposits as funding sources for digital euro accounts, data on overnight and term deposits of the population in the eurozone, covering the period from 2003 to March 2024, were used.

Central working ideas (backed by literature and research)

- Behavioural measures should be prioritised over hypothetical ones (direct survey questions) in habit-sensitive areas.
- Consumer habits and customer' profiling are crucial factors/actions in shaping marketing decisions.
- Contingent valuation surveys frequently do not reflect stable or well-defined preferences.
- Habits have a strong predictive power for future behaviour. If intentions are strong enough, they could overwrite habits.
- At the level of the euro area, there is a pretty clear divide between cash users and users of modern digital payment and transfer means.
- Most consumers in the euro area favour using a single payment instrument.
- The level of the cash propensity and the potential level of digital euro adoption should be strongly negatively correlated at the societal level.

On profiling the euro area's population

Unlike Lambert et al. (2024), who classify the euro area population into three non-mutually exclusive categories, this study divides the euro area population into six distinct, mutually exclusive categories:

- Type A - Tech-savvy who store money and who are digital-financial included, with the capacity to cope with adverse financial developments (the MinMax result below).
- Type B - Tech-savvy who store money and who are digital-financial included, without the capacity to cope with adverse financial developments.
- Type C - Unbanked individuals (without a financial institution account).
- Type D1 – Storing money individuals – non-tech-savvy (without any history regarding digital payments or money transfers) – capable of coping with adverse financial developments.
- Type D2 – Storing money individuals – non-tech-savvy (without any history regarding digital payments or money transfers) – not capable of coping with adverse financial developments.
- Type E – Banked individuals with no stored money.

Digital euro holder's profile: Introducing the MinMax methodology

The adoption of a digital euro is conditioned by willingness and capability. Individuals who have yet to use digital payment methods or are financially deprived are unlikely to adopt the digital euro shortly after its issuance. Building on this idea, I have outlined the profile of individuals who would be most prone and have the capacity and propensity to adopt the digital euro at its issuance. In this sub-section, I am building the profile of the most probable 3000 digital euro holder who will adopt

the digital euro for at least 2 out of 3 main functionalities of the digital euro. The holder of 3000 digital euro (Type A) is profiled by conditioning the choice of an eligible person on the cumulative fulfilment of five essential characteristics (Figures 1 and 2).

These five characteristics refer to digital financial inclusion, payment habits, and the capacity to withstand adverse financial events. Furthermore, considering the percentage of individuals meeting each of the five characteristics in five distinct sets, where each percentage represents the number of individuals in the set, I used the valid mathematical assumption that the maximum obtained by the intersection of the five sets is, in fact, the set with the most negligible percentage. In other words, in this situation, the maximum number of individuals satisfying all five criteria that could be found in all five sets would in fact, be represented by all the individuals in the set with the most negligible associated percentage. Next, I multiplied this result (referred to as MinMax) for each country by the number of individuals over 15 years old and the maximum value of the digital euro holding of € 3000. Thus, I obtained a result of approximately € 556.3 billion. The term, MinMax, is not new; it is found in game theory, linear algebra, and functional analysis, known as the min-max theorem, variational theorem, or Courant–Fischer–Weyl min-max principle[2]. Profiling the target audience is a common practice in marketing, merchandising, and even in the creation process for financial products and services. These practices often contribute to the market success of the products and services offered to the population. Essentially, this process identifies individuals with the same characteristics, with the same purchasing habits, or within the same group in terms of financial capacity.

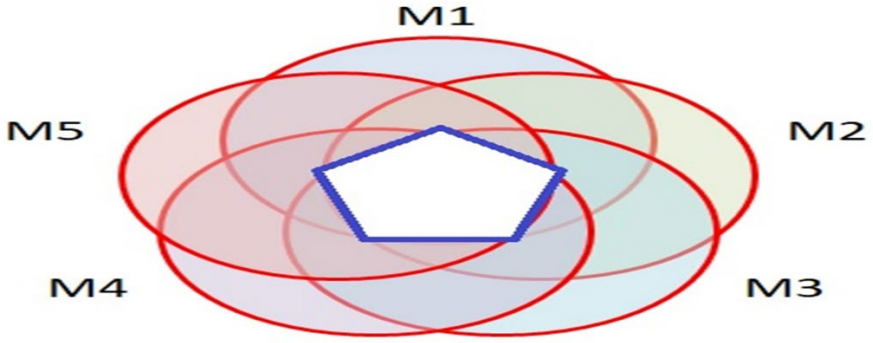


Figure 1. Venn diagram for CBDC holders – The white pentagon represents the intersection of the 5 sets

Source: Authors' own research.

(M1) IND6WB - Use a mobile phone or the Internet to make payments, buy things, or to send or receive money using a financial-institution account (% age 15+)
(M2) IND8WB - Store money using a financial institution or a mobile money account (% with an account, age 15+)
(M3) IND56ES - Individuals with minimum digital skills
(M4) IND10ES - Have the ability to face unexpected financial expenses
(M5) IND13WB - Made a digital payment (% age 15+)

Figure 2. Adopter's profile – 5 essential characteristics (MinMax indicators)

Source: Eurostat, World Bank Findex.

[2] https://en.wikipedia.org/wiki/Min-max_theorem

This value (€ 556.3 billion) is nearly half the maximum threshold of the digital euro adoption level, which, according to Adalid et al. (2022) and Meller and Soons (2023), does not lead to financial disintermediation in the euro area. Adalid et al. (2022) use approximately €1 trillion to calculate the impact on the euro area's banking sector. They conclude that this level is benign for the sector. As we will see further in this study, the MinMax result in the case of France was replaced with that for Lithuania. In the event of widespread stress in the euro area's banking sector, only the indicator, IND8WB (Store money using a financial institution or a mobile money account (% with an account, age 15+)), was considered, premised on the idea that a massive bank run in this situation would be highly likely.

Quantifying the propensity to hold and use cash in the euro area

To compare the MinMax results and to include an indicator regarding the population's propensity to hold and use cash in the euro area in a final index on the level of euro-area digital euro adoption capacity, separately by state, a composite index, the cash propensity index (CPIX), was computed. Indicators such as the number of non-cash payments per capita (negative impact on the CPIX), number of cash withdrawals per card (positive effect), utility payment using cash only (% of the total population, positive impact), received wages in cash only (% of the total population, positive impact) and receives a public-sector pension in cash only (% of the total population, positive effect) were used for the CPIX calculation (values with reference year 2021).

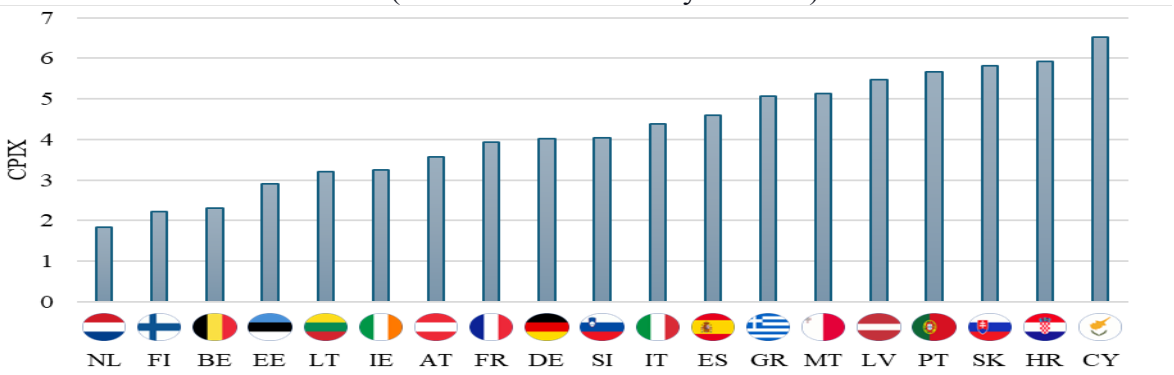


Figure 3. Propensity to hold and use cash in the euro area (mid-2022 status quo)

Source: Authors' own research.

Calculating the CBDC Adoption European Scoreboard (CAES)

The next step is to construct a composite index that measures the potential level of adoption of the digital euro. The CAES contains indicators related to the following: financial capacity; information and communications technology (ICT) skills; social, digital, and financial inclusion; income inequality; social inequality; the level of libertarianism in society; the intention to adopt the digital euro (Google Trend Index as a proxy for interest or Eurobarometer survey responses); the level of competition (the dimension of financial technology-sector (fintech-sector) development); the level of ageing in society; the informal-economy dimension; the financial-burden level; a measure of financial wealth; and proxies for risk tolerance.

Robustness checks for MinMax results

MinMax is based on the hypothesis that a holder of 3000 digital euros must cumulatively meet a series of conditions. As this is merely a hypothesis and not a quantitatively measurable

phenomenon, the results obtained from this methodology must be checked for robustness. Therefore, I first compare how euro-area member states cluster based on the MinMax results, with their clustering based on the degree of usage of financial products with functionalities similar to those of the digital euro, as well as adoption capacity (CAES). Thus, the discriminatory capacity of a univariate clustering method, which uses a single variable to group data, is evaluated in comparison to multivariate clustering methods, which use multiple variables, utilising data related to the use of private financial products with functionalities similar to those of the digital euro, plus CAES. In the second validation stage, the distribution of the MinMax results is compared with that of the CPIX results to verify if they are negatively correlated (co-existing and circulating concurrently rather than entirely replacing one another at the broader societal level, Rosl and Seitz, 2022; at the individual level most people are not using both; the latter being studied by Reimers et al., 2020). Additionally, for several countries (Germany, Spain, the Netherlands, and Austria), a comparison between the MinMax results and the proportion of the population expressing interest in holding a digital euro account (as indicated in survey responses) is conducted. These proportions are significantly lower in all these countries than the corresponding MinMax results. However, according to significant specialised studies, the results of surveys regarding the potential use or purchase of a hypothetical product should be interpreted with caution. Contingent valuation surveys frequently do not reflect stable or well-defined preferences. Instead, respondents often construct their answers spontaneously, rendering the resulting data unreliable for rigorous analysis. This issue significantly undermines the validity of such surveys (Hausman, 2012). Consumer habits are a key factor in shaping marketing decisions, yet they are often misrepresented. Two studies reveal a systematic underestimation of the influence of habit on consumer behaviour when assessed through hypothetical scenarios. This highlights the need for a more accurate approach in consumer research, prioritising behavioural measures over hypothetical ones in habit-sensitive areas (Herziger and Hoelzl, 2017).

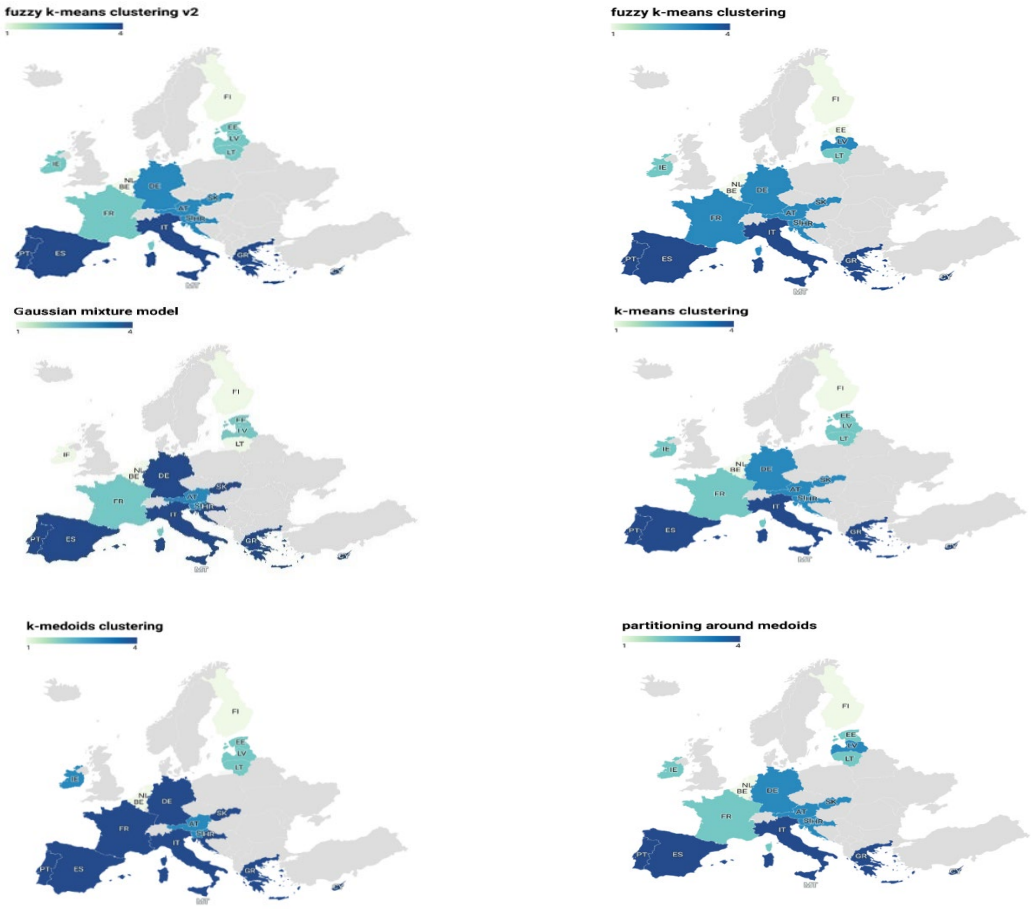
Moreover, Lambert et al. (2024) employ a structural demand model using unique consumer-level survey data from the euro area, concluding that with a holding limit of 3000 digital euros, the maximum potential demand would amount to 380 billion euros.

If the MinMax value underestimated potential demand, the holding limit would be higher than the banking sector could accommodate. This discrepancy could lead to significant challenges for financial stability. Specifically, an underestimated demand reflected by the MinMax value implies that more people might want to hold digital euros than initially anticipated. Consequently, if the holding limit is set based on this underestimated demand, it might allow for a greater accumulation of digital euros than the banking sector can support without adverse effects. This scenario could result in excessive outflows from traditional bank deposits to digital euro holdings, potentially leading to liquidity shortages in the banking sector. These liquidity shortages could force banks to sell off assets at unfavourable prices, potentially triggering a financial crisis or amplifying existing financial instability. Therefore, it is crucial to accurately calibrate the holding limit as much as possible. This calibration should be based on as much as possible realistic demand assessments to prevent excessive strain on the banking sector and maintain financial stability.

Validating through clustering techniques

In this section, a comparison of the MinMax results with digital financial behaviour was initiated using CAES and data on the usage of three functionalities, such as those of the digital euro: the per-capita number of payments through credit transfers, per-capita number of card payments, and the percentage of people who had Internet banking activities in 2021 whose degree of usage was

characterised by very high scarcity and heterogeneity at the euro-area level. For the first two functionalities, indicators related to sums paid or transferred were not used because this aspect is more related to financial well-being than to the appetite for modern means of payment or transfers. Subsequently, multivariate clustering procedures were employed (using six different methodologies as a concept and setting (Kassambara, 2017)) for functionalities such as those of the digital euro and CAES (Figures 4–9), and univariate clustering was performed using the MinMax data (Table 1 and Figure 10).



Figures 4–9. Multivariate clustering using CAES, card payments per capita, Internet banking usage, and credit transfers per capita[3]

Source: Authors' own research.

[3] Except for the fuzzy k-means clustering version 2, which uses the Jaccard-distance metric, and the Gaussian-mixture model, which does not use any specific metric, all other multivariate clustering methods employ the Euclidean-distance metric

Univariate clustering			
1	2	3	4
Belgium	**Austria**	Germany	Cyprus
Estonia	**Spain**	**France**	Greece
Finland	Lithuania	**Italy**	Croatia
Ireland		Latvia	Portugal
Netherlands		**Malta**	
Slovakia		Slovenia	

Table 1. Cluster allocation - univariate clustering with clustering MinMax

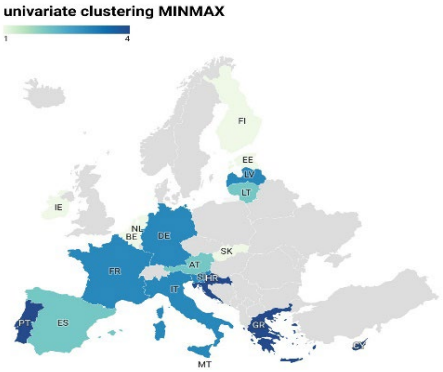


Figure 10. Univariate with MinMax values

Source: Authors' own research.

We can observe that MinMax partially overestimates (in the case of Slovakia, Austria, Spain, Italy, and Malta), meaning that, in univariate clustering, some states fall into clusters higher than those predominantly characterising them after applying the six multivariate clustering procedures, except for France. One reason for the imperfect fit between univariate and multivariate clustering might be that in the former, the data used are qualitative, obtained from surveys (whose accuracy depends heavily on the statistical representativeness of the sample), and avoiding biased responses is difficult when surveying with a certain margin of error. In contrast, the data in the latter are primarily quantitative.

In conclusion, MinMax does not underestimate the actual level of digital euro adoption.

Validating through comparisons with CPIX

The MinMax results and CPIX values should be negatively correlated. Thus, the higher a country's appetite for holding and using cash, the lower the level of digital euro adoption, and vice versa. If this hypothesis is confirmed, the MinMax results will be validated again as primarily correct. With their comprehensive research, Kotkowski and Polasik (2021) have provided strong support for the strong negative correlation between this two distributions in the euro area (MinMax and CPIX). Their findings show that the divide between cash users and users of modern digital payment and transfer means has become more evident during the pandemic, with only a small proportion of the population using both, thereby filling the gap between the two types of individuals to some extent. These findings are further corroborated by Meyer and Teppa (2024), who observe that most consumers favour using a single payment instrument, notably cash and contactless cards, especially in the aftermath of the COVID-19 pandemic. Moreover, according to Lambert et al. (2024), only 2% of the euro area population is tech-savvy and cash-affine at the same time.

Figure 11 shows that the countries are remarkably close to the trend line, indicating that the initial assumption of strong negative correlation is correct. Slovakia appears to exhibit a high propensity for cash and a relatively high MinMax value. This suggests that despite cultural or economic factors that make the population inclined toward holding cash and cash transactions, Slovakia has the potential to exhibit a great interest in the digital euro.

Next, the two distributions were normalised using a scale of 0 to 100. Table 2 indicates that the two distributions have similar statistical properties.

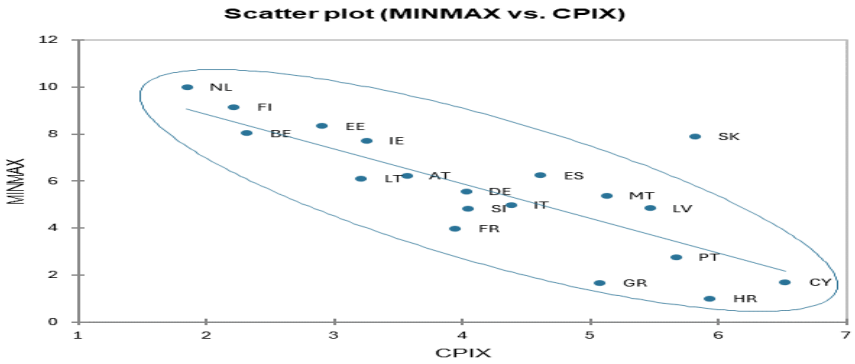


Figure 11. MinMax vs. CPIX

Source: Authors' own research.

The fact that only some countries are extremely close to the trendline (Figure 11) or scattered around it does not necessarily mean that something must be fixed. There might be cases in practice in which some member states' citizens prove to have a high/low appetite for cash, imperfectly correlated with the usage of digital solutions for payments and money transfers, like in the case of Slovakia. Moreover, the distance from the trendline in Figure 11 in the case of some countries is mainly because there is no perfect divide between cash-only users and digital payment means-only users, in the sense that there is a proportion of the population who is using both. Zamora-Pérez et al. (2024) analysis reveals a more nuanced reality within the euro area, where cash plays a vital role alongside digital payment options. Many individuals, with and without access to digital payment tools, frequently utilise cash, suggesting that the distinction between these payment methods is not as clear-cut as is often portrayed. Hence, the imperfect negative correlation of these two distributions may also be due to a proportion of the population that uses both cash and modern digital payment and transfer methods. This underscores the need for a more nuanced understanding of payment behaviour in the euro area, which can inform policy and financial services decisions.

Descriptive statistics (Quantitative data):		
Statistic	CPIX	MINMAX
Minimum	0,000	0,000
Maximum	100,000	100,000
Range	100,000	100,000
1st Quartile	29,244	35,493
Median	46,776	49,565
3rd Quartile	69,911	70,508
Sum	873,224	894,053
Mean	48,512	49,670
Variance (n)	789,088	786,752
Variance (n-1)	835,505	833,031
Standard deviation (n)	28,091	28,049
Standard deviation (n-1)	28,905	28,862
Variation coefficient (n)	0,579	0,565
Variation coefficient (n-1)	0,596	0,581
Skewness (Pearson)	0,010	-0,092
Skewness (Fisher)	0,011	-0,101
Skewness (Bowley)	0,138	0,196
Kurtosis (Pearson)	-0,957	-0,796
Kurtosis (Fisher)	-0,863	-0,647
Standard error of the mean	6,813	6,803
Lower bound on mean (95%)	34,138	35,317

Upper bound on mean (95%)	62,887	64,023
Standard error of the variance	286,576	285,727
Lower bound on variance (95%)	470,457	469,065
Upper bound on variance (95%)	1877,740	1872,182
Standard error (Skewness (Fisher))	0,536	0,536
Standard error (Kurtosis (Fisher))	1,038	1,038
Mean absolute deviation	23,444	22,364
Median absolute deviation	22,812	20,711

Table 2. Descriptive statistics: CPIX vs. MinMax (scaled values ranging from 0 to 100)

Source: Authors' own research.

Digital euro account funding sources

Consumers' sensitivity to on-term deposits interest-rate change

In this sub-section, I determine the dimension of on-term deposit-demand elasticity related to interest rates.

The population holds bank savings accounts typically for several underlying reasons: i) as a precautionary measure to have a safety net in the case of income reduction, job loss or retirement; ii) as an investment for obtaining returns or protecting against high inflation; and iii) for security, such as migrating from a troubled bank to an institution perceived as more robust. These three drivers are not mutually exclusive, and a consumer could have in mind all three when opening an on-term deposit. This section focuses on the second category as I attempt to determine whether term deposits are substitutable by holdings of digital euros under the condition that the latter will likely not be remunerated. In this regard, I conducted a standard vector autoregressive (VAR) analysis for the four largest economies in the euro area, which also account for the most significant population (approximately 75% of the total population over 15 years old in the euro area). The idea behind including only these four countries in the model is that if the digital euro were widely adopted in these four countries (Germany, France, Italy, and Spain), its success across the entire euro area would then be almost guaranteed. In the previous sections, we observed that the potential level of digital euro adoption in three of the four countries was relatively low. However, in this subsection and the following, I attempt to determine which money forms (cash, overnight deposits, and on-term deposits) could be subject to migration to digital euros and whether on-term bank depositing behaviour is less or more pronounced during periods of economic crisis or regular periods. This last question seeks to answer whether on-term deposits could migrate to digital euro holdings during and in the aftermath of an economic downturn.

Researchers have concluded that the probability of bank savings increases with the interest rate and tends toward zero at shallow interest-rate levels (Felici et al., 2023). Additionally, Fredriksson and Staal (2021) provide robust evidence of the positive effect of lagged savings interest on bank savings, while a decrease in the interest rate leads to a decline in the level of new deposits (Kharazi et al., 2022). In the case of the Netherlands, which is not included in our model but is ranked among the top five economies in Europe, studies indicate that relocating deposits from one bank to another significantly depends on differences in bank interest rates (Gerritsen et al., 2017).

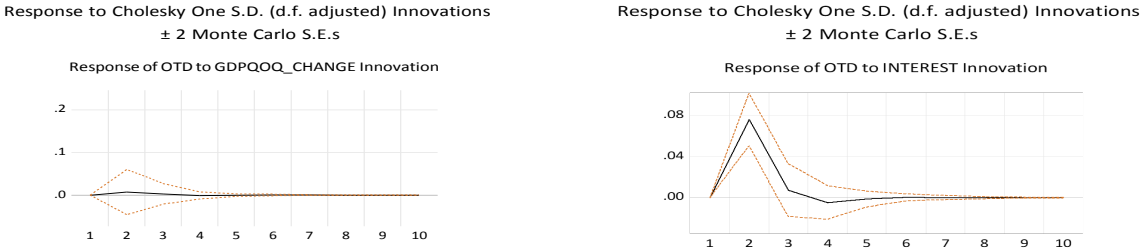
In the VAR model, I included newly constituted on-term deposits (quarterly frequency), quarterly economic growth compared to that of the same quarter of the previous year (GDP at market prices, chain-linked volumes), and the interest rate on newly constituted term deposits (quarterly frequency). The data cover nearly 20 years until Q1, 2023. I also included data regarding quantitative inflation expectations, but the results were not statistically significant. Focusing only on the second savings category, I do not include a dummy variable that lags the financial crisis.

Regarding this last variable, the literature has consistently documented that a financial crisis generates flight-to-safety or bank-run episodes. In a preliminary VAR, I use the population's quantitative inflation expectations. The results show that this variable is not statistically significant and does not impact random increases or decreases in new deposits in the four countries.

The results lead to the following main conclusions (Figures 12–19): i) Germans are the most sensitive to changes in the interest rate. Variations in economic activity do not influence Germans' on-term bank-saving behaviour (this latter conclusion is valid for all the states included in the model). ii) The French and Italians are less sensitive to changes in the interest rate than Germans. iii) The interest rate level does not influence Spaniards' decision-making process regarding bank savings. This VAR captures the short-term relationship between the level of new deposits, interest rate (the reaction of the former to the latter's random swings), and variation in economic activity. A vector error correction model is more appropriate for observing long-term relationships.

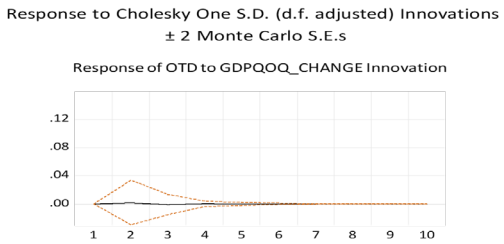
The VAR results indicate another aspect. The model disentangles the savings behaviours of citizens from the four member states. Thus, Spaniards do not necessarily invest in excess financial resources to create new bank deposits. Most likely, they save it as a precautionary measure or for security, suggesting that even when issuing a non-interest-bearing digital euro, this asset could prove attractive to Spanish citizens during regular periods, especially during financial crises. For the French and Italians, compared to Spaniards, issuing a non-interest-bearing digital euro might lead to less pronounced migration behaviour (by moving resources meant to be turned into on-term deposits) away from the commercial banking sector toward digital euro holdings. However, Germans perceive savings primarily as a form of investment; thus, only if the digital euro were to bear interest could it attract on-term depositors from the banking sector.

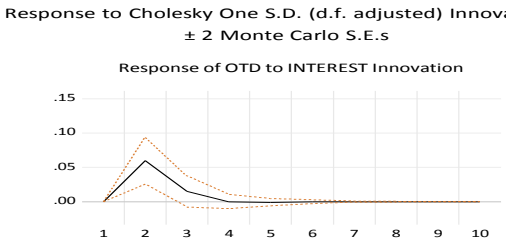
Other conclusions in this section are as follows: 1) German consumers will likely adopt the digital euro by transferring financial resources from current accounts. 2) The French and Italians will adopt the digital euro by shifting funds from current accounts initially meant to be spent, transferred, or stored, especially, and to a lesser extent, by shifting money from current accounts, which generally would be transformed into term deposits. 3) In the case of Spaniards, any of the money from current accounts, which generally would be transformed into term deposits or funds from current accounts, used to purchase goods and services or for any other purposes (such as a store of value), could be the source for fueling a digital euro account.



Figures 12,13. Impulse-response function for Germany

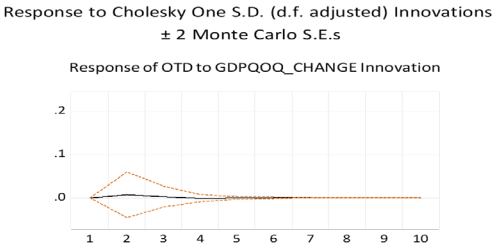
Source: Authors' own research.

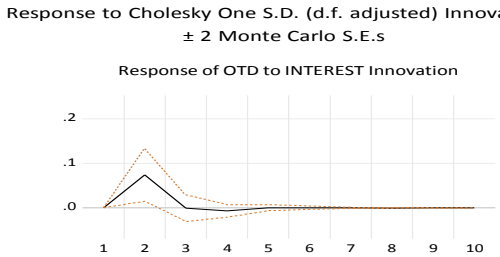


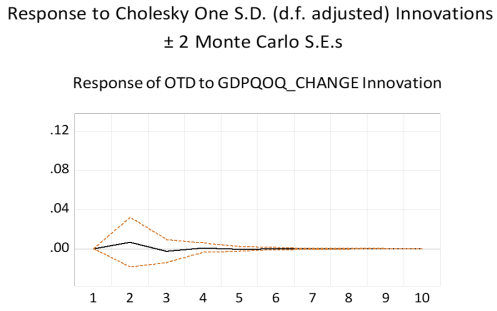


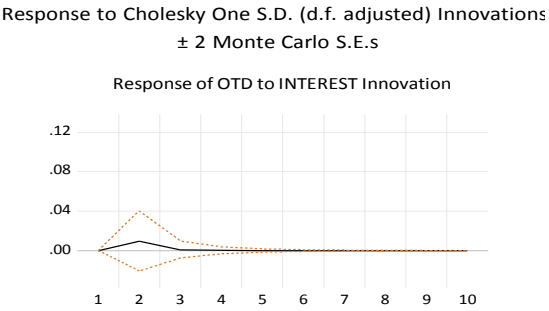
Figures 14,15. Impulse-response function for France

Source: Authors' own research.









Figures 18,19. Impulse-response function for Spain

Source: Authors' own research.

My findings are somewhat in line and complementary with the ones of Horioka and Ventura (2024), based on the Household Finance and Consumption Survey (HFCS), which the European Central Bank conducts. Their analysis reveals a significant variation in the importance of saving motives among European households. The rank ordering of saving motives varies depending on the criterion used for ranking. For instance, when the proportion of households saving for each motive is used as the ranking criterion, the precautionary motive emerges as the most prominent saving motive. However, when the quantitative significance of each motive is considered, the retirement motive becomes the most important. This diversity in saving behaviour underscores the need for a nuanced understanding of household financial decisions. Furthermore, the generosity of social safety nets influences the relative importance of each saving motive. Saving for retirement is less critical in countries with generous public pension systems while saving for precautionary reasons is less emphasised in countries with robust healthcare systems. These findings suggest that the dominance of retirement and precautionary saving motives across Europe is partly attributable to the perceived inadequacy of existing social safety nets.

It is important to note that low sensitivity to random variations of interest rates on term deposits would only sometimes lead to liquidating term deposits before maturity to migrate toward digital euro holdings. Instead, a low sensitivity to interest-rate variations could lead to a dissaving phenomenon. Specifically, individuals who do not save to gain financial benefits will save less in term deposits than before the issuance of the digital euro or will not renew their term deposits. In

conclusion, it is not term deposits that may be subject to migration toward digital euro holdings; however, overnight deposits will shift to digital euro holdings (which contain three types of money: money stored without the purpose of being transferred or spent dissaved money, and money meant to be spent or transferred). These last ideas align with the assumption from Adalid et al. (2022), who hypothesise that overnight deposits would be substituted by digital euro holdings and not on-term deposits.

The (in)flexibility and volatility of cash reserves and currency in circulation over time

According to the specialised literature, a strong positive correlation exists between the level of the informal economy and that of cash holding and usage (Reimers et al., 2020). Among the most commonly used methods to estimate the level of the informal economy in a country is the currency-demand approach (Feld and Schneider, 2010; Schneider and Enste, 2000), which is based on the premise that cash transactions account for the bulk of informal transactions (e.g., Johnson et al., 1998; Schneider, 1997). A growing body of literature claims that cash supports the shadow economy (Andrews et al., 2011; Riccardi and Levi, 2017; Schneider, 2017). A bidirectional relationship exists between cash and the informal economy in the sense that these two concepts reinforce each other, and disrupting this cycle can be achieved through the adoption of digital payment and transfer methods by those who currently prefer cash.

Figure 20 illustrates that, despite the exponential growth of the digital financial phenomenon over the years, the informal economy has only marginally decreased, with a few exceptions in small states as a number of population from 2000 to 2022. Despite the significant growth in digital transactions, this persistent presence of the informal economy underscores the crucial and urgent need for effective measures to disrupt the cash-informal economy circle.

Despite the exponential growth in digital payments and transfers, the data present a surprising trend. Figures 21–22 reveal that cash in circulation or the population's cash reserves have either insignificantly fluctuated or have increased. The proportion of cash reserves in the population's total financial assets has trended upward from 2012 to 2022, a period associated with the digital financial revolution. This unexpected increase in cash reserves within the aggregate of cash reserves and the population's term and overnight deposits is a significant finding that challenges the conventional understanding and piques our curiosity.

"Cash is by far the most popular payment method in Europe. It is so high partly due to the fact that in uncertain times, cash is perceived as particularly familiar and secure. Cash remains highly valued, reflected in the strong majority favouring cash in the next five to ten years."[4]

Even with the introduction of cash payment limits in most states of the euro area[5], the propensity of consumers to hold and use cash has not decreased. This lack of change in behaviour raises questions about the effectiveness of these measures in reducing tax evasion. Additionally, the legislative package aimed at regulating cash as a legal tender[6] continues to support its high usage.

All these aspects clearly indicate that the transition of financial operations to the digital environment has been supported not by transferring cash into current accounts (or not withdrawing from automated teller machines (ATMs)) but by using excess money from current accounts.

[4] https://www.bearingpoint.com/en/about-us/news-and-media/press-releases/survey-cash-is-number-one-in-europe/
[5] https://www.evz.de/en/shopping-internet/cash-payment-limitations.html
[6] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13429-Clarifying-the-legal-tender-status-of-euro-banknotes-and-coins_en

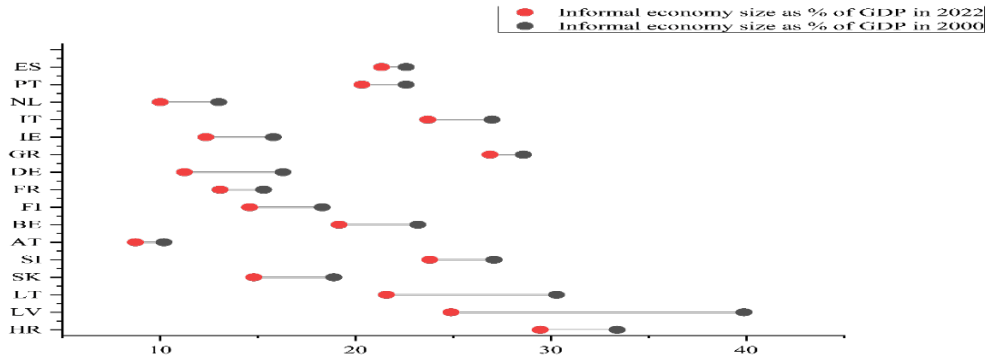


Figure 20. The size of the informal economy, 2000 vs. 2022[7]

Source: Schneider (2002), World Economics.

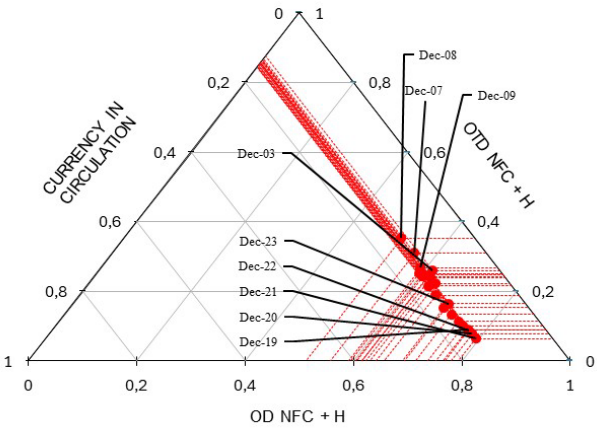


Figure 21. Ternary chart of currency in circulation, on-term deposits (non-financial companies plus households), and overnight deposits (non-financial companies plus households)

Source: ECB

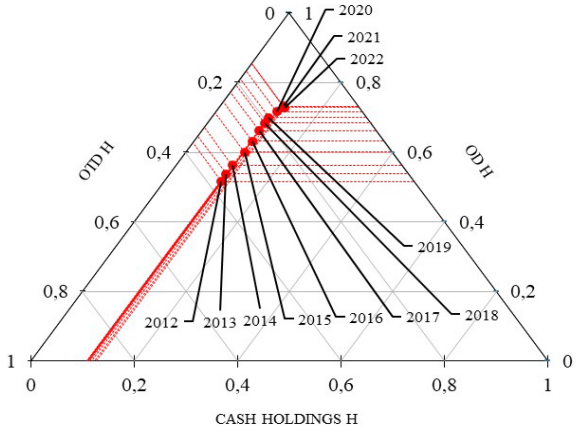


Figure 22. Ternary chart of households' cash reserves, households' on-term deposits, and households' overnight deposits

Source: ECB, Eurostat

A two or three-player game?

The next step in this section's analysis was to test the hypothesis that consumers in the euro area did not reduce their cash reserves to create term deposits in the context of a high-interest-rate environment or to fund current accounts to support the exponential growth in the number of digital payments and transfers. However, funding current accounts or creating term deposits was a two-way interplay between these elements, except for situations unrelated to reducing cash reserves.

My research, spanning over 20 years of monthly series of term and overnight deposits, has led to significant findings. I calculated the monthly variations, resulting in two distributions with over 250 data pairs. I identified a series of pairs placed outside the ellipse by creating a scatter plot and an ellipse to encompass the respective pairs (with a Fisher confidence interval of 97%). These pairs correspond to June 2005 and the beginnings/ends of years during the 2005–2009 period.

[7]https://www.researchgate.net/publication/253147023_Size_and_Measurement_of_the_Informal_Economy_in_110_Countries_Around_the_World

According to Grimaldi (2010), during this period, financial stress in the euro area was detected at a level higher than the long-term average, which generated atypical (dis)saving behaviour from euro-area consumers.

The next step was to exclude these outlier pairs and treat these series of pairs as two simple distributions, not as time series, due to breaks in them. Table 3 and Figure 23 show that between the monthly variations of term deposits and the monthly variations of overnight deposits, a second-order polynomial relationship is created (the best fit without risking to overfit; the scatterplot of residuals and predicted values does not follow any pattern/trendline) with an adjusted R squared of 0.73. A quadratic relationship between an independent variable, x, and a dependent variable, y, implies that the relationship can be described by a quadratic function, which includes a squared term. This results in a parabolic curve when plotted, indicating that the rate of change of y with respect to x is not constant but varies in a quadratic manner. The value of R squared adjusted signifies that the variation in overnight deposits explains 73% of the variation in term deposits. The fact that the adjusted R squared is not higher does not necessarily mean that people used part of their cash reserves to fund current accounts or to constitute term deposits. Given the points mentioned above regarding cash reserves, several explanations for the adjusted R-squared level may include the following: i) high cross-correlation after 2009 (albeit on a decreasing path), even when comparing od(t) with odt(t), odt(t-1)...odt(-12), and odt(t+1), odt(t+2)...odt(t+12), and vice versa, where t = 0; ii) excess amounts generated by income growth above the long-term average are not automatically converted into term deposits and may be allocated to increasing consumption rate; iii) liquidation of term deposits and direct transformation into cash without passing through current accounts; and iv) the influence of other several exogenous factors such as sale or realisation of fixed (real estate) or financial (private pensions, insurance, equities and shares, and debt securities) assets and their direct conversion into term or overnight deposits. Most of these operations largely depend on the phases of the economic and financial cycles.

	p-value	R^2 adj.	MSE	RMSE	AIC	AICC
Quadratic equation (second order)	<0,0001	0,73	0,000	0,005	-2528	-2528

otd mom change = 0,009086 - 2,216 * *od mom change* + 65,32 * *od mom change*^2

Table 3. Robustness indicators of the quadratic equation where monthly changes in households' on-term deposits are the endogenous variable and monthly changes in households' overnight deposits are the endogenous variable

Source: Authors' own research.

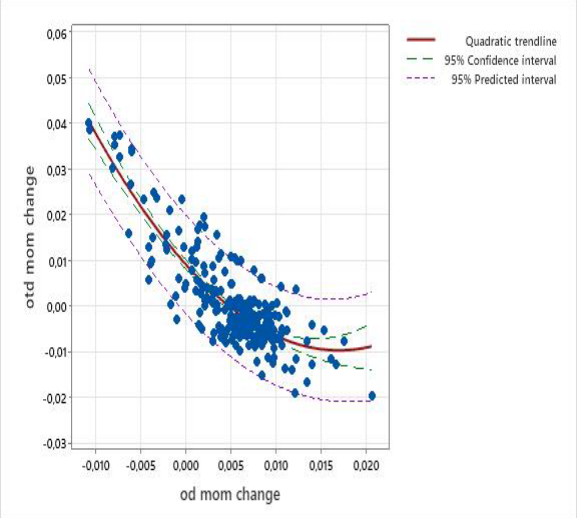


Figure 23. Visualising the quadratic equation specified in Table 9

Source: Authors' own research.

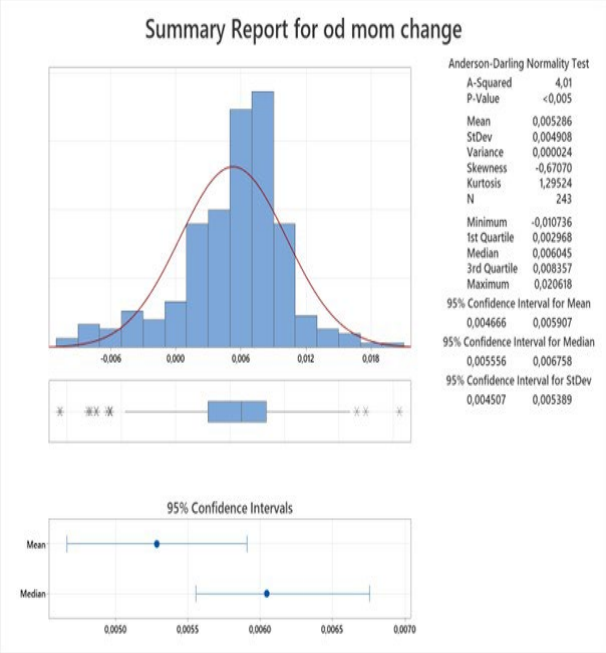


Figure 24. Summary statistics and histogram for overnight deposits Distribution of MoM changes

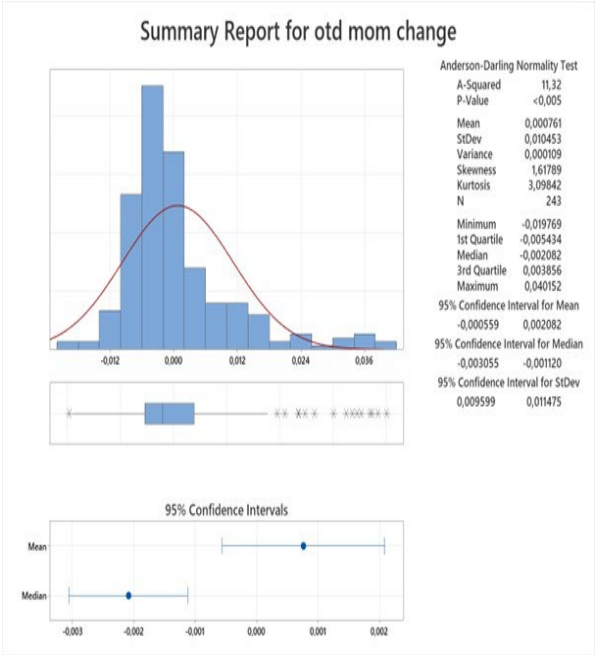


Figure 25. Summary statistics and histogram for on-term deposits Distribution of MoM changes

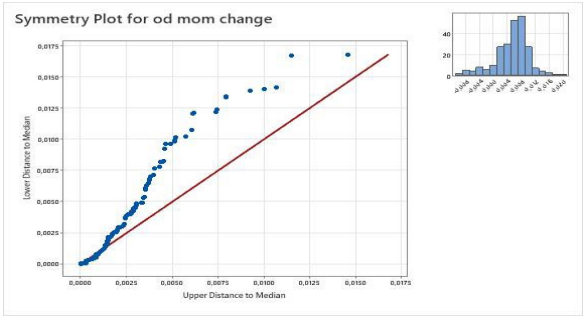


Figure 26. Symmetry plot for overnight deposits; MoM changes

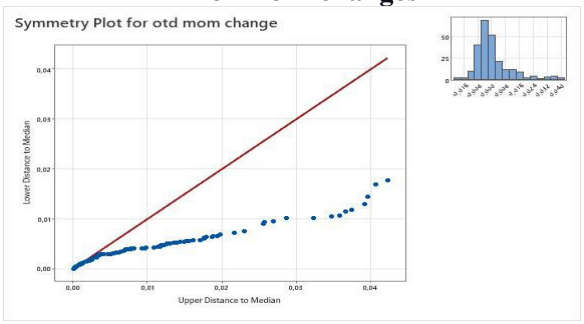


Figure 27. Symmetry plot for on-term deposits; MoM changes

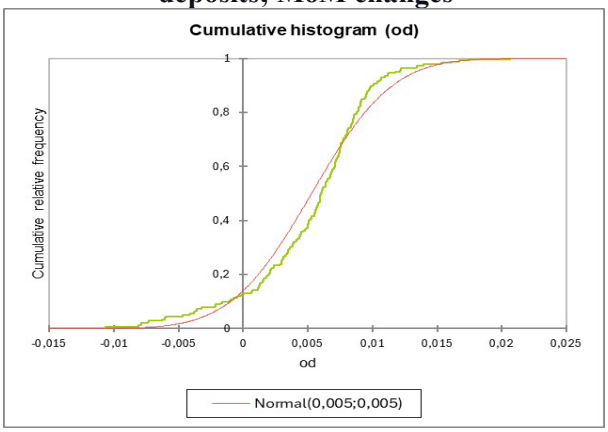


Figure 28. Cumulative histogram of overnight deposits; distribution of MoM changes

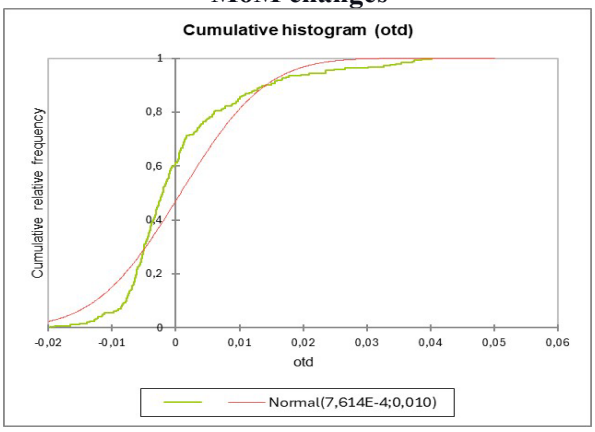


Figure 29. Cumulative histogram of on-term deposits; distribution of MoM changes

Source: Authors' own research.

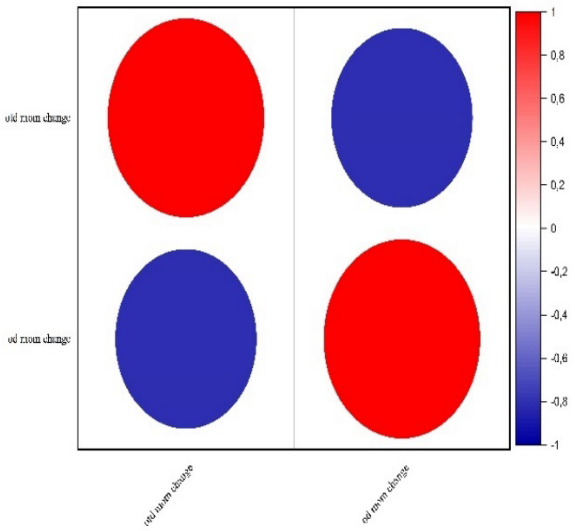


Figure 30. Pearson's correlation between on-term deposits MoM changes and overnight deposits MoM changes

Source: Authors' own research.

Considering figures 24-30, it is obvious that the distributions of monthly changes in overnight deposits and on-term deposits are mirrored and highly negatively correlated.

Figures 24-30 statistically support the previously stated hypothesis that the variations in the two elements (term and overnight deposits) strongly and negatively influence each other. All this evidence leaves no room for other interpretations than the aforementioned ones. This century, we witnessed a digital financial revolution, the occurrence of periods characterised by high interest rates and inflation (where, on the opposite than someone might think, the appetite for holding significant cash reserves was higher than the need to counter inflation), geopolitical events (where, due to geopolitical risks and the potential for their expansion within the euro area, people may prefer to maintain substantial cash reserves to support high mobility), high consumerism periods, changes in the propensity to save, Covid-19 pandemic, the great financial crisis (GFC) and the war in Ukraine. Even though some of these events would theoretically imply reducing cash holdings (such as the digital financial revolution), people not only did not reduce their cash reserves, they even increased them. Moreover, according to ECB's SPACE Survey, "37% of consumers kept cash reserves at home, outside the wallet or a bank account, up from 34% in 2019". Most likely, in people's perception, the main difference between the retail digital euro and private digital means of transfer or payment is and will be, from the consumer's perspective, that the former is the central bank's liability, and the introduction of the digital euro will not lead to the households' cash reserves reduction. Meanwhile, the money for transactions in the latter category (private money) is a liability of private financial institutions. Digital money already exists. The main novelty lies in the fact that a new provider is now entering the market. For these reasons above, I suppose that, despite the advantages of the digital euro in meeting essential consumer criteria—high privacy standards, the ability to make payments throughout the euro area, and instant payments and transfers—most probably, we would not be witnessing an immediate significant downward change in people's propensity to hold cash reserves. In addition, I presume that it is unlikely that people with the

required profile would use cash to change the provider of digital means of payment and transfer. This aspect is somewhat supported by the fact that cash holdings are less consistent among tech-savvy individuals than among those with a strong preference for cash, averaging 324 euros versus 587 euros respectively (Lambert et al., 2024)). Moreover, the scenario in which people would reduce the number and amount of cash withdrawals from ATMs is unlikely, given the low elasticity of cash in circulation in the euro area during the analysed period. However, with its clear benefits over commercial payment and money transfer solutions, the digital euro holds a promising future. Its adoption is expected to be 'heterogeneous and sparse' across euro-area countries, meaning that it will not be uniformly or densely adopted, but rather in a varied and scattered manner. Nonetheless, it is a step toward increasing digital financial inclusion.

Discussions and concluding remarks

While a range of challenges could impede the adoption of the digital euro by households in the euro area, including technological barriers, security and privacy concerns, trust issues, economic factors, behavioural and cultural resistance, regulatory and legal concerns, financial inclusion issues, transition and integration challenges, and educational and awareness gaps, it's important to remember that overcoming these challenges will pave the way for the potential benefits of the digital euro. This instils optimism and hope for its successful implementation and acceptance.

The results of this research suggest that in the best-case scenario with a capped digital euro holding, the take-up in mid-2022 would not have been more than approximately 60% of the maximum amount from Adalid et al.'s (2022) working paper (in the capped scenario). The demand for the digital euro would be relatively limited if presently issued if we considered the inertia of some individual characteristics. By combining my results with those obtained by Gross and Letizia (2023), I conclude that if the digital euro were non-remunerative, the lower boundary of adoption would then be 1% of the broad money (M3). The upper limit would be no more than 5% of the total deposit liabilities in the euro area (which is lower than the broad-money share). The main difference between these two methodologies is that Gross and Letizia (2023) employ a scenario in which digital euro holdings are not capped. In the capped scenario, the lower boundary calculated by Gross and Letizia (2023) would be less than 1% of the M3.

The contribution of my study to the domain is substantial and threefold: 1) By using the MinMax estimates, macro- and monetary-impact studies could be performed with a higher degree of accuracy than by assuming that all individuals could hold digital euros. Additionally, my results show that in a capped scenario and with a non-interest-bearing digital euro, no threat arises to the euro area's financial stability; moreover, the holding limit and potential remuneration could be more accurately calibrated to solve the trilemma mentioned above. 2) Section 8 clearly shows that the ratio between cash and deposits, as fuelling sources for digital euro holdings, tends toward 10:90. 3) Correlations show which aspects and socio-economic dimensions should be addressed to increase the appetite for the digital euro.

It must be emphasised that it is essential that the surveys measuring households' willingness to adopt the digital euro provide figures significantly below the MinMax results, which quantifies the capability to adopt the digital euro. Regarding the calibration of the holding limit, finding a balance is crucial. A limit that is too low could make the digital euro less appealing to the population, while a limit that is too high could impact the euro area's financial stability. However, a well-calibrated limit could bring about positive outcomes for both financial stability and the public's well-being (Bidder et al., 2024). Bidder et al. (2024) also suggest that, in the case of Germany, the population's interest in adopting the digital euro is linked to the stress levels in the

banking sector. Therefore, a balanced calibration of the holding limit is crucial. This will make the digital euro more attractive without triggering bank runs or flight-to-safety episodes.

All the estimates in this study will be updated in the second half of 2025 when the WB publishes its 2024 datasets. Nevertheless, considering the potential increase in MinMax indicator values upon their next publication in 2025, a holding limit of slightly less than 3000 euros could be optimal for maintaining financial stability within the euro area. After these calculations have been recompiled, near the digital euro issuance date, the potential remunerations and limits imposed on digital euro holdings can be recalibrated. The study by Lambert et al. (2024) and this research provide the European Central Bank (ECB) with quantitative measures that could be instrumental in calibrating the holding limit. Lambert et al. (2024), Nocciola and Zamora-Perez, and my work all study the same thing from different perspectives.

One might argue that individuals belonging to other profile types (B, C, D1, D2 and E) could also adopt the digital euro. This is indeed the case. However, the aim of this paper was to identify those individuals eligible to adopt the digital euro up to a threshold of €3,000, based on the premise that current payment and transfer behaviours serve as strong predictors of future adoption patterns. The maximum potential amount of digital euro adoption by individuals in Profile A would be approximately €0.55 trillion, whereas the estimated maximum aggregate holdings of digital euro in a realistic scenario would be around €0.4 trillion (according to Lambert et al. (2024)). Given that the figure obtained in this study significantly exceeds the more realistic estimate of potential adoption, it becomes imperative, from the perspective of safeguarding financial stability in the euro area, to employ the findings of the present study for accurately calibrating the individual holding limit.

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