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Quantitative easing and the price-liquidity trade-off*

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Abstract

We present a search theoretic model of over-the-counter debt with quantitative easing (QE). The impact of central bank asset purchases on yields depend on market tightness, which is determined by shares of preferred habitat investors. The model predicts that the impact of government bond purchases is higher in countries with a higher share of preferred habitat investors. Furthermore, there is a trade-off with liquidity, which is not present in other models of QE. We present a new index for the share of preferred habitat investors holding government bonds in Eurozone countries, based on the ECB's securities and holdings statistics, which we use to match the impact of QE on the observed yield changes in data and to test our model.

Keywords: Quantitative easing, liquidity, search and matching

JEL Classification: E52, E58, G12

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1 Introduction

What movements in prices and liquidity can be expected from central bank purchases of financial assets, such as government bonds, when it is conducting a policy of quantitative easing (QE)? And can different effects be expected when buying a nominal bond vs. index-linked bond, a government bond vs. a corporate bond, or a German bond vs. Portuguese bond?

Term structure models lack an explicit modelling of demand and supply of assets to explain possible variations in the impact of asset purchases by central banks. In a standard asset pricing model quantitative easing has no effect on bond prices, which are determined by the cash flows and risk aversion of the investors. In order for quantitative easing to impact yields, it must be assumed that there are certain market rigidities, e.g. from preferred-habitat investors who require a premium to move away from their preferred habitat (Vayanos and Vila (2009); Hamilton and Wu (2012)). These are investor clientele with preferences for specific maturities (and asset classes), for example due to institutional factors and regulations constraining financial intermediaries ((Modigliani and Sutch, 1966)).

The impact of quantitative easing is typically estimated through the impact the amounts of purchases have on the term premium of yields (through a reduction in supply of assets), see e.g. Gagnon, Raskin, Remache and Sack (2011); D'Amico and King (2013); McLaren, Banerjee and Latto (2014). QE can also affect the expectations component of the yields through the signalling channel Bauer and Rudebusch (2014), from which we abstract here. The only source of variation in the impact of quantitative easing in most of these models is in the amounts purchased. However, the amounts purchased as a share of long-term bonds by the ECB during its public sector purchase programme were similar among the larger countries. Therefore, supply factors of the portfolio rebalancing channel alone cannot account for the observed differences in the impact on yields across euro zone countries.

This paper provides a theory of the impact of asset purchases by central banks on prices and liquidity, where the impact depends on the demand and supply of the bond purchased. In a search theoretic framework of over-the-counter debt with arbitrageurs and preferred habitat investors based on (Duffie, Garleanu and Pedersen, 2005), the impact of quantitative easing depends on the demand and supply of the bond purchased, or the tightness of the market. The tightness of the bond market, which is critical to our results, is equivalent to the tightness in labour market search models, although it is between sellers and buyers of bonds, instead sellers and buyers of labour. Similarly, the price of the bond

is equivalent to the wage in those models. The more preferred habitat investors there are, the "tighter" is the bond market, and the larger is the price movement following purchases by the central bank. Heterogeneity in the share of preferred habitat investors between countries is able to explain differences in the impact of QE.

The model also predicts a trade-off between price and liquidity. The impact on liquidity depends also on the tightness of the bond market. QE improves liquidity initially, as the central bank adds another large buyer to the market. However, as the central bank reduces the stock of bonds on the secondary market available for sale by holding the bonds to maturity, it subsequently reduces liquidity. After the end of the purchase programme, liquidity is expected to be worse than before the start of the purchases as long as the central bank holds the bonds because the stock of bonds traded on the secondary market is lower.

Our results depend on whether the entry of buyers is endogenous in the model. When the buyers enter endogenously, they compare their outside option to the value of becoming a buyer, to decide whether to enter the market. Central bank asset purchases reduce the value of being a buyer by increasing the price of the asset the buyers have to pay. As a result, the buyers reduce their entry to the market. QE *crowds out buyers*. With this mechanism in place, the price impact of purchases falls the more buyers are crowded out, as the positive impact from demand is smaller. Also, the reduction in liquidity is larger, because there are fewer buyers to match with sellers, especially when the central bank stops the purchases.

The effects of QE in this model are permanent, as long as the central bank keeps holding the bonds it purchases. As long as the central bank holds the bonds, the number of bonds traded on the market is lower and the yields are lower. We abstract from the effect of QE on the component of the yield curve related to monetary policy expectations. Once QE begins to increase inflation, yields rise as investors expect policy rate increase in the future from the central bank.[1] The term premium component however that is modelled here can stay low even if interest rates rise.

We calibrate the model for larger Eurozone countries and match its predictions with the announcement effects of ECBs sovereign asset purchase programme on sovereign bond yields. The key to the results is the share of preferred habitat investor holdings (pension

[1]Soderstrom and Ellingsen (2004) show for conventional monetary policy that unexpected endogeneous policy rate changes move the short and long end of the yield curve in the same direction whereas unexpected exogenous monetary policy shifts short and long rates in the opposite direction.

funds, life-insurance companies, and foreign exchange reserves) of the bonds. We measure their prevalence from the ECB's securities holding statistics, and calibrate the model to those shares. To our knowledge, there are no comparable measures for preferred habitat investors at this level of detail. In the model, demand for bonds by preferred habitat investors is less price elastic than the demand by arbitrageurs and that explains the differential impact. At the first announcement of the ECB's public sector purchase programme, bond yields fell relatively more in countries with a high share of preferred habitat investors than in countries with a low share of preferred habitat investors. Simulation of our model matches these results.

Our analysis can be extended to different types of bonds. For example, if the market for index-linked bonds is less liquid on the buyers side than the market for nominal bonds.[2], liquidity can be expected to improve more when central bank purchases increase demand for those bonds. The model also tells us that the liquidity can be worse for those bonds when the central bank purchases end, as long as the central banks keeps holding the bonds.

In our model, liquidity relates both to the traditional definition of liquidity and to scarcity of assets. Traditionally, liquidity has been about ease of finding a buyer, which central bank asset purchases initially improve. However, liquidity can also be defined as the ease of finding sellers, or the premium an investor has to pay to obtain an asset. In this model, this type of scarcity of assets is expressed as an inverse of traditional liquidity. Especially well-rated countries are affected by scarcity from QE, as the tightness on those markets tends to be on the sellers side. The demand from preferred habitat investors is positively correlated with both the rating and size of sovereign bond markets.

There have been various indications of the impact of asset purchase programmes on liquidity and scarcity. It is less straightforward to measure the impact on liquidity than on prices. In surveys, however, investors have raised the issue of reduced liquidity since the start of the quantitative easing programmes. In a Riksbank market survey, investors have reported worsening liquidity, with one of the cited reasons the Riksbanks government bond purchases.[3] In a quarterly survey of the Eurosystem among large banks and dealers of financial conditions in the bond and derivatives markets concerning credit terms and conditions in the euro area.[4] ,investors also have reported decreased liquidity since the

[2]See an analysis of the Treasury inflation-protected securities market Michael Fleming and Neel Krishnan (2012)

[3]See Riksbank's Risk Surveys since 2015 published on Riksbank's website `www.riksbank.se`

[4]Survey on credit terms and conditions in euro-dominated securities financing and OTC derivatives markets (SESFOD). The June 2016 survey can be found at: `https://www.ecb.europa.eu/press/pr/date/2016/html/pr160711.en.html`

start of ECB's quantitative easing programme. (Coroneo, 2015) posits two effects from the Federal Reserve's purchases of Treasury Inflation Protected Securities (TIPS), one is improved liquidity from increased demand by the Fed, and the other is increased scarcity due to hold-to-maturity investment by the central bank. By obtaining a model free measure of the TIPS liquidity premium, she shows that the scarcity effect of the purchases dominated the liquidity channel. Christensen and Gillan (2013) find in contrast that liquidity improved. Depending on the timing, both can be in line with our model, which predicts that purchases initially improve liquidity, and subsequently reduce it. Kandrac (2013) studies the mortgage-bakced securities (MBS) market during the period when the Federal Reserve purchased MBSs. He finds that purchases negatively affected volumes, trade-sizes, and implied financing rates in dollar roll transactions, but not bid-ask spreads.[5]

Scarcity can spill over to other markets that rely on government bond yields. An example is the market for forward contracts and repurchase agreements (repos) that are larger in size than the underlying government bond markets.[6] D'Amico et al. (2013) analyse the repo market in the US and show that there is a considerable and highly persistent scarcity premium on the government bonds, especially at short maturities and it can be partly due to the Fed's QE programme. Indeed, the Federal Reserve introduced the Term Securities Lending Facility to lend bonds it purchased back on the repo market to ensure the functioning of the market. Bank of England observed that the government bond market became "dislodged" during its QE programme, and began to lend back a proportion of the gilts it had bought (Paul Fisher (2010)). Recently the International Capital Markets Association (2016) released a study warning of reduced liquidity in the European repo market due to regulation and QE. Corradin and Maddaloni (2015) show that during the ECB securities purchases programme (SMP), the government bonds that were purchased became *special*, meaning that their price contained a scarcity premium. During the first public sector asset purchase programme, initially the same effect was at play, but once the ECB began to sell the bonds it purchased back on the repo market, the specialness premium on the bonds diminished (European Securities and Market Authority (2016)).

Bacchetta, Benhima and Kalantzis (2016); Caballero, Farhi and Gourinchas (2016); Caballero and Farhi (2014) study the scarcity of safe asset at the zero lower bound. In Bacchetta, Benhima and Kalantzis (2016) at ZLB with negative shadow rates agents hold

[5]Dollar roll transactions of MBSs are similar to repo transactions. For more details, see the paper by Kandrac (2013).

[6]This difference in size can be attributed to rehypothetication where one underlying bond is used on many repo transactions.

too much money in relation to real bonds. QE in that model deepens the liquidity trap by taking away a part of public supply of bonds, and by decreasing the shadow real interest rate. In Caballero, Farhi and Gourinchas (2016); Caballero and Farhi (2014) the effect depends on the type of assets the central bank buys. If it swaps risky assets to safe assets (QE1 in the US, LTRO in the euro area), the scarcity situation improves. If it swaps long-term government debt for short-term government debt, the situation worsens and liquidity trap persists. The safe asset scarcity emerges from a crisis where the supply of safe assets falls, and demand for safe assets increases. Interest rates that are at zero lower bound cannot clear the market and the economy enters into a liquidity trap that can only be cleared by an increase in the supply of safe assets.

The model by De Pooter, Martin and Pruitt (2015) is closest to ours. To our knowledge, it is the only other paper that uses a search model to study the impact of QE on bond prices. They study the liquidity effects of Securities Markets Programme, during which the ECB purchased Greek, Italian, Irish, Portuguese, and Spanish sovereign bonds in a standard search theoretic framework. They find that the purchases led to decreases in bond liquidity premia. The reason why there is no liquidity trade-off in their model is that the bonds the central bank purchases are not held to maturity, and therefore the stock of bonds falls only temporarily until the central bank "switches type" to an impatient investor in Duffie et al. (2005) terms, or faces a liquidity shock in terms of our model. For this reason, the stock reduction effects of central bank purchases on yields are also temporary. By extension there are also no preferred habitat investors in the model, which means that the impact of QE depends only on the amounts purchased.

In the next section we describe the preferred habitat investor index we have constructed and discuss the results of the QE announcement event study. In section 3 we describe the model results, and in section 4 we calibrate the model for the Eurozone.

2 Empirical results

2.1 Constructing a preferred habitat investor index

We construct an index of preferred habitat investors on the basis of the ESCB securities holdings statistics (SHS).[7] This relatively new database contains quarterly data on the holdings of securities, among which government debt securities, at a security-by-security level. Compared to the more standard aggregate data, it allows for an overview of the

[7]For more information on the SHS database, see (Rousov and Caloca, 2015; European Central Bank, 2015; Boermans and Vermeulen, 2016)

holders and issuers of securities by economic sectors at a very granular level of detail (excluding Eurosystem holdings), including their interdependencies. Previously, this kind of detailed data was in the Euro area only available for deposits and loans, or more recently only at the macro level in the who-to-whom tables in National Accounts statistics. As with any data set, there are some caveats related to the collection of the data, which are elaborated in more detail in appendix C

Our index of preferred habitat investors is a composite indicator, consisting of the holdings of economic sectors that are likely to be preferred habitat investors, as a share of the total government debt securities issued by euro area countries (excluding Eurosystem holdings). In particular, we consider central banks and general government outside the Euro area, insurance companies, and pension funds (both in and outside the Euro area) to be more likely to preferred habitat investors than other investors in Euro area sovereign bonds.[8]

Our euro area index of preferred habitat investors is new. To our knowledge, there exists no comparable cross-country comparable data on the holders of government debt nor a measure for preferred habitat investors at this level of detail. Blattner and Joyce (2016) is one of the few papers to consider the impact of foreign official holdings of euro area debt on the term structure, by constructing a estimate of the free floating debt (i.e. excluding foreign official holdings) on the basis of IMF data of official holdings. However, using an methodology suggested by Arslanalp and Poghosyan (2014) their measurement on a proxy measure on the basis of publicly available information on foreign official holdings of debt and it does not consider holdings by pension funds, and insurance companies. Andritzky (2012) develops a measure of institutional investors from public sources for the G20 countries, which includes a breakdown to domestic banks, pension funds and insurance companies, and domestic central bank, but excludes foreign central bank holdings.

There are a few other papers that use the security holdings database, but with a different approach to ours. Boermans, Frost and Steins Bisschop (2016) use the security holdings data base at a security-by-security level to study the effect of market liquidity and ownership on bond price volatility, but focus on concentration of ownership rather than investor characteristics. Koijen, Koulischer, Nguyen and Yogo (2016) do focus on investor characteristics and use security level holdings data to construct a measure of risks exposures across major investor sectors and countries. Studying portfolio flows and the

[8]For examples of papers that model preferred habitat investors in a macro model, see Andrés, López-Salido and Nelson (2004); De Graeve and Iversen (2016)

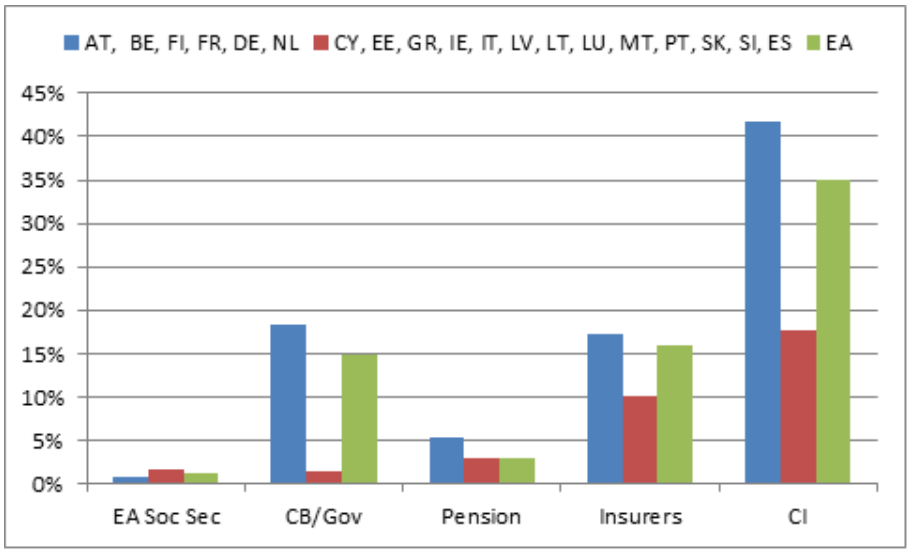

Figure 1: Preferred habitat investors index per sector, 2014 average, for (unweighted) country groupings and the (weighted) euro area average.

dynamics of risk exposures during the PSPP programme from 2015Q2 to 2015Q4, they find that foreign investors, banks and mutual funds rebalance their portfolios, whereas euro area insurers and pension funds purchase the same bonds as the ECB.

In figure 1 the index is presented by (unweighted) country groupings, separating between the larger and higher rated countries and the other Eurozone countries, and the (weighted) Eurozone average, while showing the three components of the index. It is clear that the high difference in the index between the two sets of countries is particularly large on account of the holdings of central banks and general governments outside the Euro area, whereas the distribution is less dispersed for insurance companies and pension funds. However, at the individual country level, there is more dispersion that is partly evened out in the country groupings. For more information on the SHS data and the preferred habitat index, see appendix C.

2.2 Empirical results

Many other studies before us examine the positive impact of quantitative easing on reducing bond yields in the US and the UK. The studies confirm that the purchases do indeed tend to lead to a decline in the yields of the bonds purchased, see Altavilla, Carboni and Motto (2015); Andrade, Breckenfelder, De Fiore, Karadi and Tristani (2016); Gagnon, Raskin, Remache and Sack (2011); Krishnamurthy and Vissing-Jorgensen (2011); McLaren, Banerjee and Latto (2014); De Santis (2016); Wright (2012). However, there are not many that explain what the size of the impact depends on.

To test our model, we compute the shares of bonds purchased in each country by the Eurozone central banks. There is some heterogeneity because the purchases are divided according to the capital key while debt levels vary in each country. The initial purchases, on which our study concentrates on, amounted to 912 billion euros over 19 months (March 2015 until September 2016) with approximately 48 billion government bonds bought each month. The 912 billion euros of purchases is divided among the Eurozone countries according to the capital key.

Table 1 shows the results of our calculations of shares of outstanding long-term debt securities purchased in each Eurozone country. Some small Eurozone countries in particular stand out here. Those countries have very small debt markets, especially Estonia that hardly has any outstanding long-term debt. Similarly the government of Luxembourg only issues bonds occasionally and the market for those bonds is small and fairly illiquid. As a result, the central banks of Estonia and Luxembourg are mainly buying bonds of international institutions in Europe.

For the calibration of our model, we focus on the larger Eurozone countries, on account of the larger impact of ECB purchases on their markets and the availability of other data. Also, we omit countries in an EU/IMF adjustment programme. Figure 2 shows the preferred habitat index for the 10 countries under consideration, which we divide in two groups. Group I consists of Eurozone countries with higher sovereign credit rating (Austria, Belgium, Germany, Finland, France, and Netherlands) and group II consists of four lower rated countries (Ireland, Italy, Portugal, and Spain). The group I countries are within a red box.

There is not a very large difference in the shares of long-term bonds purchased across the high- and low-rating countries, and therefore the difference in impact in yields in those countries cannot be explained by the reduction in the supply of bonds alone.

Table 1: Purchases as a percentage of outstanding long-term debt securities

Country	Capital Key	Debt to GDP	% Purchases LT debt securities	% Purchases Debt	**% Purchases Debt_limit**
SK	1.10	54	26.86	24.84	**24.84**
LV	0.40	40	61.76	37.94	**20.27**
LU	0.29	24	43.47	23.64	**17.95**
MT	0.09	68	16.57	15.50	**15.50**
SI	0.49	81	17.59	14.86	**14.86**
FI	1.78	59	16.81	13.45	**13.45**
NL	5.69	69	15.19	11.50	**11.50**
ES	12.56	98	14.15	11.08	**11.08**
DE	25.57	75	15.07	10.75	**10.75**
CY	0.21	108	31.52	10.42	**10.42**
PO	2.48	130	19.71	10.03	**10.03**
AT	2.79	85	11.09	9.15	**9.15**
FR	20.14	95	11.84	9.02	**9.02**
BE	3.52	107	9.73	7.49	**7.49**
IT	17.49	132	9.17	7.47	**7.47**
IE	1.65	110	12.21	7.40	**7.40**
GR	2.89	177	38.47	8.31	**7.13**
EE	0.27	11	1471.52	120.53	**2.70**

In the fourth column are computed the shares of purchases as a percentage of long-term securities. The purchases themselves are the capital key times the total size of the asset purchases programme. In the fifth column the purchases are taken as a share of total government debt. In the last column are the same figures as in fifth column, except that they are adjusted to the amount the central banks are able to buy. The central banks are able to purchase only 33% of each country's bonds without becoming a senior debt holder. For example in case of Latvia, the purchases would amount to over 60% of outstanding long-term securities. The maximum central banks can purchase is 33% of the securities, which is 20.27% of total debt.

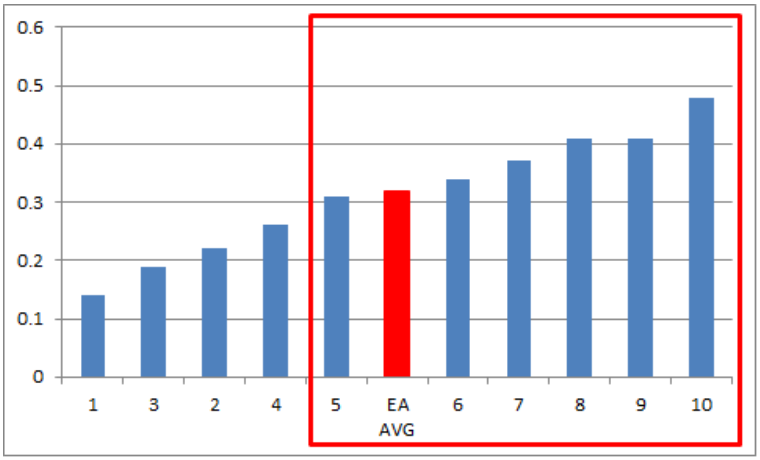

Figure 2: Preferred habitat investor index per Eurozone country, 2014. Countries used in calibration.

We can now compute the announcement effect of quantitative easing on 10-year benchmark yields in various Eurozone countries. The first public sector purchase programme was announced in a press conference on 22 January 2015. The announcement was well anticipated but the expectations should have been the same for all of the concerned countries and should not affect the results.[9] We control for the change in the local stock market index to ensure that the impact is not tainted by concomitant local events. The Greek debt negotiations were happening at the same time and for this reason we control also for the Greek stock index.

We estimate the equation 1 where the yield is the 10-year benchmark yield for each country, QE is a dummy that is zero on non-announcement days, and one on the announcement day, 22 January 2015. Note that the yields are computed from end of day prices so that the difference on the announcement day is the difference in yield at the end of 22 January 2015 and end of the day 21 January 2015. Stocks variable is the local stock market index and GRstocks is the Greek stock market index. All variables are added contemporaneously.

$$D.log(yield)_t = QE_t + D.log(bidask_t) + D.log(stocks_t) + D.log(GRstocks_t) + \epsilon_t \quad (1)$$

The results are in table 2. We have not included the new Eurozone entrant countries as the share of the bonds purchased are quite large in these countries, as shown in table 1. Looking at the log basis point (percentage) changes in the yields, the ordering of the impact is identical to ordering the countries by their credit ratings. The higher the share of preferred habitat investors (correlated with the credit rating), the larger is the impact of quantitative easing, as predicted by our search theoretical model. In appendix A we show that the results are similar for other QE announcements by the ECB.

The results can be compared to typical (mean) changes in ten year yields in the sample period running from early 1995 to 2015. The impact of QE on ten year yields on the announcement day is about 2-3 times the typical movement in yields.

In macro models, it is the level of the interest rate that matters for consumption, saving, and investment decisions. Therefore, since the decline in basis points was larger in lower rated countries, the impact of QE can be thought to be larger in those countries. However,

[9]For an assessment of expectations of QE, see Altavilla, Carboni and Motto (2015); De Santis (2016)

Table 2: Impact of asset purchases in the Eurozone

Country	Basis points	Log(basis points)	Rating	Abs mean change
Germany	-9.3	-15.5***	AAA	3.2
Netherlands	-9.9	-15.3***	AA+	3.1
Finland	-7.7	-14.8***	AA+	3.7
Austria	-9.3	-14.3***	AA+	3.3
France	-7.6	-11.0***	AA	3.5
Belgium	-7.0	-9.5***	AA	4
Ireland	-9.4	-9.0***	A-	4.1
Spain	-10.7	-8.2***	BBB	3.9
Italy	-8.3	-7.1***	BBB	4
Portugal	-17.6*	-6.3**	BB	7.5

Change in 10-year benchmark yields of Eurozone sovereign bonds following announcement of QE on 22 Jan 2015, controlling for bid-ask spreads, local stock index, and Greek stock index. Ratings are S&P's long-term sovereign ratings. Absolute mean change is the average daily change in basis points. The sample is from 3 January 1995 to 29 March 2015.

the differences between most countries are small, even though there were considerable differences in the yield levels across euro zone countries before the QE announcement. In addition, the change in yields in basis points is not significant for any of the countries except Portugal. The reason for this is that the yields have decreased by a great deal over the sample and at the same time their volatility has declined. This means that the impact on yields from macro news is smaller and it is harder to find significant results.

Note that Altavilla, Carboni and Motto (2015) assume that the impact of macro news on bond yields is larger, the lower the credit rating. The same assumption holds here, bonds with lower rating have ceteris paribus a higher yield, and due to the higher level, have also higher volatility.

In order to assess the announcement impact on yields across euro zone countries, we prefer to smooth the volatility, which is typically done by using logs of the variables. As an example, a 0.5 percentage point movement might not be very large when yields are at 10%, while it is large when yields are at 1%. Cox, Ingersoll and Ross (1985) model short rates with the zero lower bound explicitly, showing that the volatility of the short rate depends on its level.

3 Search theoretic model of over-the-counter debt

The model is based on a search theoretic model of over-the-counter debt by Duffie, Garleanu and Pedersen (2005) that first showed how liquidity in an over-the-count market

could be modelled through search frictions. We adapt the model to study quantitative easing by adding debt that matures stochastically, a central bank as an additional buyer and passive investors that hold debt to maturity (preferred habitat investors).

Investor flows are shown in figure 3. Investors in the model are sellers, patient debtholders, passive investors, buyers, and central bankers with measures $\alpha_s, \alpha_{po}, \alpha_{pa}, \alpha_b, \alpha_{cb}$ respectively. They meet each other randomly and trade if there are benefits to trade for both. Each buyer or seller holds one bond in the model. Investor flows are shown in figure 3.

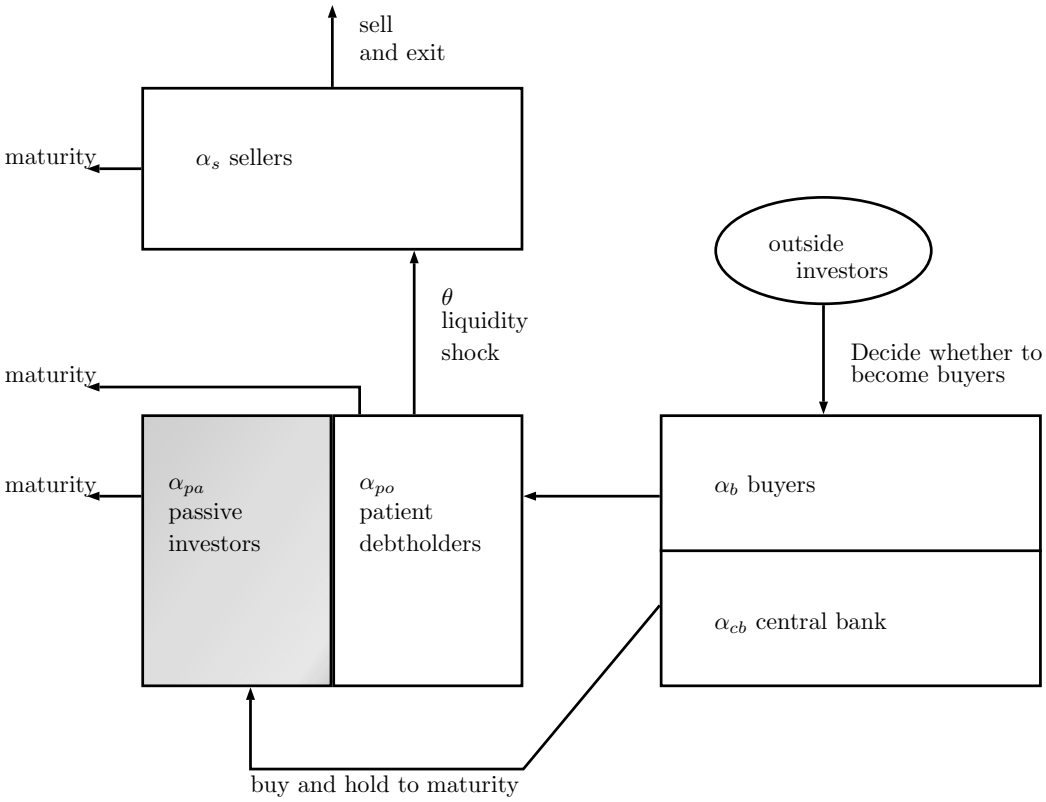

Figure 3: Flows of investors

The first type of bondholder are sellers who are impatient and want to liquidate their bond. They search for buyers on the market in order to sell their bond. The probability that they meet a buyer depends on how many buyers are on the market, it is easier to find a buyer, the more of them are around. Once a seller finds a buyer, it receives a price P for the bond and exits the market.

The buyers, whose measure is α_b become patient debtholders after buying the bond. Because they are patient, those debtholders do not sell their bonds. They can however, receive a liquidity shock with probability θ, and become sellers, at which point they try to

find a buyer to liquidate their bond. The liquidity shock in this case is a funding liquidity shock, as opposed to a market liquidity shock. Brunnermeier and Pedersen (2009) show in a model of stock markets that the two can depend on each other and be mutually destabilising. When markets are thin, then prices are more volatile and that deters investors from entering the market, making markets even more thinner. The volatility increases the risk of financing a trade, leading to higher margins required to take on the position. That in turn makes funding liquidity worse, which feeds back to lower number of trades and worse market liquidity.

There is a stock of passive investors on the market, who hold bonds to maturity, without a possibility of selling the bonds. Therefore, they do not participate in the search market and effectively withdraw a fraction of bonds from the market. One can think of them as the quantity of bonds held by preferred habitat investors (e.g. pension funds, foreign exchange reserves, and life-insurance companies) that is less elastic to price changes.

A central bank adds to that stock of preferred habitat investors by holding the bonds it purchases to maturity. Therefore, central bank purchases reduce the number of bonds on the market, with implications on yields and liquidity. One effect of the central bank undertaking QE is to withdraw bonds off the market, another is to increase the number of buyers. Sellers benefit from the addition of buyers on the market, because it makes it easier to for them to find one. On the other hand, it becomes harder for other buyers to find a seller because the measure of sellers has remained constant while the measure of buyers has increased.

Governments are passive in the model, having supplied a stock D of bonds to the secondary market. Those bonds mature stochastically at rate δ. That means that the bonds held by sellers may mature before they find a buyer, while the bonds of patient debtholders might mature before they receive a liquidity shock. When a bond matures, the government will have to pay 1 to the investor holding the maturing bond. With a default probability q, the government does not honour its repayments and investors receive only a recovery value $\gamma < 1$ for the bond.

Matching on the market depends on the relative measures of investors. The probability that any of the agents meets another, depends on the measures of those investors on the market. The more sellers there are, the easier it is for the buyers to find them and the more buyers there are, the easier it is for the sellers to find them. This feature makes the model a supply and demand model. The supply of bonds is the measure of sellers on the secondary market, while the demand is the measure of buyers on the secondary market.

An increase in demand, or buyers, makes it easier for the sellers to find a counterparty to their trade, while an increase in supply, or measure of sellers on the market make it easier for buyers to find a bond to purchase.

The ratio of buyers to sellers, or demand to supply, $\frac{\alpha_b+\alpha_{cb}}{\alpha_s}$ is a measure of tightness on the market. If the ratio is far from 1, then there are many on the buying side relative to the selling side (or vice versa) and the markets are tight. The party with most agents on the market has a harder time finding a counterparty.

3.1 Solution of the model with exogenous entry of buyers

We now set up the expected utilities, and the bargaining process required to solve the model and to reach the first results. We show that the price in the market is affected by QE in two ways. Firstly, the central bankers add a buyer to the market, increasing demand. Secondly, the central bank withdraws bonds of the market, reducing supply of bonds on the secondary market.

The expected utility of a seller depends on the price. The higher the price he receives for the bond he sells, the higher his utility. The value function of the seller is in equation 2. Sellers are the only impatient agents in the model, and have a discount factor ρ. The other agents in the model have a discount factor of zero.

The first two terms of the sellers' value function inside the brackets describe the situation where the bond matures. With probability δ the debt matures before the seller finds a buyer. When that happens, if the government does not default with probability $(1-q)$, seller recovers 1, while if the government defaults with probability q, he receives only the recovery value γ.

The probability of meeting a counterparty depends on the mass of those counterparties on the market. With probabilities $\lambda\alpha_b$ and $\lambda\alpha_{cb}$, the seller meets a buyer, and a central bank respectively, and gets a price P for the bond when the transaction succeeds. Note that λ is the Poisson probability of meeting a counterparty, so that $1/\lambda$ reflects the time it takes to find one.

$$J_s = \frac{1}{(1+\rho)}\left[\delta(1-q) + \delta\gamma q + (\lambda\alpha_b + \lambda\alpha_{cb})P + (1-\delta-\lambda\alpha_b-\lambda\alpha_{cb})J_s\right] \tag{2}$$

Buyers' value function in equation 3 depends negatively on price. The higher price a buyer has to pay, the lower the value of being a buyer. The probability of meeting a seller

$\lambda\alpha_s$ also has an impact. The easier it is to meet a seller, the better. When a buyer buys a bond, she becomes a patient debtholder, getting a value J_{po} and paying a price P for the bond. Buyers also have a small search cost, e that they have to pay in each period they are actively searching.

$$J_b = -e + \lambda\alpha_s(J_{po} - P) + (1 - \lambda\alpha_s)J_b \tag{3}$$

Patient debtholders' debt matures with the same probability δ as sellers. Similarly, the repayments in case of default and non-default are also the same. The debtholder can be hit by a liquidity shock that arrives with probability θ, after which they become sellers.

$$J_{po} = \delta(1 - q) + \delta\gamma q + \theta J_s + (1 - \delta - \theta)J_{po} \tag{4}$$

Similarly, passive-, or preferred habitat investors' bonds mature with probability δ. In case of default or non-default, their repayments are as those of sellers and patient debtholders. The passive investors value function is described in more detail in appendix B.1.

3.2 Bargaining over asset price

When a seller and a buyer meet, they bargain over the price of the bond. The bargaining problem is complicated by having several types of buyers, the buyers, and the central bankers. In appendix B.1 we describe how the bargaining problem reduces to two players once we assume that the value function of a patient debtholder is equal to the value function of a passive investors. Once we assume that $J_{po} = J_{pa}$ holds, it follows that also $J_b = J_{cb}$ holds.

Bargaining is through Nash bargaining such that:

$$P = \beta J_s + (1 - \beta)(J_{po} - J_b) \tag{5}$$

where β is the bargaining power of the buyers and $(1 - \beta)$ is the bargaining power of the sellers. This is equivalent to the seller and central bank bargaining for $J_{po} = J_{pa}$.

With the pricing equation, we can solve for all value functions and prices:

$$J_b = -\frac{e}{\lambda\alpha_s} + \frac{(\delta(1-q)+\delta\gamma q)\rho - \theta k(\rho+\delta) - \delta k(\rho+\delta+\lambda\alpha_b+\lambda\alpha_{cb})}{(\delta+\theta)(\rho+\delta)} \tag{6a}$$

$$J_s = \frac{(\delta(1-q)+\delta\gamma q) + k(\lambda\alpha_b+\lambda\alpha_{cb})}{\rho+\delta} \tag{6b}$$

$$J_{po} = \frac{(\delta(1-q)+\delta\gamma q)(\rho+\delta+\theta) + \theta k(\lambda\alpha_b+\lambda\alpha_{cb})}{(\delta+\theta)(\rho+\delta)} \tag{6c}$$

$$P = \underbrace{\frac{(\delta(1-q)+\delta\gamma q)}{\rho+\delta}}_{\text{fundamental value}} + \underbrace{\frac{(1-\beta)}{\beta}\frac{e(\lambda\alpha_b+\lambda\alpha_{cb}+\rho+\delta)}{\lambda\alpha_s(\rho+\delta)}}_{\text{liquidity premium}} \tag{6d}$$

where $k = \frac{(1-\beta)}{(\beta)}\frac{e}{\lambda\alpha_s}$

Price consists of two parts, its *fundamental value*, and a *liquidity premium*. The fundamental value is a function of bond characteristics: maturity, default probability, recovery rate, and a discount factor. These are factors that enter a standard bond pricing equation.

The key feature of the model is the liquidity premium that is modelled here to be fully dependent on the supply and demand for the asset. Demand comes from the buyers on the market, $\alpha_b + \alpha_{cb}$, while supply is equal to the measure of sellers on the secondary market, α_s. The ratio of these two investor groups, $\frac{\alpha_b+\alpha_{cb}}{\alpha_s}$ measures the tightness of the secondary market for government bonds.

Traditionally liquidity is about having enough buyers on the market so that a seller can sell his bond without affecting the price. If a seller is in distress due to a funding liquidity problem, then it is essential that he can sell the bond without his trade moving the price against him. Therefore, traditionally illiquidity is about the mass of buyers being low relative to the mass of sellers, i.e. $\frac{\alpha_b+\alpha_{cb}}{\alpha_s}$ is low on account of the numerator. QE clearly helps in this case by increasing the numerator through increasing α_{cb}.

Since the start of the QE programmes, investors have complained about Basel III regulations and QE worsening liquidity, which in this case means that there is a lack of sellers on the market and they have to pay a scarcity premium for the bonds. This scarcity premium is the inverse of the liquidity premium. Bonds are scarce if there are not enough sellers relative to buyers. In the model, the scarcity would be reflected in a high ratio, $\frac{\alpha_b+\alpha_{cb}}{\alpha_s}$, but on account of a low number of sellers.

In this way, the same liquidity premium in this model can account for both situations, the traditional illiquidity situation where there is a lack of buyers, and the scarcity situation where there is a lack of sellers. Through this mechanism, the model is able to characterise the price of a bond through supply and demand (which with the assumption of each buyer or seller holding one bond equals the masses of sellers and buyers), and not only through bond and borrower characteristics.

We now explore the key results of the model below, and in order to do that, we first assume that α_s and α_b are exogenous.

Proposition 1. *Price depends on the supply and demand for an asset.*

As an example, lets assume that the mass of sellers relative to buyers is large. Then the liquidity premium component of the price in equation 6d shows that in this case, price is low. We can arrive at this result by looking at the terms in the Nash bargaining relationship in 5. Because there are many sellers, it is easy for a buyer to find one, α_s is high, implying that the buyers' value function is high, in 3. On the other hand, because there are few buyers, the value functions of the seller and patient debtholder are low. As a result, the buyer has an upper hand in this process. If the bargaining process fails, he can more easily find another seller than the seller can find another buyer. Therefore, price is low. When there is a large number of buyers relative to sellers, the situation is reversed and price is higher.

Proposition 2. *Central bank purchases increase price*

When a central bank purchases bonds, it increases the share of buyers relative to the share of sellers. The rate at which sellers meet central bankers, $\lambda\alpha_{cb}$ increases, increasing the value of a seller in 2. On the other hand, the value of being a buyer remains constant. These are the two terms entering the Nash bargaining problem that determines the price. From the liquidity premium component of the price in 6d we can see that price increases. It becomes easier for sellers to meet other buyers in case the bargaining process fails, and therefore the sellers can ask for a higher price. Through this channel, we have the first result that central bank purchases lead to an increase in bond prices and consequently, a decline in yields, by increasing demand for bonds.

The second result is that the price falls with a decline in supply of bonds, that is, with a decline in the measure of sellers, α_s. When the central bank buys the bonds, it holds them to maturity, thereby withdrawing those bonds off the secondary market. As the measure

of sellers, α_s falls, the probability that a buyer meets one, $\lambda\alpha_s$ also falls. This leads to a decline in the buyers' value function, while the sellers' value function remains constant. As a result, price increases, and in this case it is because bonds become scarcer, it becomes harder to find a seller of bonds.

We can also see this below in equation 7. The total amount of debt in the economy is the sum of bonds held by all the investors: $D = \alpha_s + \alpha_{po} + \alpha_{pa}$. We can replace the measure of sellers in the equation for price 6d to see that the increase in the passive investors (central bank holding bonds to liquidity) leads to a higher price.

$$P = \frac{(\delta(1-q) + \delta\gamma q)}{\rho + \delta} + \frac{(1-\beta)}{\beta} \frac{e}{\lambda(D - \alpha_{po} - \alpha_{pa})} \frac{(\rho + \delta + \lambda\alpha_b + \lambda\alpha_{cb})}{\rho + \delta} \tag{7}$$

This is the portfolio balance channel of quantitative easing. In term structure models such as (Hamilton and Wu, 2012), it is the purchases from preferred habitat investors that drive the price. These investors do not want to move away from their preferred maturity, and rating class of bonds and therefore require a premium to move. Here the mechanism is more directly related to bond supply and demand. Even without any preferred habitat investors, bond prices move simply due to changes in the relative mass of buyers and sellers. QE here works purely through the demand and supply mechanism, even in presence of only arbitrageurs on the market.

We now extend the analysis to the impact of asset purchases on liquidity of the bonds.

Proposition 3. *Liquidity improves initially as the central bank increases demand for bonds. It worsens subsequently when the central bank withdraws bonds off the secondary market.*

Liquidity is modelled as a measure of transactions, or meetings on the market, $(\lambda\alpha_s\alpha_b + \lambda\alpha_s\alpha_{cb})$. It is easy to see that when the central bank increases demand for bonds, increasing α_{cb}, it makes it easier for sellers to match with a buyer, increasing the number of transactions on the market. On the other hand, since the central bank as a preferred habitat investor effectively withdraws bonds off the market, it reduces the mass of possible sellers on the market, leading to a decline in liquidity.

3.3 Equilibrium with endogenous entry of buyers

Making the entry of buyers endogenous adds another dimension to QE. As was shown in the previous section, when a central bank purchases bonds, it reduces the number of sellers on the market, and increases the number of buyers. Both of these actions lead to the price

being higher in equilibrium. As a result, the value function of a buyer is lower with QE. We now add outside investors to the model, who compare the value function of their outside option to the value function of a buyer to decide whether to enter the market as a buyer. When the value function of a buyer declines, fewer outside investors find it profitable to enter the market. Quantitative easing therefore *crowds out other buyers*. This is more important for markets that already have a relative scarcity of buyers, and less important for markets where the supply of bonds is relatively scarce and demand is less sensitive to price on account of changes in the liquidity premium.

We now endogenise the entry of buyers in the model. The entry flows of outside investors are denoted by g. Those outside investors compare the value of their outside option K, to the value of becoming a buyer, J_b. If the value of the outside option J_K is lower than the value of a buyer, the investor decides to enter the market and becomes a buyer. The outside investors are heterogeneous in their outside option K_i. For simplicity, we assume that the value of the outside option J_{Ki} of each outside investor equals K_i. The marginal investor, the one that is indifferent to entering is denoted by K_m. Every outside investor with a value of the outside option less than or equal to K_m will enter, and every outside investor with a value of the outside option greater than K_m do not enter. Therefore we get that:

$$g = \int_{\underline{K}}^{K_m} f(K)dK = F(K_m) \tag{8}$$

At equilibrium, $J_K = K_m = J_b$. We can write the above therefore as $g = F(J_b)$. This is the equilibrium condition. We call g the entry flows and $F(J_b)$ the buyer value.

Equilibrium solution involves solving both the function g and J_b for α_s and looking for the α_s that solves the system. In order to do that, we need to specify the investor flows. In steady state the inflows of outside investors to the economy g, must equal the outflows, the matches of sellers with buyers and the central bank, i.e. $g = \lambda\alpha_s\alpha_b + \lambda\alpha_s\alpha_{cb}$.

The flows of patient debtholders, α_{po} can be written out explicitly. Buyers, when they are matched with a seller, become patient debtholders. Their inflows are therefore marked by $\lambda\alpha_s\alpha_b$. With probability θ, the patient debtholders receive a liquidity shock, and with probability δ, their debt matures:

$$\dot{\alpha}_{po} = \lambda\alpha_s\alpha_b - \theta\alpha_{po} - \delta\alpha_{po} \tag{9}$$

In equilibrium $\dot{\alpha}_{po} = 0$, allowing us to get that $\lambda\alpha_s\alpha_b = (\theta + \delta)\alpha_{po}$. We can substitute this into the equation for inflows of outside investors g above and get that $g = (\theta+\delta)\alpha_{po} + \lambda\alpha_s\alpha_{cb}$.

The flows of passive investors are similar to the flows of patient debtholders. Inflows consist of central bankers that have met a seller and become now a hold-to-maturity investor. The only way these investors leave their position is through their bond maturing, which happens with probability δ:

$$\dot{\alpha}_{pa} = \lambda\alpha_s\alpha_{cb} - \delta\alpha_{pa} \tag{10}$$

Setting the passive investor flows to zero, the equation can again be substituted to the equation for g, together with the condition that the total amount of debt in the economy consists of bonds held by the sellers, patient debtholders and preferred habitat investors, $D = \alpha_s + \alpha_{po} + \alpha_{pa}$. Finally, we get:

$$g = (\theta + \delta)(D - \alpha_s) - \theta\alpha_{pa} \tag{11}$$

From the same flow equations above, we get α_b as a function of α_s and parameters only:

$$\alpha_b = \frac{(\theta + \delta)(D - \alpha_s - \alpha_{pa})}{\lambda\alpha_s} \tag{12}$$

Substituting α_b into the equation for J_b in 6a, we get J_b as a function of α_s and parameters only:

$$J_b = \frac{\rho(\delta - (1-\gamma)\delta q)}{(\delta+\theta)(\rho+\delta)} - \frac{(1-\beta)}{\beta}\frac{e}{\lambda\alpha_s}\left[2 + \frac{\delta\lambda\alpha_{cb}}{(\delta+\theta)(\rho+\delta)} + \frac{\delta\lambda(D - \alpha_s - \alpha_{pa})}{\lambda\alpha_s(\rho+\delta)}\right] \tag{13}$$

We can now search for the α_s that solves for the intersection of the entry flows in equation 11 and buyers value function $F(J_b)$ where J_b is described in equation 13. The intersection of $F(J_b)$ and g gives us the equilibrium α_s and with those we can derive all the other variables of the model.

Rest of the results follow from the solution to these two key equations. The buyers' value function is upward sloping in α_s. This is consistent with the results of the previous

section. The more sellers there are, the lower the price. When price is lower, value function of the buyer is higher because a buyer can pay a lower price for a bond.

The entry flow condition, g in 11 is downward sloping for α_s. The result comes purely from solving the investor flows in equilibrium. With more sellers for a given amount of debt, it means that more of them are exiting. At the same time, if the mass of sellers is larger, the mass of patient debtholders is smaller, meaning that fewer are entering the market also. In equilibrium, the mass of investors entering and exiting is equal.

Since the buyer value function is upward sloping for α_s, and the entry condition of buyers is downward sloping, we can solve the equilibrium in the model by searching for the α_s where the two curves intersect.

3.4 Results with endogenous entry of buyers

Asset purchases increase the price of the bond by increasing demand

We start by analysing the impact of central bank bond purchases on the price of bonds.

Result 1. *Central bank purchases increases price, but the effect is partially muted by changes in the measure of sellers and buyers.*

As was shown in the case with exogenous α_s and α_b, the demand from central bank, i.e. an increase in α_{cb} leads to an increase in price. However, now also the measure of both sellers and buyers adjust.

The increase in central bank demand affects only the buyer value function $F(J_b)$. The derivative of J_b with respect to the purchases is:

$$\frac{\partial J_b}{\partial \alpha_{cb}} = -\frac{1-\beta}{\beta}\frac{e}{\lambda \alpha_s}\frac{\delta}{(\delta+\theta)(\rho+\delta)} \tag{14}$$

As a result, the buyer value function $F(J_b)$ shifts down as α_{cb} increases, since price increase through the central bank purchases lower the value function of other buyers. When $F(J_b)$ shifts down, the intersection shifts to the right, meaning that equilibrium values of both g and $F(J_b)$ are lower, and that the equilibrium mass of sellers is higher. By equation 12, α_b then decreases. These two effects put a counteracting downward pressure on price (equation 6d. Therefore, price rises by less when the entry of buyers is endogenous.

Result 2. *Central bank asset purchases crowd out other buyers.*

Central bank purchases lower both g, and α_b as was shown above. This is the crowding out effect. With endogenous entry of buyers, the outside investors can now decide whether to enter the market, depending on the central bank purchases' effect on their entry condition. Central bank purchases lead to a higher price, which reduces the value of becoming a buyer. Since the value of the outside option does not change, there are more investors for whom the value of their outside option is higher than the value of becoming a buyer. Fewer investors therefore enter the market. Central bank purchases crowd out those investors.

If the share of preferred habitat investors is higher, who have a less price-elastic demand for bonds, entry of buyers will be crowded out to a smaller extent.

Falling supply of bonds increases the bond price

Result 3. *Central bank purchases add to the stock of preferred habitat investors, which leads to an increase in price.*

We now turn to supply factors. As the central bank purchases bonds with the intention to hold them to maturity, it adds to the stock of preferred habitat investors, and α_{pa} increases. After a seller sells the bond to the central bank, it exits the market, without replacement. When the central bank purchases shrink the stock of sellers in this way, it makes it harder for buyers to find a counterparty. Compare this to the case where other buyers purchase bonds and become patient debtholders, after which with probability θ they receive a liquidity shock feeding them back to the stock of sellers.

Given that it becomes harder to find a seller, buyers are discouraged from entering the market, which reduces entry flow of outside investors, g . In equation 11, g shifts down by $\theta\Delta\alpha_{pa}$ as the share of preferred habitat investors increases. The shift in the entry flow of buyers leads to a lower g and J_b That means that as the measure of preferred habitat investors increases, g and J_b both decline, and the measure of sellers decreases. This is intuitive, the more preferred habitat investors there are, the fewer sellers there are on the market, given limited number of bonds. Finally, through the liquidity premium component of the price equation in 6d, price increases as the mass of sellers falls, and the mass of preferred habitat investors increases.

Result 4. *The more preferred habitat investors there are initially on the market, the more the price changes as a result of purchases.*

For a given amount of purchases, the amounts purchased, α_{cb} and the amount of bonds moved to be held to maturity $\Delta\alpha_{pa}$ are the same. The only difference the initial share of

preferred habitat investors can make is to the counteracting impact of purchases on the measure of sellers and buyers. Looking at equation 14, the impact of purchases on the buyer value function, the impact is larger, the lower the share of sellers, i.e. the more preferred habitat investors there are on the market initially. The effect is larger because the buyer value function at that point is steeper, when drawn for the measure of sellers. That means that when the buyer value function shifts down, the counteracting effects from the increase in the measure of sellers and the decrease in the measure of buyers is less the more preferred habitat investors hold the bonds. Therefore, the impact of purchases is larger in that case. This also means that the more the central bank purchases, the larger the price impact becomes, because the measure of sellers is lower. It is also intuitive, the fewer bonds there are available, the larger premium the central bank will have to pay to acquire those bonds.

Impact on liquidity

Result 5. *Liquidity of the bonds improves initially as the central bank announces purchases. It however declines thereafter as the central bank withdraws bonds off the secondary market, adding to the measure of preferred habitat investors* α_{pa}.

The measure of liquidity is the measure of transactions, $\lambda\alpha_s\alpha_b + \lambda\alpha_s\alpha_{cb}$. Central bank purchases, α_{cb} initially improve liquidity. At the same time, with endogenous entry, α_s increases, further improving liquidity, while decreasing α_b mutes the response somewhat.

As the central bank purchases add bonds to the stock of passive investors, the measure of sellers begins to decrease, leading to a decline in liquidity. Note that both the demand and supply effects lead to a decline in the entry of buyers g, which has a negative effect on liquidity.

How much central bank purchases affect liquidity depends on the existing demand for bonds. If there are already many buyers relative to sellers, then central bank purchases, the increase in α_{cb} will have less of an effect. If there are not many buyers, compared to sellers, then central bank purchases can make a bigger difference to liquidity. The sellers can then sell to the central bank instead of one of the scarce buyers.

Countries with a high number of preferred habitat investors have relatively fewer sellers, and more buyers, while countries with less preferred habitat investors have a larger number of sellers and few buyers. As a result, in countries with a lower share of preferred habitat investors, central bank purchases can improve liquidity by adding a large buyer to the market. In countries with a large number of preferred habitat investors, central bank

purchases do not improve liquidity as much initially.

We can similarly assess the impact of reducing the supply of bonds on liquidity. In this case, the impact will be largest in countries with fewest sellers, i.e. countries with largest share of preferred habitat investors. In those countries reducing the number of sellers by withdrawing bonds off the secondary market will reduce the ratio of buyers to sellers further. In a situation with regulatory reasons for holding the bonds, bonds become scarcer will worsen.

When the central bank purchases also crowd out other buyers, the liquidity situation is worse after the central bank ends the purchases because there are both fewer sellers and buyers.

4 Simulation of central bank asset purchases

There is no closed form solution for the model, so we simulate it numerically by looking for the measure of sellers, α_s that solves the equilibrium condition.

4.1 Calibration of the model

Calibration of the model is shown below in table 4. Bargaining power of the buyers, β is set to 0.5. Correspondingly, the bargaining power of the sellers, $(1-\beta)$ is also 0.5. The average sovereign debt maturity in the Eurozone is 7 years and the value is quite similar for most of the countries. We therefore set δ, the probability of debt being rolled over in any given year to 0.14. The sellers are the only agents in the model with a discount factor, and that is set to 0.05. As is common in literature, we set the recovery value to 0.4. λ in this model is constant, as we are only interested in cases where the agents do not find each other instantly. We set it to 600, which means that if the measure of sellers is one, it takes about a half of a business day on average to find a seller. The probability of liquidity shock is harder to calibrate, and we set it to 0.10. In each year there is a 10% probability of getting a liquidity shock. It should not be too unreasonable given that it is an annual probability. e the buyer search cost is set very low at 0.001. We assume a beta distribution for the entry condition, and set the parameters of the distribution α and β to 1 and 2 respectively.

We calibrate the model to the Eurozone. Ideally we would calibrate the model to each country separately, but due to confidentiality of the data, we cannot reveal the preferred habitat index for each country. For this reason, we split the sample in two, to countries with high and low share of preferred habitat investors holding their bonds. The group of

Table 3: Calibration

Buyers bargaining power	β	0.5	Probability of a liquidity shock	θ	0.1
Probability of debt maturing	δ	0.14	Buyers' search cost	e	0.001
Sellers' discount factor	ρ	0.05	alpha of the beta distribution		1
Recovery rate	γ	0.4	beta of the beta distribution		2
Search intensity	λ	600			

countries with high share of preferred habitat investors includes Austria, Belgium, Germany, Finland, France, and Netherlands while the group with a low share includes Ireland, Italy, Portugal, and Spain. The shares of preferred habitat investors in these countries can be seen in figure 2 on page 9. The sample could also be split equally to groups of five countries, but we decided on this specification as country number 5 is closer to the high rating country in terms of preferred habitat investors. There's a clearer difference between country 4 and 5 than between country 5 and 6.

Some statistics for these countries are shown below in table 4. The share of preferred habitat investors in these country groups is quite large. In the high group, 40% of debt is held by preferred habitat investors, while in the low group the figure is 21%. The amounts purchased as a share of long-term bonds are very similar in both countries and therefore cannot be the explanation for differences in impact on yields. The exact calculation of purchases in each Eurozone country is explained in section 2.1 and the results are in table 1.

Table 4: Calibration of groups

	Preferred habitat	Default probability	Purchases as a share of long-term bonds	Average maturity
High preferred habitat	0.42	0.23	13.29	6.68
Low preferred habitat	0.21	2.14	13.81	7.48

The default probabilities are computed from benchmark 10 year sovereign yields on 1st of December 2014, 3 days before the ECB press conference where Draghi hinted about the upcoming asset purchases programme. An approximation for a risk-neutral default intensity that we use is $\frac{y-r}{1-RR}$ where y is the yield on 1st of December 2014, r is the risk free rate, German benchmark yield in this case and RR is the recovery rate that we set to 40% as in the calibration.

Average maturity of loans in both groups is very similar, and it is even longer in the low rating group. This is mostly due to the low rating groups having official loans with very long maturities. We calibrate the average maturity to be 7 years for both of these

groups.

We get yields from a bond pricing formula through the following equation, where y is the yield and maturity is $1/\delta$:

$$y = (1/P)^{\delta} - 1 \tag{15}$$

Graph 4 shows the results of the calibration. We show four periods of simulation. In the first period purchases are zero and the share of preferred habitat investors is set to the initial levels we find in data for each group. The demand and supply side of purchases are separated in the following two periods. In period two, the central bank purchases 13% of the bonds in each group. In period three those purchases are added to the stock of preferred habitat investors and again the central bank purchases 13% of the bonds. The period three value can be understood as the combined supply and demand effect on yields and liquidity. Note that in both periods we keep the measure of buyers constant in order to show it separately. In period four the central bank stops the purchases, while the central bank holds the share of bonds it purchased in the previous period. We now allow the measure of buyers adjust endogenously in order to show the crowding out effect. The period four effect is therefore the effect of ending the asset purchases that leads to an increase in yields due to the fall in central bank demand.

In the group with a high share of preferred habitat investors holding the bonds, yields fall more than in the group with a low share of preferred habitat investors because of the tightness in the bond market. The maximum impact on yields in the two groups of countries is very close to the results we find in our empirical estimates in section 2.

Liquidity improves more in the countries with few preferred habitat investors. This is because those markets have more sellers than buyers so that an increase in buyers (central bankers) increases liquidity more rapidly. Eventually, as the central bank stops the purchases but keeps holding the purchased bonds, liquidity falls to a lower level than it was initially. This is because we allow the entry of buyers to adjust endogenously in the last period, where the central bank holdings then crowd out potential buyers.

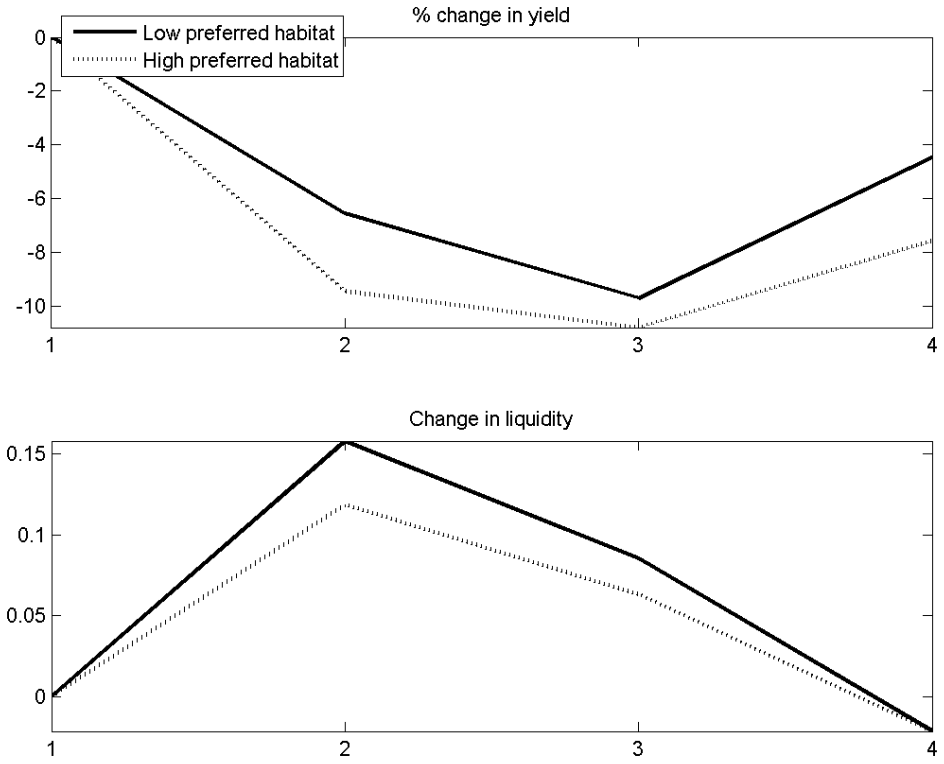

Figure 4: Price and liquidity impact from the calibrated model

5 Conclusion

We presented a search-theoretic model of over-the counter debt that allows us to analyse the impact of central bank purchases on yields. The impact is predominantly determined by tightness of the bond market, the ratio between sellers and buyers. In turn, the tightness of the market is influenced by the share of preferred habitat investors. These investors are unwilling to sell their bonds to the central banks and for this reason, prices and yields move more in markets with a higher share of preferred habitat investors, i.e. markets that are tighter.

With data from the ECB securities and holding statistics, we construct a new index for the share of preferred habitat investors in Eurozone countries. This index varies strongly across Eurozone countries, and is positively correlated with sovereign debt ratings and the size of the bond market. We calibrate the model to the share of preferred habitat investors for two groups of higher and lower rated larger Eurozone countries, and match the observed impact on sovereign yields from the announcement of the ECB asset purchase programme.

The model also predicts a liquidity trade-off effect. The impact on liquidity depends also on the tightness of the bond market. Asset purchases by the central bank improve liquidity initially, as they represent the addition of another large buyer to the market. However, as the central bank reduces the stock of bonds on the secondary market available for sale by holding the bonds to maturity, it subsequently reduces liquidity. In countries with fewer preferred habitat investors, liquidity at the end of purchases is lower than before the start of the purchases.

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Appendix A : Empirical results

Tables 5 and 6 show the change in the yield between t and $t-1$ in percentage points and basis points respectively for different announcement days of (features of) the ECBs PSPP programme. Countries are ordered by sovereign rating. On most announcement days, the impact of announcement on basis point is larger for lower rated countries, but the relative impact is larger for countries with higher credit rating. The 10 March 2016 announcement seemed to be less than was expected by the markets, since impact on yields is positive.

Table 5: One day change in yields, percentage

	10 year yields				15 year yields			
	22-Jan 2015	5-Mar 2015	22-oct 2015	10-mar 2016	22-Jan 2015	5-Mar 2015	22-oct 2015	10-mar 2016
DE	-16%	-10%	-14%	24%	-9%	-9%	-9%	13%
NL	-15%	-8%	-11%	16%	.	.	.	.
FI	-16%	-10%	-9%	8%	.	.	.	.
AT	-16%	-7%	-10%	10%	-11%	-7%	-8%	8%
FR	-13%	-5%	-10%	8%	-7%	-4%	-6%	4%
BE	-12%	-5%	-10%	7%	-9%	-4%	-8%	5%
IE	-8%	-5%	-9%	6%	-6%	-4%	-6%	4%
ES	-9%	-6%	-9%	2%	.	.	.	.
IT	-9%	-6%	-10%	4%	-8%	-3%	-7%	1%
PT	-7%	-5%	-5%	-1%	-6%	-4%	-4%	-1%

Table 6: One day change in yields, basis points

	10 year yields				15 year yields			
	22-Jan 2015	5-Mar 2015	22-oct 2015	10-mar 2016	22-Jan 2015	5-Mar 2015	22-oct 2015	10-mar 2016
DE	-8	-3	-7	7	-7	-6	-7	6
NL	-8	-3	-8	6				
FI	-8	-4	-7	5				
AT	-9	-3	-8	5	-7	-4	-8	5
FR	-9	-3	-9	5	-8	-4	-9	5
BE	-9	-3	-9	5	-8	-3	-9	5
IE	-10	-4	-10	5	-9	-5	-10	5
ES	-13	-8	-15	2				
IT	-14	-9	-16	5	-19	-6	-15	2
PT	-18	-9	-13	-3	-21	-10	-11	-4

Appendix B : Proofs

B.1 Bargaining problem

We start by writing out the value functions of a buyer and a central bank explicitly:

$$J_b = -e + \lambda\alpha_s(J_{po} - P) + (1 - \lambda\alpha_s)J_b$$
$$J_{cb} = -e + \lambda\alpha_s(J_{pa} - P) + (1 - \lambda\alpha_s)J_{cb}$$

where e is the small search cost, and $\lambda\alpha_s$ is the probability of meeting a seller. Once we assume that $J_{po} = J_{pa}$, it follows that $J_b = J_{cb}$. Then the surplus will be the same for both the buyer and the central bank, and subsequently, also the price will be the same for both. We do not observe that central banks pay different prices than other market players, even though central bank purchases certainly increase prices.

The implication of setting the value functions of the patient debtholder and the passive investor to equal can be seen if we write out also those value functions explicitly.

$$J_{po} = \delta(1 - q) + \delta q\gamma + \theta J_s + (1 - \delta - \theta)J_{po}$$
$$J_{pa} = \delta(1 - q) + \delta q\gamma + \theta J'_{pa} + (1 - \delta - \theta)J_{pa}$$

The difference here is that the patient debtholders have a probability θ of being hit by a liquidity shock and becoming sellers. We can assume that similarly, the passive investors are hit by liquidity shocks, but are not able to liquidate the bonds, instead they bare the cost and get J'_{pa} in that case that we assume to be equal to J_s.

Note that J_{po} cannot be greater than J_{pa}. If we leave out the $\theta J'_{pa}$ term from J_{pa} below, then the difference between the two is θJ_s. The seller has the same probability of maturing, and being paid 1 at maturity as the other bond holders, but if it finds a buyer before maturity, it sells the bond for price P which is less than 1 it would get at maturity. The value function of the seller is also discounted. Therefore, J_{po} cannot be higher than J_{pa} without $\theta J'_{pa}$ term. Similarly, J_{pa} cannot be greater than J_{po}. If that was the case, all investors would choose to hold bonds to maturity, which is not what we observe.

Appendix C : Preferred habitat investor index

Securities Holding Statistics (SHS)

Securities Holding Statistics data are collected on a security by security level (based on Regulation ECB/2012/24, as amended by ECB/2015/18) for four security types: short- and long-term debt securities, quoted shares and investment funds shares/units, and subsequently linked with reference data on individual securities from the Centralised Securities Database (CSDB) with additional attributes referring to individual securities and their issuers. The data cover holdings of securities aggregated by selected investor sectors of each Euro area country, excluding the holdings by the eurosystem. The main holding sectors available are (i) deposit-taking corporations, (ii) money market funds, (iii) investment funds, (iv) financial vehicle corporations, (v) insurance corporations, (vi) pension funds, (vii) other financial corporations, (viii) general government, (ix) non-financial corporations, (x) households and (xi) non-profit institutions serving households. For holdings by non-Euro area investors, the mandatory sector breakdown is more restricted and distinguishes only between holdings by General Government and NCBs and the remaining investors.

For our purpose, we focus on the debt securities issues by Eurozone general governments that are held by (i) central banks and governments outside the Eurozone; (ii) insurance companies, both inside and outside the Eurozone, and (iii) pension funds, both inside and outside the Eurozone.

A caveat to be taken into account concerns the collection of data of the holdings of Euro area securities by non-euro area investors, which is to a large extent collected indirectly via custodians and thus may not capture the country of the final investor (i.e., the data suffer from custodial bias). This custodial bias presents a potential risk of double-counting with euro area holdings, where they are held by euro area financial investors in custody outside the euro area (or of double counting euro area holdings, in case of chains of custodians).

Custodial bias would not be expected to significantly influence the data on the holdings of non-euro area central bank and general government, insurance companies and pension funds. If at all, there could be a potential undercounting of the holdings of euro area securities by these sectors ,in particular those by insurance corporations and pension funds. Given the larger than average contribution of holdings outside the euro area to the index of the countries with the highest share of preferred habitat investors in our index, this would likely imply an even larger dispersion across countries.

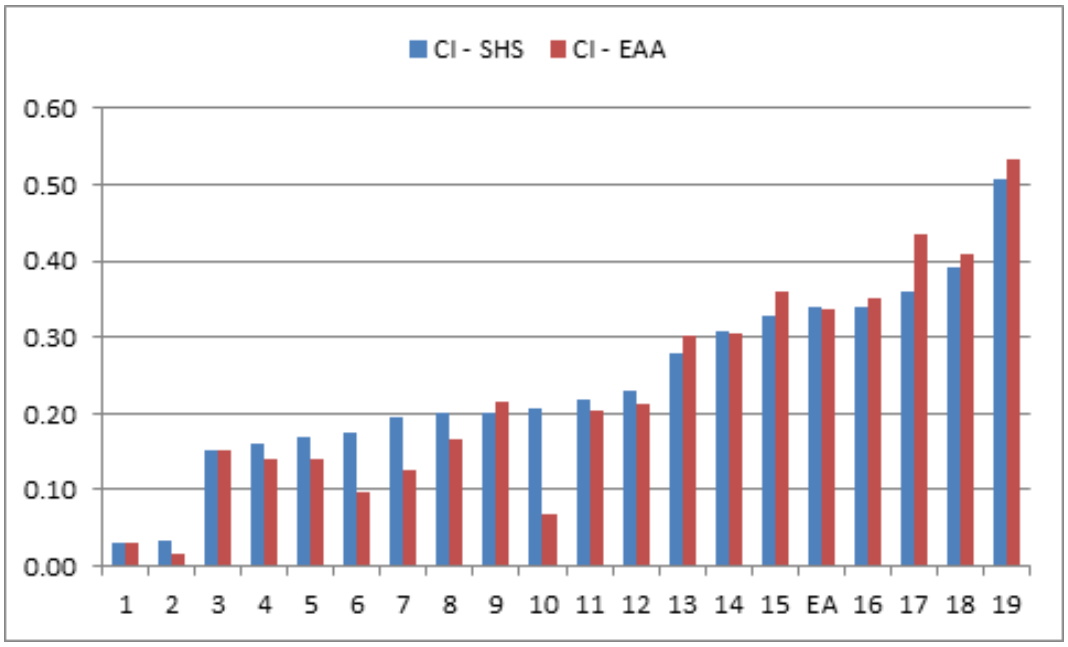

Figure 5: Preferred habitat index (CI) as a share of securities in the SHS and EEA databases

Through the potential double counting, custodial bias could influence the total amount of securities held, which is covered in the data base. Since we express our index as a share of total securities issued, we investigate this potential bias by comparing the total amount of securities included with the amount of general government debt issued by EA countries according to a different data source, the Euro Area Accounts (EEA). This check also allows to address the lack of Eurosystem data in SHSS. While the total amount of debt covered by both databases is very similar (close to 100% for the euro area), there are some differences across countries. In particular, the SHS data base includes smaller amounts held of securities issued by smaller countries than the debt issued according to the EEA, whereas the amount attributed to larger countries with larger financial sectors is higher. Figure 5 shows the preferred habitat index calculated with denominator based on the SHS and on the EEA database. For most countries, the differences are limited, but if there are differences they increase the dispersion of the index across countries. Since the EEA database provides a full coverage of the issued securities, we base the denominator of our index on this database, with the numerator based on the SHS database.

Preferred habitat investor index

Our index of preferred habitat investors is a composite indicator, consisting of the holdings of economic sectors that are likely to be preferred habitat investors, as a share of

the total government debt securities issued by euro area countries (excluding Eurosystem holdings). In particular, we consider central banks and general government outside the Euro area, insurance companies, and pension funds (both in and outside the Euro area) to be more likely to preferred habitat investors than other investors in Euro area sovereign bonds.

Central banks hold government bonds of other countries as foreign reserves, assets that can be easily sold in distress. This gives them a special preference for liquid and safe assets and is considered as a particular form of preferred habitat investment (see for instance in Krishnamurthy and Vissing-Jorgensen (2011) for the US Treasuries). While there are few detailed statistics about the holdings of central banks, the ones that do publish show a clear preference for higher-rated and more liquid sovereigns. See table 7 For example, the Riksbank mostly holds German bonds, and more Austrian than Italian bonds. Likewise, the Swiss National Bank, which does not publish a country breakdown, holds most of its foreign currency fixed income assets in securities of AAA-rated countries.

Table 7: Fixed income assets in foreign reserves, end 2014

Riksbank		**Swiss National Bank**	
Germany	68%	AAA -rated	60%
France	12%	AA -rated	25%
Netherlands	9%	A -rated	10%
Belgium	5%	Other	5%
Austria	4%		
Italy	2%		

Riksbank: holdings of foreign currency bonds in the Eurozone`http://www.riksbank.se/en/The-Riksbank/The-Riksbanks-asset-management/Gold-and-foreign-currency-reserve/` Swiss National Bank: holdings of foreign currency fixed income assets: `http://www.snb.ch/en/iabout/assets/id/assets_reserves`.

General government holdings outside the Euro are aggregated together with central banks in the SHS database. However, we consider it likely that the entities in general government that hold foreign sovereign bonds, such as social security funds or sovereign wealth funds, display the same preferred habitat investor characteristics as pension funds and insurers.

According to the preferred habitat theory, institutional factors and regulations influences the behaviour of certain investors, which determines the maturity and asset classes in which they will invest. We consider this to primarily be the case for insurers and pension funds, which both have long-term obligations and are subject to supervision and regula-

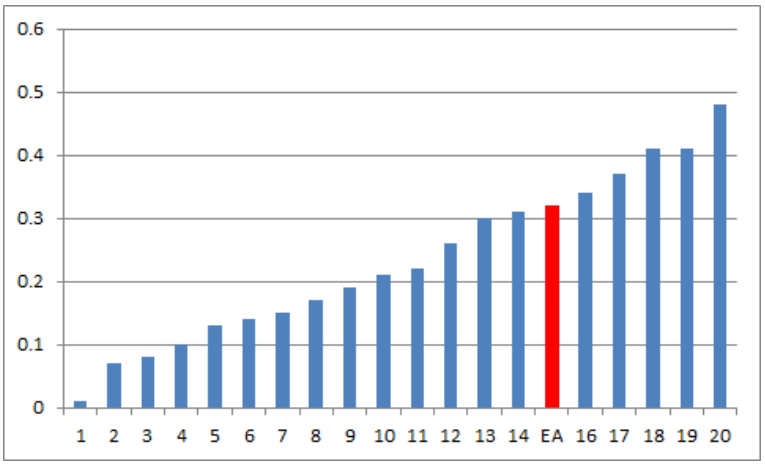

Figure 6: Preferred habitat investor index per Eurozone country, 2014. All Eurozone countries.

tions, including sometimes restrictions on the geographical area or rating of instruments to invest in. For example, held to maturity accounting rules discourage insurance companies, and other long-term investors of selling bonds on the secondary market. These rules state that if an entity sells and therefore marks to market more than an insignificant amount of bonds it holds, it will not be able to account any financial assets as held to maturity in the current and the following two financial years, including all assets in its portfolio. (International Accounting Standards 39 (n.d.))

Our index is a proxy index, based on the characteristics of the investor, rather than the actual behaviour. It is of course possible that for example pension funds act as arbitrageurs with all or part of their sovereign debt holdings, or that other investor sectors act as preferred habitat investors. It is also a broad proxy as the SHS database limits the level of disaggregation of investor sectors that can be considered. In particular, the holding of insurers cannot be broken down in different types of insurers (e.g. life insurers), which might be relevant for the type of maturity that is preferred.

Due to confidentiality of the data we are unable to identify individual countries. However, we can mention some broad characteristics and present country groupings. First, there is a strong correlation between the size of the country and the preferred habitat index. For example, the nine Eurozone countries with the lowest preferred habitat index represent cumulatively less than 10% of the ECB capital key (which reflects the respective country's share in the total population and gross domestic product, and is the basis for the distribution of the ECB asset purchase programme). Second, there is a strong correlation between the rating of the sovereign and the preferred habitat index, with higher

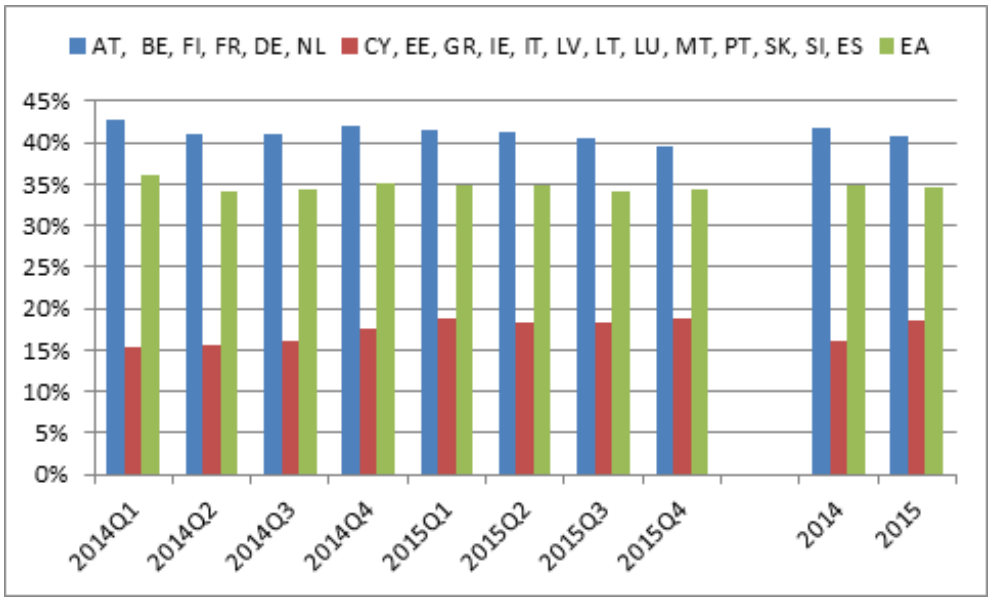

Figure 7: Evolution of the preferred habitat investors index

rated countries having a higher share of preferred habitat investors. Thirdly, when we consider the different components of the index, it is noteworthy that countries with a large second-pillar pension system or a large insurance sector also have a high share of sovereign holdings by these sectors.

Our preferred habitat investor index is relatively stable over time. In figure 7, the quarterly evolution of the index in 2014 and 2015 is shown for the Euro area average and selected country groupings, as well as the annual averages. [10] While there has been some convergence in this period between higher and lower rated sovereigns, the different score on the index remain pronounced, both before and after the start of QE. It should be noted that the index might be influenced by various factors, e.g. the sale of foreign reserves by central banks outside the Euro area, the emergence of some Euro area countries out of EU/IMF financial adjustment programmes, etc.

[10]The SHS data base contains only experimental data before 2013-Q4.

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