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Modelling the Exchange Rate: Evidence from the Impacts of Quantitative Easing in Sweden

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Abstract: Quantitative easing, the unconventional monetary policy measure used by many central banks to combat low inflation when interest rates are at the lower bound, has shown to be an effective tool for depreciating the domestic currency. Although the exchange rate is of particular importance in a small open economy as it directly impacts inflation dynamics, trade competitiveness and plays a substantial role in shaping monetary policy, few papers have investigated how the depreciating effect of QE to the exchange rate works. In this thesis, we employ a Bayesian vector autoregressive model (BVAR) and find that the Swedish Riksbank's quantitative easing (QE) programme between 2015-2017 depreciated the domestic currency to a larger extent than previous research has shown, even when accounting for spillovers from the European Central Bank's (ECB) QE during the same period. The depreciation is robust to various potential omitted variables and priors, suggesting the Riksbank's QE may have had greater consequences for the domestic exchange rate than initially thought. The greater persistence and magnitude in the depreciation can partly be attributed to the inclusion of the US short rate in the model, suggesting that short-term market sentiment and influence from the US play a considerable role in Swedish economy. As there isn't enough research on the krona in a VAR-setting to make a comparison, this result can be seen as a suggestion to account for US short-term influences when modelling the Swedish exchange rate. By using a two-step approach inspired by previous literature, we also find novel evidence of how quantitative easing in Sweden transmits to depreciate the exchange rate. Support is found for the signalling and portfolio channel, but not for the confidence channel, suggesting that quantitative easing depreciates the exchange rate by reducing the market's interest rate expectations and as investors substitute Swedish bonds for higher yielding foreign assets, but not through increasing confidence in the market.

Keywords: Quantitative easing, exchange rate, Bayesian VAR model, small open economy, triangular factorisation.
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Contents

1 Introduction

After the global financial crisis in 2007-2009, many central banks adopted unconventional policy tools to further stimulate the economy when interest rates were already reduced to the lower or zero bound. Quantitative easing (QE) emerged as one of these tools, allowing central banks to expand their balance sheets by purchasing bonds and thus inject money into the economic system. The motivation behind these asset purchases is to reduce the long-term interest rate when the traditional policy tools are not effective[1], and there is convincing evidence that QE indeed lowers the interest rate and stimulates the aggregate economy[2]. In response to the economic challenges following the global financial crisis, the Swedish central bank, the Riksbank, decided that the domestic monetary policy needed to be more expansive and announced its first round of quantitative easing in February 2015[3].

If quantitative easing works as it is intended, it should encourage investors to purchase foreign financial assets instead of domestic ones as a consequence of a reduced interest rate at home, depreciating the domestic currency[1]. Although a depreciating effect is often found empirically, it is less clear how this impact operates, what the magnitude is and which transmission channels it has[4]. Notably, even though the exchange rate is of particular importance for a small open economy such as Sweden, there is scarce research on the effects of the Riksbank's asset purchases on the exchange rate. In the paper of Di Casola & Stockhammar (2022), the exchange rate is included, however, their primary emphasis lies in analysing the broader effects of QE on Swedish macroeconomics rather than specifically delving into its implications for the currency. As pointed out by Johnson et al., (2020), quantitative easing, especially during prolonged periods and in small open economies, can lead to substantial unintended consequences[5], and gaining a more thorough understanding of these dynamics holds considerable importance. In a review of the Swedish asset purchase programmes, the Riksbank also calls for more research about QE, underlining the importance to understand the impact of quantitative easing on the exchange rate in small open economies (Andersson et al., 2022).

Given that the exchange rate directly impacts inflation dynamics, trade competitiveness and plays a substantial role in shaping monetary policy in a small open economy, it becomes crucial to gain a more comprehensive understanding of how QE impacts this part of the economy (Aloui, 2021; Andersson et al., 2022). In this thesis, we will therefore model the Swedish real exchange rate, conduct an analysis of the impacts resulting from domestic quantitative easing, and attempt a particular two-step approach to systematically identify the transmission channels involved. By modelling the real exchange rate to reflect a theoretical set up of a New Keynesian small open economy, combining the approach seen in Bjørnland (2009) and the QE specific model in Di Casola & Stockhammar (2022), we use impulse response functions to show that the quantitative easing period of the Riksbank between 2015-2017 indeed depreciated the domestic currency. The depreciation is of higher magnitude and persistence than what previous research has shown, even when accounting for spillovers of ECB's quantitative easing. The persistent result is partly driven by the inclusion of the Federal Reserve's interest rate in the model, suggesting that a depreciation of the Swedish krona in response to domestic QE may be understated when US data is not accounted for. To the best of our knowledge, this is the first study which extends the impulse response analysis to investigate through which channels the Swedish quantitative easing potentially transmits through to depreciate the currency. We find evidence for the signalling and the portfolio channel, supporting that quantitative easing depreciates the exchange rate by reducing the market's interest rate expectations and by investors substituting Swedish bonds for higher yielding foreign assets. No support is found for the confidence channel, indicating that the quantitative easing announcements did not affect the exchange rate by altering financial or household confidence in the market. Interestingly, this is the case even though we also show that it is the announcements of QE, i.e., the communication to the public, and not the actual purchases that primarily affects the economy.

[1] See for example the review of unconventional monetary policy by Clouse et al., (2003), the Riksbank's study of asset purchases by Andersson et al., (2022), and the seminal paper of the Fed's and Bank of England's asset purchase programme by Christensen & Rudebusch (2012).

[2] See for example the recent review of the effectiveness of unconventional monetary policy tools by Johnson et al., (2020), the performance comparison by Fabo et al., (2021) or the study of the Riksbank's asset purchases by Andersson et al., (2022), De Rezende & Ristiniemi, (2023) or Rebucci et al., (2022) for Swedish examples.

[3] See the minutes of the monetary policy meeting held on 11 February 2015 and Andersson et al., (2022).

[4] See for example the literature review of the performance of QE by Johnson et al., (2020) and Bhattarai & Neely (2022). Within the QE literature, many papers attempt to determine the magnitude and channels through which QE transmits to the macroeconomy, see e.g. Kirshnamurthy & Vissing-Jorgensen (2011), but the exchange rate is one aspect that has received limited attention, see Andersson et al., (2022), Dedola et al., (2021), Gern et al., (2015) and Aloui (2021), particularly in small open economies.

[5] For instance, abnormal expanded balance sheets can limit policy measures in case of an emergency or have greater and more persistent effect on the macroeconomy and financial stability than expected, leading to long-term costs for the society.

2 Quantitative Easing and its Transmission Channels

2.1 Quantitative Easing

When inflation is at low levels, the conventional monetary policy tools a central bank have access to are blunter and less reliable (Phelps, 1972). The rationale behind this is that sufficiently high inflation operates as a safeguard, ensuring that the central bank maintains a capacity to navigate economic uncertainties effectively through its primary monetary policy instrument, the interest rate. In an environment of low inflation, a central bank may eventually face a situation where the policy rate is lowered to the zero bound, limiting the opportunity to provide enough monetary stimulus in case of an economic downturn. To maintain a liquid economy and avoid the risks associated with inflation near the zero bound, researchers suggest an inflation target around 2% (see for example Svensson, 1999).[6]

The inflation target, albeit forming a credible commitment of a sufficiently high inflation, does not guarantee that the price level never drops to near zero, and does not either eliminate the problems around the zero bound. If inflation hits the lower bounds, central banks might therefore need to stimulate aggregate demand in an environment where its conventional tool is less effective. This scenario arises when a reduction in the policy rate fails to translate into a decrease in longer-term interest rates. By the renowned analysis of Keynes[7], a central bank which faces these issues is called to be in a liquidity trap as (conventional) monetary policy ceases to be an effective instrument. While successful monetary policy is often associated with a proactive approach, avoiding deflation at all cost, quantitative easing ensures that the central bank is not powerless in such circumstances[8].

In March 2001, Bank of Japan initiated the first ever rounds of quantitative easing (See for example Ugai, 2007). Since then, the policy measure has become an option for central banks around the world when conventional tools are limited by the lower bound[9]. The ultimate goal of QE is to through expanding the central banks balance sheet with asset purchases, align both inflation and inflation expectations with the central bank's target, while also stimulating economic growth, reducing unemployment and depreciating the currency. Particularly, the QE programmes are designed to lower long-term interest rates to stimulate economic activity[6]. Overall, the international experiences of quantitative easing are positive, where QE is recognised for its ability to stimulate economic activity, increase inflation and control the yield curve[10](Johnson et al., 2020; Bhattarai & Neely 2022), particularly from the central bank's point of view (Fabo et al., 2021). In main stream media, although the positive effects are also highlighted, quantitative easing is often associated with its unconventional narrative: the notion of 'printing money' and its potential negative consequences as risks for inflation and asset bubbles[11].

As briefly mentioned in the introduction, previous research investigating the impact of quantitative easing has indeed found that asset purchases depreciates the domestic currency. In an international setting, Neely (2011) uses an event study and find the US dollar to depreciate in response to the Federal Reserve's large scale asset purchase programme initiated in 2009. In Europe, applying a regression framework on high frequency data, Dedola et al., (2021) finds that the Euro persistently depreciated against the US dollar in the response of a QE shock using data from 2008-2019. For Sweden, the event study by Rebucci et al., (2022), investigates the impact on the exchange rate of the first three days after a QE-announcement, and find the domestic currency to depreciate against the US dollar during all three days. Extending the analysis past the first few days, De Rezende & Ristiniemi (2023) use pooled and single regressions and find the Swedish currency to depreciate in response to unconventional monetary policy, although the impact of conventional policy is greater. The summary of the performance of QE by Johnson et al., (2020) and study of the Riksbank, Andersson et al., (2022), also confirms QE's effectiveness in depreciating the local currency for both small and larger open economies.

Delving into the VAR-literature of this subject, Di Casola & Stockhammar (2022) is particularly interesting. The novel ap-

[6] See Eggertsson & Woodford, (2003) seminal paper on optimal monetary policy around the zero bound and Clouse et al., (2003) for a review of the origin of asset purchases and the purpose of other expansionary policies at the lower bound. See the review of new monetary policy tools by prior Fed chairman Ben Bernake (2020) or Kirshnamurthy & Vissing-Jorgensen (2011) for a review of asset purchases with a focus on the strategies used by the Fed and the Riksbank's study of the asset purchases (Andersson et al., 2022) for a Swedish example.

[7] See Hicks (1937) interpretation of Keynes.

[8] See Bernake, (2020), or seminal paper on optimal policy around the zero bound by Eggertsson & Woodford, (2003).

[9] For instance, the Federal Reserve, the Bank of England, the ECB, the Swedish Riksbank, the Swiss National Bank, the Bank of Canada, the Reserve Bank of Australia, and the Reserve Bank of New Zealand are some of the central banks that have employed QE as a policy tool.

[10] The yield curve is a graphical representation of interest rates for a range of maturities, reflecting the relationship between the time to maturity and the corresponding yields. Easier put, the yield curve is often considered a representation of the markets expectations of the interest rate.

[11] See for example the article *Quantitative Easing Explained* by Forbes (2023).

proach in Di Casola and Stockhammar takes into account the quantitative easing of the ECB and the Riksbank on Swedish macroeconomic fundamentals, finding positive effects of domestic QE and large spillovers from the foreign QE[12]. The authors employ a Bayesian vector autoregressive model (BVAR) on data between 2015-2018, covering the first asset purchase period of the Riksbank and find a depreciation in the domestic currency in response to QE, with a significant effect lasting no more than 5 months. Whilst various contributions are made, it is worth noting that the methodology of Di Casola & Stockhammar is in turn inspired by Weale and Wieladek (2016), which studies asset purchases by the Bank of England and the Federal Reserve. Wieladek & Pascual (2016) also follow the approach of Weale and Wieladek but extend the analysis to include a counterfactual. Both papers find that QE was effective in stimulating the aggregate economy in the Euro zone, the UK and the US.

2.2 Sweden's Asset Purchase Programme

Before the Riksbank initiated the first round of asset purchases in early 2015, the Swedish economy was marked with low inflation coupled with strong indications that the long-term inflation expectations were below the target. In light of growing uncertainties in the global markets, and the announcement of the ECB quantitative easing programme, the Riksbank decided that the monetary policy needed to be more expansive. Based on this, the Riksbank took the historical decision of reducing the interest rate to -0.10% and to initiate the first round of asset purchases by buying government bonds measuring at SEK 10 billion[13]. Since then, the Riksbank has engaged in two separate waves of asset purchases in an effort to stimulate the economy. During the first quantitative easing programme between 2015-2017, the Riksbank purchased government bonds from the secondary market reaching a total of SEK 290 billion. Including previous purchases, the total amount of bonds in holding reached SEK 350 million in the end of 2018, see Figure 1. For the first wave, the one analysed in this thesis (see section 4 for full explanation), the primary goal was to enact as expansive monetary policy in times when the Riksbank's interest rate was at the zero bound. The second wave of purchases, 2020-2021, was initiated to keep interest rates low, enable credit provisions and support the Swedish economy during the pandemic (Andersson et al., 2022).

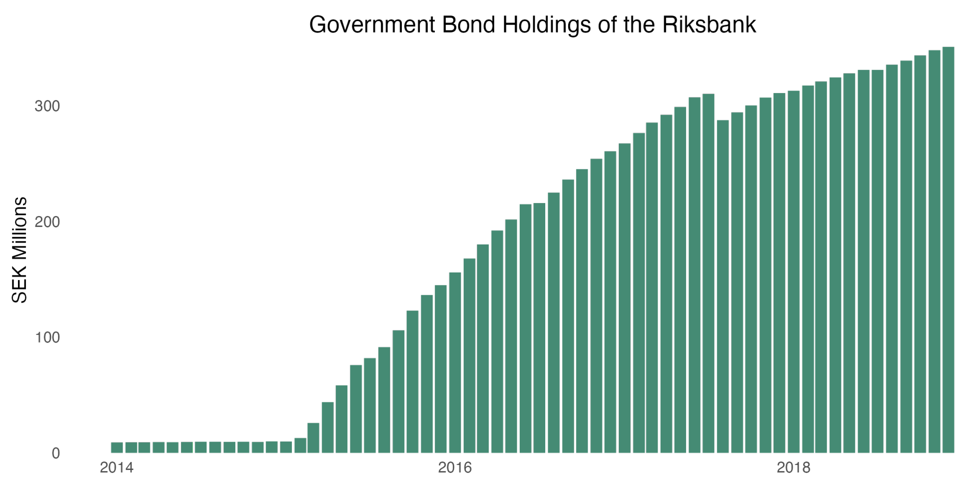

Figure 1: Total government bond holdings of the Riksbank 2014-2018

Previous studies on the effect of the Riksbanks asset purchases between 2015-2017 (for example De Rezende, 2017 or De Rezende & Ristiniemi, 2023) indicate that the purchases did indeed reduce the long-term interest rates on government bonds. There is also evidence that the Swedish QE stimulated the aggregate economy and increased inflation (See for example Di Casola & Stockhammar, 2022). The previously mentioned study of the Riksbank also concludes that QE has contributed to more expansive financial conditions, lower rates and a weaker exchange rate (Andersson et al., 2022). Although these results are in line with the international literature (See Johnson et al., 2020 and Bhattarai & Neely 2020), one should note that the spread of estimated effects in this literature is quite large between studies. Particularly in Sweden and other small open economies, less is known about the effects of QE (Andersson et al., 2022).

[12] With the spillovers being partly explained by that the Riksbank as a response of ECB's quantitative easing announcements also initiated its own QE programme.

[13] See the minutes of the monetary policy meeting held on 11 February 2015.

2.3 The Transmission Channels of QE

The QE literature mainly identifies two channels of which the effects of asset purchases transmits to the economy. First, a signalling channel where the monetary policy measure is theorised to convey information about the central banks intentions for the short-term interest rate, which alters the expectations of the market and all bond interest rates (See for example Christensen & Rudebusch, 2012). Second, a portfolio rebalancing channel known as a substitution effect coming from the shift in asset holdings as the purchases by the central bank bids up the price and hence lowers the yield on bond assets (see e.g. Kirshnamurthy & Vissing-Jorgensen, 2011). A third possible channel is the effect of QE on the confidence in the market, which contributes to a reduction of financial uncertainty in the economy. Though less recognised and inherently dependent on the market's expected success of the QE programme[14], the potential increase in confidence is a viable transmission mechanism (Weale & Wieladek, 2016; Gern et al., 2015)[15]. The extent to which the transmission mechanisms of QE operates depends on the presence of financial frictions in the government bond market (Weale & Wieladek, 2016). For instance, the key theoretical reference for the portfolio balancing channel is the theory of preferred habitat by Vayanos & Vila (2021)[16], where investors have preferences over bond maturities and thus require compensation to be willing to change the composition of their portfolio.

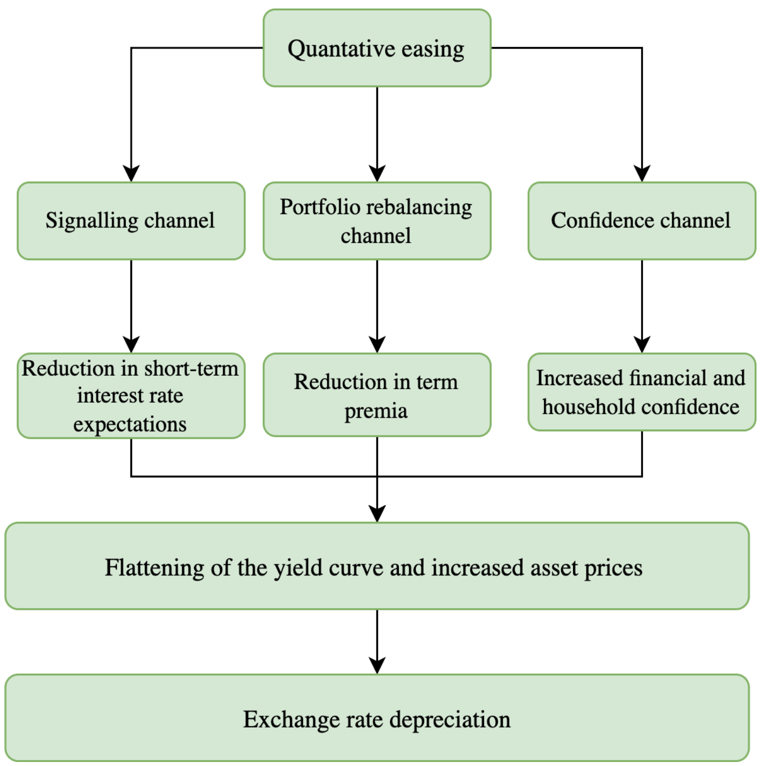

Figure 2: Graphical representation of how quantitative easing affects the exchange rate through the channels proposed by theory. Flow chart is inspired by Gern et al., (2015) and modified to display the relevant relationships.

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[14] Only if there are expectations of QE being successfully transmitted, i.e. lowering long-term interest rates and stimulating the economy, can we expect to see an increase in market confidence without a time lag.

[15] In some sources this is called the uncertainty channel.

[16] First published in 2009.

2.3.1 Signalling channel

Eggertson and Woodford (2003) emphasise the role of expectations in policy measures constrained by the lower bound and argue that a central bank's actions should be geared towards signalling a credible policy commitment which the bank also intends to pursue. Expanding on this, Clouse et al., (2003) classifies a credible policy commitment as one where the central bank faces potential capital losses unless it keeps the intended trajectory. Asset purchases is an attempt to serve this purpose as the central bank will realise losses on the bond purchases if the interest rate increases in the near future[17]. The central bank can thus convince market participants of a low interest rate path, particularly as long as the asset purchases are continuing (Bernake, 2020). This relates to the idea of forward guidance, in which a central bank can shape market expectations by communicating its future monetary policy intentions (De Rezende, 2017). When the central bank then considers these losses in its objective function, engaging in QE by buying long-term assets represents a reliable commitment to maintaining low interest rates. Also note that the signalling channel is expected to impact yields on all bond maturities as the commitment of a low policy rate impacts all interest rates (Kirshnamurthy & Vissing-Jorgensen, 2011).

2.3.2 Portfolio balance channel

As described in Tobin (1982), portfolio rebalancing effects arise because financial assets are imperfect substitutes. This is the case as investors inherit varying levels of risk attitude and as bonds have different levels of risk characteristics. In this view, short and long-term bonds are not substitutable and as concluded in Vayanos & Vila (2021), this requires the theoretical assumption of the preferred-habitat view, where investors demand only the bond corresponding to their desired maturity. This channel therefore requires a departure from a frictionless economy (Vayanos & Vila, 2021). When a central bank purchases bond assets in the market, the relative supply of assets held by the private market will change, inducing higher bond prices, lower risk premiums and lower yields (Christensen & Rudebusch, 2012). In other words, investors need to be willing to sell their holdings to the central bank and hence, they require compensation in the form of higher bond prices (Kirshnamurthy& Vissing-Jorgensen, 2011). A determined central bank, with the capacity to absorb a large enough supply of bonds, is therefore able lower the interest rates of these bonds (Clouse et al., 2003). This is the case even though the short-term government bond interest rate would be zero (Tobin, 1982). Particularly important when investigating this channel is to understand which assets that are substitutes for those which the central bank purchases. Because of increased bond prices, investors will experience a wealth effect, which affects their spending or arbitrage behaviour. Note that this behaviour can vary with investor preferences, which is for instance formed by social conditions or place of living (Kirshnamurthy & Vissing-Jorgensen, 2011).

2.3.3 Confidence channel

A third transmission mechanism of QE, via increased market confidence, is also theorised to exist. Gern et al, (2015) argues that a central bank can affect the economy solely by restoring confidence in the market through reducing financial and household uncertainty. Particularly in times of financial distress, the confidence in the market which quantitative easing possibly contributes with, can reduce the risk of the economy falling deeper in a recession. In Weale & Wieladek (2016), this is described as a channel which can manage the expectations about future financial outcomes and subsequently reduce financial uncertainty, leading to a flattening of the yield curve and increased asset prices. Wieladek & Pascual (2016) argue that this is an important channel as it effects the perception of uncertainty. Namely, the commitment of QE can show that the central bank is willing to do "whatever it takes" to keep expectations of future inflation low. Lastly, this can be viewed as a channel aimed to investigate if the common public reacts and changes their behaviour in response to a quantitative easing announcement.

2.4 Empirical evidence

When it comes to the empirical experiences, there is undoubtedly ambiguity in the relative importance of respective transmission channel. A number of studies indicate that both the signalling channel and the portfolio channel hold similar levels of importance (Gern et al., 2015), but a number of studies also show that one channel is more important than the other. In the US, the signalling channel has shown to hold more importance in reducing interest rates (Kirshnamurthy & Vissing-Jorgensen, 2011), whereas in the UK, reduction in rates seems to be driven solely by the portfolio channel (Christensen & Rudebusch, 2012). This result differs from Weale & Wieladek (2016), which finds a relatively more important role for the portfolio channel than the signalling channel in the US. In the UK, Weale & Wieladek don't find evidence for any of

[17] This is because higher interest rate equals a lower price on the bond.

the channels. In both countries however, there seems to be evidence for the confidence channel, with the QE purchases reducing financial and household uncertainty. In the Euro zone, Wieladek & Pascual (2016) find some support for the signalling channel but ultimately find the portfolio balance channel to be the strongest transmission channel for QE to the economy. Unlike the findings in the US and the UK, the confidence channel does not seem to be relevant in the Euro-zone. In Swedish empirical findings, the asset purchases seem to have both important portfolio balance and signalling effects (De Rezende, 2017; Di Casola & Stockhammar, 2022; Melander, 2021). Christensen and Rudebusch attribute differences like the ones above to the underlying economic rationales in each country and that the financial markets are different overall[18].

[18] For instance, the portfolio channel operates through depressing the term premia on bonds, making investor preferences and arbitrage behaviors play a vital role. Evidently, this does not need to be identical between countries.

3 The Exchange Rate

Exchange rate determination often takes a monetary interpretation, assuming strict purchasing power parity (PPP) [19]. First presented in a theoretical framework by Swedish economist Gustav Cassel in 1918[20], the purchasing power parity has since been used in a wide range of applications such as forecasting the real exchange rates and addressing price differentials in international comparisons. The technical fundamentals of PPP also serves as the foundation of various practical theories such as the law of one price (Dornbusch, 1980). Purchasing power parity establishes that relative changes in money supply, interest rate, and real income affect the exchange rate. While the degree to which this theory aligns with empirical evidence has been a subject of debate in the exchange rate literature, many economist believe purchasing power parity to be an anchor for the long-run equilibrium of the exchange rate (Rogoff, 1996; Taylor & Taylor, 2002). In an attempt to explain why the PPP doesn't always hold, Dornbusch (1976) presents an overshoot model, where the hypothesis is that the exchange rate tends to immediately overshoot its long run equilibrium value before gradually adjusting. This is in line with uncovered interest rate parity (UIP), which states:

"Given the long-run exchange rate, there is a unique level of the spot rate such that the expected appreciation, or depreciation, matches the interest differential". (Dornbusch, 1976, page 1164).

This suggests a negative relationship between the interest differential and the exchange rate (Frankel, 1979), which often is a cornerstone in macroeconomic models (Engel, 2014). Based on these theoretical foundations on exchange rates, a vast literature on exchange rate determination has emerged[21], and while the traditional theoretical models naturally include macroeconomic fundamentals such as money supply, interest rate and output, which should explain exchange rates well, the short-run relationship between the exchange rate and these fundamentals have shown to be weak[22]. Particularly, exchange rates are surprisingly volatile and random, despite a strong link to the economy (Obstfeld & Rogoff, 2000). Rich frameworks are therefore suggested to be one way to overcome difficulties in modelling the exchange rate, but there are still various puzzles within international economics in pairing empirical and theoretical understandings of the determination of exchange rates (Obstfeld & Rogoff, 1996). Today even there seems to not be a compelling way to explain the movements in exchange rate, especially since the demand and supply dynamics of the nominal exchange rates will affect the market equilibrium (Engel, 2014).

Given the unpredictability of exchange rates, numerous economists have tried to model the movements of their behaviour and an important strand of this literature investigates the impact of monetary shocks using structural vector autoregressive models (SVAR) (Engel, 2014). The seminal paper of this literature is Eichenbaum and Evans (1995), where a five variable VAR model using recursive identification strategies provides empirical evidence of a US exchange rate appreciation after a monetary policy contraction increased the interest rate. Key result in Eichenbaum and Evans is that the peak appreciation did not happen immediately, but 24–39 months after the shock, contradicting uncovered interest parity and Dornbusch's overshooting hypothesis. This concept is called delayed overshooting and various studies, e.g. Scholl & Uhlig (2008) and Cushman & Zha (1997), similarly finds that a contraction of monetary policy appreciates the currency with a delay. On the contrary, Bjørnland (2009) examines the small open economy of Norway and provides evidence of that a contractionary monetary policy shock has a strong and immediate effect on the exchange rate, which shows a maximum appreciation after one or two quarters. The mentioned papers are part of New Keynesian literature, applying variations of open economy monetary models. In simple terms, these models can be interpreted as a modern approach to exchange rate determination, where exchange rates and interest rates are endogenous macroeconomic variables which expands the traditional micro economic wage and price stickiness (Engel, 2014). Realising a small open economy is indeed affected by fundamentals abroad, New Keynesian theory allows domestic prices and aggregate demand to evolve independently and thus applies more realistic assumptions on exchange rates (Gordon, 1990).

[19] See for example the June 1976 issue of The Scandinavian Journal of Economics, dedicated to 'Flexible Exchange Rates and Stabilization Policy,' where a collection of articles highlights this type exchange rate determination, e.g. Frankel, (2019).

[20] See Cassel (1918).

[21] See for example the overview of theoretical and empirical contributions on exchange rate determination by Charles Engel (2014).

[22] For a review of the exchange rate disconnect puzzle see Obstfeld & Rogoff (2000). See Meese & Rogoff (1983) for an empirical study of out-of-sample exchange rate forecasts where standard macroeconomic models did no better than a naive random walk in the short run. Notably, Obstfeld & Rogoff (1996) conclude "The undeniable difficulties that international economists encounter in empirically explaining nominal exchange rate movements are an embarrassment" (Chapter 9, page 625).

4 Variable selection & Data

This thesis uses monthly time series data from 2015 to 2018, covering the first Riksbank asset purchase programme[23]. Motivation of choosing the first period is by the more conventional usage of QE during this time and because the behaviour of the times series is superior for modelling purposes[24]. The full time period 2015-2022 is not used as the assumption of a stable reaction function would not hold[25]. The variables in the model are chosen to reflect a New Keynesian small open economy, inspired by Bjørnland (2009) and Di Casola & Stockhammar (2022). In the baseline model, the variables are the following: Foreign interest rate, log GDP, log CPIF, quantitative easing, term spread, and the log real exchange rate. More specifically, a foreign interest rate variable is included in the model as in Bjørnland, (2009), whereas the rest of the variables match the set-up in Di Casola & Stockhammar (2022). The reasoning behind modifying Di Casola and Stockhammar's system is to build a model specifically of the exchange rate in a domestic QE-setting, aiming to capture influence of macroeconomic variation originating abroad on the conduct on domestic monetary policy and currency. Motivation of this is partly based on the seminal papers of modelling a small open economy by Svensson (2000) and Clarida et al., (2001), which include the foreign interest rate and highlights its importance. The other part lies in the unconventional notion of that the foreign interest rate is important for exchange rate determination in a small open economy[26]. Including the foreign interest rate in VAR models to estimate exchange rates movements of monetary policy is also a widely recognised approach [27].

Foreign exchange rate (i*) is a trade weighted variable with Sweden's biggest trade partners: index is roughly 85% of ECB's short-term interest rate and 15% of the US short-term interest rate[28], with motivation of the division of weights taken from Di Casola & Stockhammar (2022). Inclusion of the US interest rate is also motivated with the paper of Dedola et al., (2017), which analyses spillover effects of US monetary policy and find Sweden's real exchange rate to be largely impacted of policy conducted in the US[29]. Reasoning to include the short rate and not the term spread (as is done with the domestic interest rate) is to have the foreign rate which has the biggest impact on the domestic currency, and this is arguably the short rate compared to the long rate[30]. Aggregated Swedish activity (GDP) is represented by the monthly GDP indicator published by Statistics of Sweden and inflation (CPIF) is measured by the consumer price index with fixed interest rate, also from Statistics of Sweden. The variable quantitative easing (QE) is calculated by the cumulative asset purchases in Sweden during the first wave starting in 2015 (see Table A.1 for announcement dates and purchase volume), an approach pioneered by Weale & Wieladek (2016). Di Casola & Stockhammar extended this approach to solve for endogeneity coming from the effects of QE on instantaneous GDP levels by scaling cumulative purchases to GDP levels in 2014. Kindly, Di Casola and Stockhammar provided this variable for us. The term spread (T) is the difference between the Swedish 10 year and 3 month government bond yields[31], both rates are from the Riksbank's database. Lastly, the real exchange rate (RER) is the real effective krona exchange rate[32], trade weighted with roughly 85% versus 15% to Euro Area and the US, again, this measure was provided by Di Casola & Stockhammar. By extending the baseline model to test for the existence of different transmission channels of QE, interest rate expectations (RIBA), a stock market index (S&P 500), a stock market volatility index (VIX) and an index for household confidence is used. For full list of variables and their transformations, including those used in robustness tests, see appendix subsection A.1.

[23] Note that the first wave of purchases was 2015-2017. We use data from 2015-2018 to capture the full QE period plus the effects in the variables the year after.

[24] For instance, Di Casola and Stockhammar (2022) argue that this time period is superior as concerns of structural breaks can be ruled out for most of the macroeconomic variables. The time period is also substantially longer, five vs two years.

[25] A common critique when modelling monetary policy is that the weights the central bank places on each variable when deciding upon policy is assumed to be stable over time. The drastic swift in policy aims comparing the Riksbank's first wave of QE to the second one, most likely breaks this assumption. Taking this into consideration restricts the thesis to a shorter time series and thus reduces the effective size of the model. However, by using a time period where the Riksbank had clear policy goals, the stable reaction assumption is more likely to hold and the estimated coefficients are more likely to be reliable. (Kilian & Lütkepohl, 2017).

[26] Recall the traditional exchange rate literature, such as PPP or UIP. Particularly, see Svensson (2000) for an example applied on the Swedish economy.

[27] For example, see Meese and Rogoff's (1983) application of the UIP-based framework where the interest rate differential is included; e.g. Frenkel-Bilson model, the sticky-price monetary (Dornbusch-Frankel) model, and the sticky-price asset (Hooper-Morton) model. An example of the inclusion of the foreign interest rate (not differential) is seminal paper Cushman & Zha (1997).

[28] Short-term interest rate is here defined as the interest rate that impacts the shorter end of the yield curve. For both the Euro area and the US, this is measured with the 3 month government bond yield.

[29] Dedola et al., (2017) finds the krona to have one of the largest peak depreciations in the real exchange rate in response to a US shock in a sample of 36 other economies.

[30] As the short-rate is more linked to current economic conditions, monetary policy expectations, and immediate market sentiments.

[31] The term spread encapsulates that the central bank conducted policy rate cuts during the same period.

[32] Real exchange rate is here defined as $RER = ER * \frac{P^*}{P}$. An increase in this measure thus represents a depreciation.

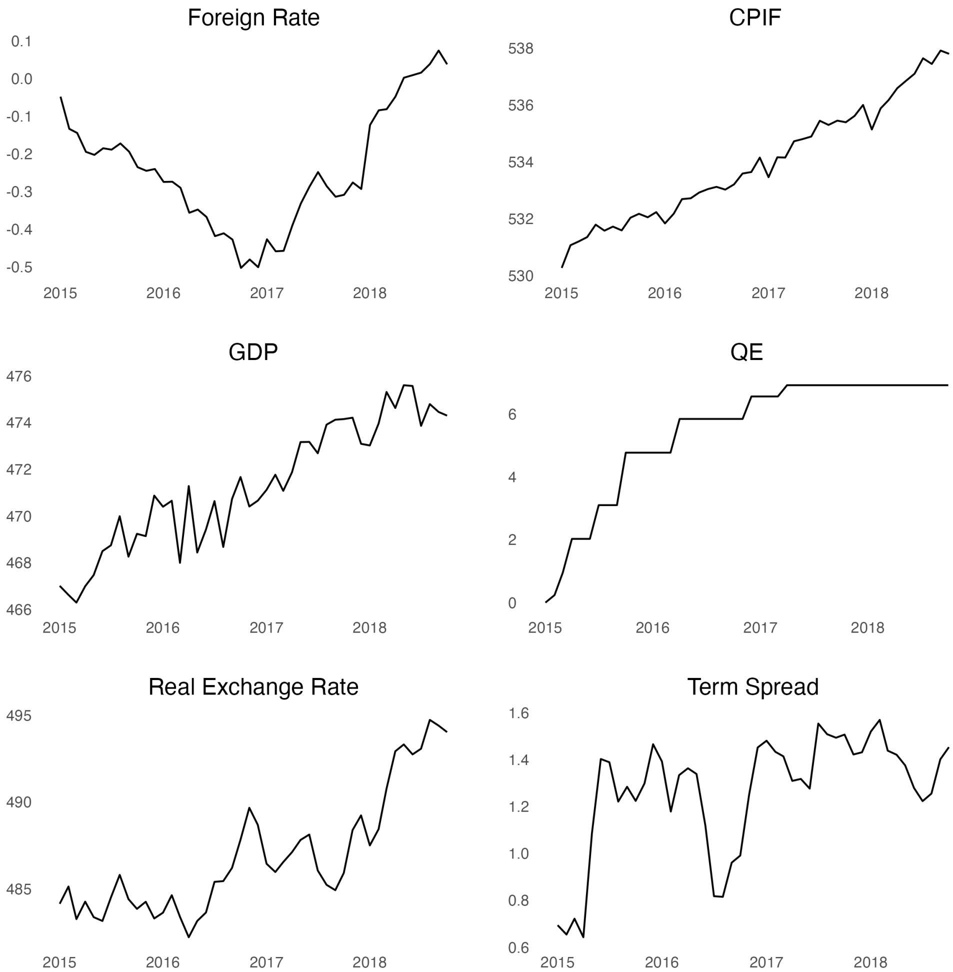

Figure 3: Baseline variables of the model

5 Methodology

This paper aims to analyse the impact of quantitative easing on the Swedish real exchange rate through impulse response function (IRF) analysis, achieved by estimating a structural vector autoregressive model (SVAR) using a Bayesian method (BVAR). Given that this framework integrates various statistical principles, the methodology section will start off with describing the background of Bayesian inference and the intuition behind using BVAR models. In the second part, the model specification and the identification scheme is defined, along with a review of impulse response functions. Lastly, the third part includes the process of how the model is estimated. To employ the model, the Bayesian Estimation, Analysis and Regression toolbox (BEAR) by Alistair Dieppe and Björn van Roye is used[33].

5.1 Bayesian Vector Autoregressive Models

Sims (1980) introduced VAR models in macroeconomics, objecting the then-common structural econometric macroeconomic models which relies on strong assumptions and implausible identification restrictions. Following Sims (1980), vector autoregressive (VAR) models attempt to capture joint dynamics of multiple time series variables by modelling each variable as a function of its own lagged values and the lagged values of other variables. Since then, VAR frameworks has become a common approach for estimating relationships in macroeconomic models. However, given that standard macroeconomic datasets are often characterised by a relatively low frequency of data points, such as monthly, quarterly, or annual observations, VAR applied to macroeconomic data often encounter the challenge of being overparameterised[34]. Actually, macroeconomic VAR models are notorious for generating imprecise estimates when ordinary (frequentist) methods are used on short time series (Koop & Korobilis, 2010). A proposed solution is to introduce priors, i.e. incorporating extraneous information in the estimation. This process can effectively constrain the unrestricted model and result in a reduction of parameter uncertainty and an improvement of model accuracy[35]. Doan, Litterman and Sims (1984) is often considered the first paper to introduce Bayesian inference in VAR models, justifying using Bayesian methods when the purpose is to find complex relationships in a small sample. The motivation is that within a Bayesian VAR framework, the VAR model is coupled with the introduction of informative priors, which serves to compensate for potential data reliability limitations in the case of a small sample.[36]

By introducing Bayesian inference in a model, we introduce ideas that differ fundamentally from the regular frequentist approach. As opposed to the frequentist methods, where the assumption is that there exists a true parameter vector of the model, a Bayesian investigator is concerned about the prior beliefs of this vector. These beliefs are expressed in the form of a probability distribution and the prior information that they introduce to the model is combined with the information contained in the data, the likelihood function, resulting in the posterior probability distribution. The posterior distribution captures all the information available of the parameter vector, it is thus the foundation of Bayesian estimation and is ultimately what we are interested in obtaining. (Dieppe et al., 2018; Kilian & Lütkepohl, 2017). In other words, the principle of a Bayesian VAR framework is to combine known information, for instance derived from economic theory, with the actual data and obtain an updated posterior distribution, which then serves as a basis of estimation and inference (Doan et al., 1984).

A remark on the criticism of Bayesian VAR is that it relies on this inclusion of priors - the need to articulate a prior belief of the prior probability distribution. The concern is that priors may be unintentionally informative and favor certain values of the parameters. Priors are also subjective of the researcher, resulting in a lack of consensus on appropriate priors. As a result, priors are often chosen by convention, that is, commonly used or standard priors that are widely accepted in the research community. In economic time series analysis, Minnesota priors are commonly chosen based on their consistency with theory on how economic variables behave. While it has shown to be a useful prior for economic time series, its important to consider that it may not always be the case (Kilian & Lütkepohl, 2017). Three alternative priors are therefore added as a robustness test, see subsection 8.3.

[33] The BEAR toolbox is a Matlab toolbox created to facilitate Bayesian estimation of multivariate time-series models. In this thesis we have used the developer's interface and the code can thus be provided to the interested reader.

[34] See for example Agrippino & Ricco (2018), Lütkepohl (2005) or Koop & Korobilis (2010)

[35] See for example the review of Bayesian VAR models in Kilian & Lütkepohl, (Chapter 5, 2017).

[36] In this thesis, as the data is limited, attempted SVAR models were indeed overparameterized and yielded imprecise estimates. A Bayesian VAR model is therefore employed as the framework conveniently overcomes these issues by including prior knowledge about how certain variables behave.

5.2 Model specification

In a VAR framework, the economic analysis has to be performed using a Structural VAR (SVAR) model, as it only through that model we can be sure to obtain meaningful and economically interpretable results. A SVAR model is however less receptive to ordinary estimation techniques, which is why a reduced form VAR model is used for estimation, in line with convention (Lütkepohl, 2005). Hence, we display both specifications below.

The SVAR model of interest takes the following form:

$$D_0 Y_t = F + D_1 Y_{t-1} + D_2 Y_{t-2} + \eta, \eta \sim N\left(0, \mathbf{\Gamma}\right). \tag{1}$$

Where Y_t denotes a vector of the following endogenous variables: foreign interest rate, inflation, output, quantitative easing, term spread and the real exchange rate. Y_{t-1} and Y_{t-2} denotes the same variables but with one and two lags respectively[37]. D_0 denotes a 6x6 matrix of the instantaneous coefficients and D_1 along with D_2, denotes a 6x6 coefficient matrix but for the endogenous variables with one and two lags. F denotes a vector of intercepts and η denotes the error terms. The SVAR model's error terms are assumed to be distributed as a vector white noise process $\eta \sim N(0, \mathbf{\Gamma})$, meaning that the error terms expected values are equal to zero and that its variance properties are characterised by a diagonal variance covariance matrix, Γ. Importantly, a diagonal variance covariance matrix assumes that none of the variables error terms are correlated with each other.

In line with Weale and Wieladek (2016), the estimated reduced form VAR model is defined as:

$$Y_t = \alpha_c + A_1 Y_{t-1} + A_2 Y_{t-1} + e_t, e_t \sim N\left(0, \mathbf{\Sigma}\right). \tag{2}$$

Y_t, Y_{t-1} and Y_{t-2} are vectors of the same endogenous variables as in the SVAR model and A_1 and A_2 are two 6x6 coefficients matrices for the Y_{t-1} and Y_{t-2} vectors but in a reduced form context. α_c is a vector of intercepts. e_t is a vector of error terms. In contrast to the SVAR models, the variance-covariance matrix in the reduced form, Σ, allows for correlation between the endogenous variables error terms.[38].

The principle behind a Bayesian estimation of a VAR model is to treat the parameters of the model as random variables, where the parameter of interest, the posterior distribution of β, is unknown. Recall that the posterior distribution is obtained by combining prior information of the model parameters with the available data to obtain an updated distribution (See e.g. Dieppe et al., 2018 or Kilian & Lütkepohl, 2017). In a Bayesian VAR framework, this is done by using Bayes theorem. By using the classical Bayes theorem it follows that:

$$\pi(\beta \mid y) \propto f(y \mid \beta)\pi(\beta). \tag{3}$$

By this equation, the posterior distribution of the coefficients in the reduced form, $\pi(\beta \mid y)$, are obtained by using the likelihood function, $f(y \mid \beta)$, and the prior distribution $\pi(\beta)$. As mentioned, the posterior distribution is the foundation of Bayesian estimation and is used for making inferences about parameter values, for example by calculating point estimates, drawing model comparisons, and other related tasks (Dieppe et al., 2018). As the variables are treated as random in Bayesian inference, we receive an entire distribution of estimates for each coefficient upon estimation. Along this distribution, a single point estimate must be chosen, which will then be treated as the estimated coefficient in the ordinary VAR framework. The median is typically chosen over the mean because the median is more likely to be in the center of the distribution and within the bounds of the credibility interval (Dieppe et al., 2018). For this reason, the median of the distribution is chosen to be the point estimate in this thesis.

[37] Lag selection is chosen based on a comprehensive view of both Bayes factor and previous empirical research. For instance, by using Jeffrey's (1961) guidelines we find decisive evidence in support of choosing 2 lags compared to 1 and 3 lags. This is also in line with previous research, e.g. Di Casola & Stockhammar 2022 and Weale & Wieladek, 2016.

[38] To avoid confusion, the reader should note that the reduced form model (VAR) is estimated by using a Bayesian approach. What is actually estimated is thus a Bayesian autoregressive model (BVAR).

5.3 Identification

To get economically interpretable results, the estimated coefficients in the reduced form has to be translated to the SVAR framework. Conveniently, it is possible to move between the structural and reduced form by using an inverse of the instantaneous coefficient matrix D_0^{-1} and the corresponding SVAR model's error terms variance covariance matrix Γ. Once these are derived, the estimated coefficients in the reduced form framework can be transformed into the parameters of the SVAR model. The principle problem is that the reduced form VAR's residual covariance matrix, Σ, is not diagonal and thus, allows for correlation between the variables error terms. The interpretation of estimated relationships between the variables will therefore not be economically meaningful as the components of the matrix may be instantaneously correlated. The solution is to apply appropriate identifying restrictions based on macroeconomic theory, which then provides a mapping from the estimates of the reduced form VAR to the SVAR such that the results can be economically interpreted.[39]

Specifically, it is needed to orthogonalize the reduced form errors, i.e. make them uncorrelated, by applying structural restrictions on the parameters in D_0^{-1}. In other words, this means to place casual links derived from theoretical considerations on the reduced form model (Lütkepohl, 2005). Sims (1986) describes identification as making connections between data and consequences of decisions, such that it is possible to analyse the impact or effects of an action or a specific cause. As such, improper identification can yield misleading results and the assumptions behind the decomposition must therefore have a theoretical foundation. Thus, by imposing restrictions based on economic theory on the variables in the model, we can define an identify scheme such that we can recover structural results with a meaningful economic interpretation from the reduced form representation. In this thesis, the method of identification is triangular factorisation.

5.3.1 Triangular factorisation

Triangular factorisation is a way of recursively identify a model and is a popular way to orthogonalize the reduced form errors. It implies that a particular instantaneous causal chain of the elements is enforced, meaning there is a specific order in which the variables are arranged and allowed to immediately affect each other[40]. For triangular factorisation, the assumptions are, in addition to that Γ is diagonal and that instantaneous restrictions are employed, that the scheme also imposes a restriction of unit contemporaneous responses of variables to their own shocks. In other words, that D_0^{-1} is lower triangular, and its main diagonal is made of ones (Dieppe et al., 2018; Kilian & Lütkepohl, 2017). Note that the Cholevski decomposition is also a popular way to orthogonalize the errors, but it relies on the assumption that the reduced form covariance matrix is normalised such that $E(e_t e_t') \equiv \Sigma = I_K$, meaning the variance of all structural shocks is normalised to unity. Indeed, under this assumption, it is implied that all structural shocks have a unit variance, even though their actual variances may deviate from unity. As different shocks may exhibit large variations in magnitude, a straightforward approach to addressing this issue is to employ triangular factorisation (Dieppe et al., 2018).

As mentioned, it is the inverse of the instantaneous coefficient D_0^{-1} and the SVAR models error terms variance covariance matrix Γ that allows us to recover the structural innovations from the reduced form VAR residuals. Defining $D_0^{-1} = D$, and following Hamilton (2020), the proof can be expressed as below:

$$\begin{aligned}\Sigma &= E(e_t e_t') = E(D\eta_t\eta_t' D') = DE(\eta_t\eta_t')D' \\ &= D\Gamma D'.\end{aligned} \tag{4}$$

In practice, to be able to identify Γ and Σ from (4), n^2 constraints are needed, where n is the number of variables in the model. As the structural covariance matrix Γ is diagonal, the zeros below the diagonal generate $n*(n-1)/2$ of the n^2 needed constraints. D, being lower triangular with zeros above the diagonal and ones across, makes up the other $n*(n-1)/2$ constraints needed. The system of nonlinear equations in the error term can be then solved for the unknown parameters in D as the number of unknown parameters does not exceed the number of independent equations (Kilian & Lütkepohl, 2017; Dieppe et al., 2018). Importantly, it is the order of the variables that steers what the zeros imply for the model and its interpretation. It is a way of imposing restrictions on selected elements, as the specific ordering equals exclusion restrictions, eliminating the possibility for some variables to impact the other's instantaneously.

[39] See for example Agrippino & Ricco (2018), Enders (2015), Kilian & Lütkepohl (2017), Lütkepohl (2005).
[40] Note that this is solely for instantaneous effects.

5.3.2 Identification of the triangular matrix

A key step in VAR analysis aimed to analyse the effect of a certain monetary policy is to credibly identify the monetary policy shock. While recursively identified models are popular ways to do this, it is only appropriate if it can be justified on economic grounds. The reason is that the forced order of the variables is a mechanical solution, reflecting a casual chain imposed by the econometrician and not by the data (Kilian & Lütkepohl, 2017). The ordering in the identification scheme should be credible from a theoretical rationale, but the narrative of the movements should also reasonable from an economist perspective (Uhlig, 2005)[41]. Successful and credible identification should therefore match conventional wisdom as well as economic theory. As the order of the variables is crucial, and must be credibly argued for by using, for instance, empirical or theoretical knowledge (Kilian & Lütkepohl, 2017), the next section is dedicated to defend the employed order of the thesis.

Formally, the following recursive order of the baseline model variables is used: foreign interest rate (i^*) inflation (P), GDP (Y), quantitative easing (QE), Term spread (T) and real exchange rate (RER). In Table 1, the ordering of the variables along with the zeros above the main diagonal will specify which variables that are allowed to impact each other instantaneously, and which ones that are not.

Table 1: Structural Decomposition Matrix

	Foreign rate	CPIF	GDP	RBQE	Term spread	RER
Foreign rate	1	0	0	0	0	0
CPIF	d_{21}	1	0	0	0	0
GDP	d_{31}	d_{32}	1	0	0	0
RBQE	d_{41}	d_{42}	d_{43}	1	0	0
Term spread	d_{51}	d_{52}	d_{53}	d_{54}	1	0
RER	d_{61}	d_{62}	d_{63}	d_{64}	d_{65}	1

Following the structural VAR model applied in Bjørnland (2009), foreign interest rate is placed first in the ordering, reflecting that it will solely be affected by exogenous foreign interest rate policy: arguably an unconventional assumption for a small open economy[42]. It is also unconventional to model this foreign interest rate as exogenous (e.g. in line with seminal paper Cushman & Zhao, 1997 or Di Casola & Stockhammar, 2022) as the foreign interest rate of the Euro area or the US are arguably variables which cannot be set or influenced within Sweden. To have (P) and (Y) as the next variables in the ordering, it is necessary to assume that the government is able to observe price level (P) and output (Y) when choosing the policy instrument (QE). This makes the identification assumption that output and prices react with a lag to monetary policy and that the policy instrument does not instantaneously react to any other variables than inflation and output (and the foreign interest rate). Placing the slower moving macroeconomic variables before the policy instrument is framed as a benchmark order in VAR literature[43]. While it is commonly critiqued that the price level and output are typically only known with a delay, we agree with the counterargument of Christiano et al., (1999) on that the a central bank would have enough available data and indicators of aggregate economic activity along with a substantial amount of information about the price level upon making monetary policy decisions[44]. That monetary policy has a delayed impact on domestic macroeconomic variables is also in line with the theoretical set-up in the seminal paper of Svensson (1997), where monetary policy affects output and price level with a one period lag. On the ordering of inflation before output, we follow Weale & Wieladek (2016) which Di Casola & Stockhammar (2022) along with Wieladek & Pascual (2016) also has followed[45].

The policy instrument, quantitative easing (QE), is placed fourth in the ordering, before the term spread (T) and the real exchange rate (RER), making the identifying assumption that the term spread along with the real exchange rate are

[41] For example, it can be assumed to be trivial that a contraction in monetary policy should increase the interest rate, lower the price level and reduce output.

[42] When modelling a small open economy, Cushman & Zha's (1997) seminal paper order all foreign variables first in a recursive order, which more recent papers such as Bjørnland (2009) also adopts.

[43] See the three benchmark models in Chapter 2 "Monetary policy shocks: What have we learned and to what end?" in Handbook of Macroeconomics (Christiano et al., 1999).

[44] This is also the order of the US economy VAR as in Eichenbaum and Evans (1995) as well as the small open economy in Cushman & Zhao (1997). With indicators of aggregate economic activity we refer to high frequency data and insights such as detailed forecasts.

[45] As it is arguably equally reasonable to order output (Y) before inflation (P), we also tested that recursive order decomposition. The results obtained little to no variation when the order was interchanged.

impacted instantaneously by quantitative easing. In short, this is as economic theory suggests that asset purchases immediately can impact the interest rate (see full discussion in subsection 2.3 on transmissions channels of QE) Lastly, as standard VAR literature suggests, the exchange rate is placed last (such as in Eichenbaum and Evans, 1995; Faust & Rogers, 2003; Scholl & Uhlig, 2008). This is also in line with theoretical and empirical evidence of exchange rate determination, where rich frameworks (here: currency modelled with highest amount of instantaneous effects) are recommended to capture movements in the exchange rate (Obstfeld & Rogoff, 1996).

A remark on the rationale for the chosen ordering above is that it is derived from economic theory and empirical evidence. While we claim rationality of the order, it is important to acknowledge that this order and the justification of it, is not necessarily the optimal approach, and opinions on its appropriateness may vary. The insights we base the ordering on are derived from assumptions we've made on information delays, physical constraints, institutional knowledge and market structure, which may not hold in reality. We test one alternative recursive order, where the arguably equally convincing order of GDP before inflation did not yield any variation in the results. To conduct further robustness analysis with more alternative orderings can however decrease the credibility of the current order. This is as we then claim to believe in the proposed order, but also propose multiple other orderings. Evidently, the credibility of the current ordering decreases if we propose other orderings which we argue may be equally justifiable. (Kilian & Lütkepohl, 2017).

5.4 Impulse response function

Sims (1980) asserts that within a VAR framework, the most effective method for analysis and for drawing meaningful economic interpretations is to study a system's response to random shocks. In essence, the aim of an impulse response function (IRF) analysis is most often to recover structural innovations (shocks) in the error term via economic theory such that the impulse response functions are interpretable as the response of a structural economic shock (Enders, 2015). These shocks are artificial and not created out of past values in the variables, resulting in an unexpected or new positive residual of one unit in each equation of the system (Sims, 1980). If one variable in the system responds to an impulse in another variable, we may characterise the latter as causally related to the former. Hence, to study this type of behavioural causality between the variables, the aim is to trace the effect of an exogenous shock (Lütkepohl, 2005).

It is here the issues with potential correlation in the reduced form model's residual covariance matrix, Σ, becomes evident. Particularly, the impulses in different variables can only be economically interpreted if they are assumed to be independent. If the reduced form shocks in each of the variables are not independent, i.e. if there is correlation in the reduced form variance covariance matrix, it signifies that the error terms encompasses all the factors and variables that are not explicitly part of the y-variables set, obscuring the relationship between the variables (Lütkepohl, 2005)[46]. As such, in VAR models, the main challenge often becomes to disentangle the structural shocks, η_t, from the reduced form shocks, e_t, such that the structural shocks can be recovered from the reduced form estimates. As discussed above in subsection 5.3, the reduced form errors in this thesis is made uncorrelated through orthogonalization by triangular factorisation.

An IRF analysis begins by assuming that the reduced form model is in its long-run equilibrium. Subsequently, a one period shock is introduced via the error term and this shock is then transmitted to other variables over time through the estimated coefficients (Dieppe et al., 2018). In the reduced form context, the impact of a shock, e_t, on the endogenous variables contained in the y_t vector in h periods ahead, can be written as:

$$\frac{\partial y_{t+h}}{\partial e_t} = \Psi_h. \tag{5}$$

Where Ψ_h matrix represents the impulse response functions of the reduced form model, tracing the responses over time of each variable y_t to each structural shock e_t. Since the error terms in the reduced form are allowed to be correlated, the IRF estimation has to be translated to the structural model's (SVAR), using matrix D to obtain the economically interpretable results. For the first time period, $t = 0$, the coefficients are captured by the instantaneous matrix:

$$\widetilde{\Psi}_0 \equiv D. \tag{6}$$

Subsequent time periods, t= 1, 2,..., 40, the SVAR IRF is calculated by:

$$\widetilde{\Psi}_t \equiv \Psi_t D. \tag{7}$$

[46]In other words, because of the potential correlation in the error terms, it is difficult to isolate the effects of a unit shock in one equation. This is since other error terms in the model inherently will react to the shock, resulting in shocks in several equations at the same time.

When D is estimated, it follows from (6) that the coefficients represents the instantaneous dynamics, capturing the impact of a shock in first time period, that is when t=0. Visually, this means that the result of a unit shock in the system for period 0, is shown in the intercepts of the IRF function. In the subsequent periods, the structure obtained in the estimated D matrix is used to transform the reduced form estimates to economically interpretable ones, $\widetilde{\Psi}_t$. In other words, this means that the recursive ordering of the triangular factorisation only constrains the IRFs in the first time period.

The credibility intervals of the Bayesian impulse response function are derived by choosing quarterlies of the posterior distribution (Dieppe et al., 2018). In a Bayesian framework, the credibility intervals reflect the posterior distribution by delivering a span of plausible estimates instead of just one point estimate. More specifically, a Bayesian credibility interval specifies where the probability mass of the posterior distribution is concentrated (Kilian & Lütkepohl, 2017). In line with the default settings in the BEAR toolbox (Dieppe et al., 2018) and previous research (See for instance Di Casola & Stockhammar, 2022 and Weale & Wieladek, 2016), this is set to 68%.

5.5 Estimation of the model

The following section will describe the process of esimating the model using Minnesota priors.

5.5.1 Minnesota priors

Proposed by Litterman (1986), the Minnesota priors (or Litterman prior) can be referred to as specific Gaussian priors of the VAR parameters[47]. The estimator of this prior imposes that the reasonable behaviour of an economic variable is a random walk around an unknown, deterministic, value. In other words, it shrinks the reduced form parameter estimates to a multivariate random walk model (Kilian & Lütkepohl, 2017; Litterman, 1986). Note that the Minnesota priors are not solely motivated by economic theory but also by being a computationally convenient prior that captures a testable hypotheses about how the specific time series behave. The fundamental idea behind this is that the behavior of the majority of macroeconomic variables can be effectively modeled as a random walk with drift (Agrippino & Ricco, 2018). The choice of Minnesota priors are also shared with other researchers using the similar time series (see for example Di Casola & Stockhammar, 2022).[48]

By using Minnesota priors, the reduced form model's variance-covariance matrix, Σ, is assumed to be known and diagonal, which reduces the analysis to only determine the vector of parameters of the model, that is β. Following equation (3) it is the likelihood function for the data and a prior distribution that is needed. Starting with the former, following Dieppe et al., (2018), the likelihood function can be written as:

$$f(y \mid \beta \,, \Sigma_e) \propto exp[-\frac{1}{2}(y - X\beta)'\Sigma_e^{-1}(y - X\beta)]. \tag{8}$$

Continuing with the prior distribution, it is assumed to follow a multivariate normal distribution with mean β_0 and covariance matrix Ω_0, it implies then that the prior distribution can be formalised as:

$$\pi(\beta) \propto exp[-1/2(\beta - \beta_0)'\Omega_0^{-1}(\beta - \beta_0)]. \tag{9}$$

By using equation (8) and (9), equation (3) can be rewritten and later simplified in the following ways:

$$\pi(\beta \mid y) \propto exp[-1/2(\beta - \overline{\beta})'\overline{\Omega}^{-1})(\beta - \overline{\beta})], \tag{10}$$

$$\overline{\Omega} = [\Omega_0^{-1} + \Sigma^{-1} \otimes {}^{49} X'X]^{-1}, \tag{11}$$

$$\overline{\beta} = \overline{\Omega}[\Omega_0^{-1}\beta_0 + (\Sigma^{-1} \otimes X')y]. \tag{12}$$

Hence, by adopting the Minnesota priors, this implies that the posterior of β is given by:

$$\pi(\beta \mid y) \sim \mathcal{N}(\overline{\beta}, \overline{\Omega}). \tag{13}$$

[47] In macroeconomic applied work, some kind of Gaussian priors are the most common (Kilian & Lütkepohl, 2017).

[48] To test the robustness of this prior, the baseline model is re-estimated using Independent Normal Wishart and the Normal-diffuse prior. The Bayesian performance metric, Deviation Information Criteria (DIC) and Bayes factor, indicates that the baseline model with Minnesota prior is superior.

[49] $\otimes$ denotes the Kronecker product.

In this context, $\overline{\beta}$ are the coefficients of the model and $\overline{\Omega}$ is the estimated variance covariance matrix[50]. This posterior distribution of β is then used to derive the point estimates and their credibility intervals, using the median as point estimate. The impulse response function can be calculated using several different methods, and by the BEAR toolbox, IRFs of the reduced form model is estimated by obtaining the posterior predictive distribution and adopting a repeating algorithm based on Gibbs sampler[51].

[50]To incorporate that the foreign variable is exogenous, two minor adjustments of the β_0 and Ω_0 are made. β_0 is altered by setting all prior means to zero for all coefficients that effects foreign interest rates, except for foreign rates lagged variables. The Minnesota variance matrix Ω_0 is manipulated by multiplying the exogenous variance by $(\lambda_5)^2$ (Dieppe et al., 2018). In line with Di Casola & Stockhammar, (2022), the following hyperparameters are chosen: $\lambda_1 = 0.2$, $\lambda_2 = 0.5$, $\lambda_3 = 1$, $\lambda_4 = 100$, $\lambda_5 = 0.001$, and AR=0.9. These hyperparameters determine the prior distribution of the coefficients of interest and they are introduced in the Ω_0 matrix (Dieppe et al., 2018).

[51]The Gibbs algorithm is described in the technical appendix, subsection A.10.

6 Results

In the results section, we first provide an analysis of the response of a shock in quantitative easing on the real exchange. Second, the responses of the exchange rate following a shock in the rest of the model's variables are presented, along with a rationalisation of the results they yield. Lastly, the three possible transmission channels of quantitative easing are tested if they transmit to the exchange rate.

6.1 IRF analysis

In an impulse response analysis, the aim is to study behavioural causality between the variables in the system, tracing the effects of an exogenous shock. In simple terms, these functions are retrieved by pairing the structure obtained by the triangular decomposition with the estimated VAR-coefficients. As such, the IRF's can be economically interpretable as the dynamic response of a shock. For the purpose of this analysis, we focus exclusively on the effects on the real exchange rate variable. This includes an analysis of both the instantaneous and full period impacts to understand the structural form behind the impulse response functions as well as the longer term impacts. Conveniently, the instantaneous magnitudes depicted in the structural decomposition matrix, D, is also the intercept of the corresponding IRF function, allowing us to assess the immediate impact without diverting attention by providing the entire matrix.[52]

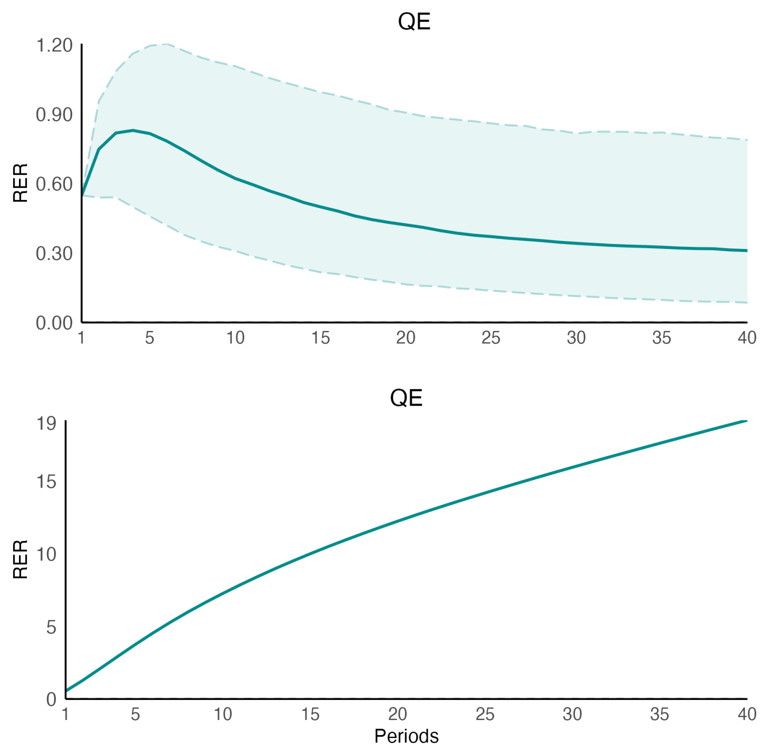

Figure 4: Impulse response function of a unit shock in quantitative easing on the real exchange rate (top graph) and the cumulative representation (lower graph). Cumulative impact is calculated by taking the sum of the median responses (line in top graph). Results are computed using the baseline model with triangular factorisation and 2000 draws with 500 burn-ins. Y-axis displays the responses in percentage terms while the dashed line represents the 68% credibility intervals.

The estimated response of the exchange rate to a shock in quantitative easing is immediately positive with a peak effect around 5 months, which later tapers off closer to zero as the periods increase, giving it a hump-shape. For all 40 months, the credibility intervals are not containing zero, indicating a significant longer run impact of QE may be present for the exchange rate. The dynamic response of a shock in quantitative easing is thus seen to immediately induce the real exchange rate to depreciate, particularly upon impact, and the effect seems to persist even in the longer run. While the magnitude is

[52] The interested reader can find the VAR-coefficients, the full structural decomposition matrix, D, and the variance covariance matrix (depicting the variance of the shocks) in the appendix.

not substantial, the structural innovations in the error term of QE can definitely be associated with a significant impulse to the system, reflecting a depreciating reaction of the real exchange rate. Quantifying the response in the real exchange rate of a shock in QE throughout all periods, the cumulative response indicates a 19% depreciation from the baseline over the total of 40 months. While the model itself is novel in a QE-setting, the direction of the effect is in line with previous literature (see review of the performance of quantitative easing by Johnson et al., 2020) and these results are thus in one aspect a confirmation of the model's effectiveness to capture economic relationships.[53]

In regards to the magnitude, the only other known paper applying a BVAR on the Swedish economy, Di Casola & Stockhammar, (2022) can secure a significant effect only for the first 5 periods[54], whilst this model captures a depreciation for all 40 months[55]. One explanation of this persistent effect is that we particularly aim to model the exchange rate and have provided a model which to a greater extent captures this currency depreciation. More specifically, it is the Fed-component of the foreign interest rate index which drives these effects. When the foreign rate index is fully weighted with the ECB rate, the depreciating magnitude is halved, and the effect only persistent for the first few periods, similar to in Di Casola & Stockhammar, who also include a fully weighted ECB policy measure. More comments on this can be found in the sections of robustness and limitations. Also note that the variance covariance matrix, representing the variance of the structural shocks, indicate a high variance (0.913) of RER, suggesting the variance of the real exchange rate shocks are subject to significant variability and potentially unpredictable fluctuations. This aligns with both theoretical and empirical evidence regarding the exchange rate (See section 3 for further details), as well as the substantial instantaneous magnitudes found in some of the shocks.

To further analyse the exchange rate, the reactions of the real exchange rate to a shock in each of the model's variables are included below. The objective of this analysis is to rationalise the response functions in an attempt to understand the dynamics of the real exchange rate and investigate the economy which is generated in this model. As familiar, the order of the variables is crucial. In line with the decomposition, the foreign rate is allowed to instantaneously impact all the other variables in the system whereas the real exchange rate is not allowed to impact any other variable instantaneously. Note that the exogenous assumption ensures that the domestic variables are not allowed to impact the foreign rate, in any period. Accordingly, the IRF's represent the total effect of an artificial shock in a given variable, meaning both the direct effect on a variable, but also the indirect effect it has through other variables in the system. Because of this, the total direction and magnitude might not always be in line with foundational economic theory.

[53] The focus of the thesis is not specifically to trace the effects of QE throughout the entire macroeconomy (See Di Casola & Stockhammar, 2022, if interested), but these results are still produced and presented as a robustness check as they also can be seen as a justification of the model's capacity to capture realistic macroeconomic dynamics. See subsection 8.1.

[54] See Figure 1 of their paper.

[55] The effect on the real exchange rate is significant for at least 30 time periods when credibility intervals are increased to 90%, indicating a robust effect on the exchange rate.

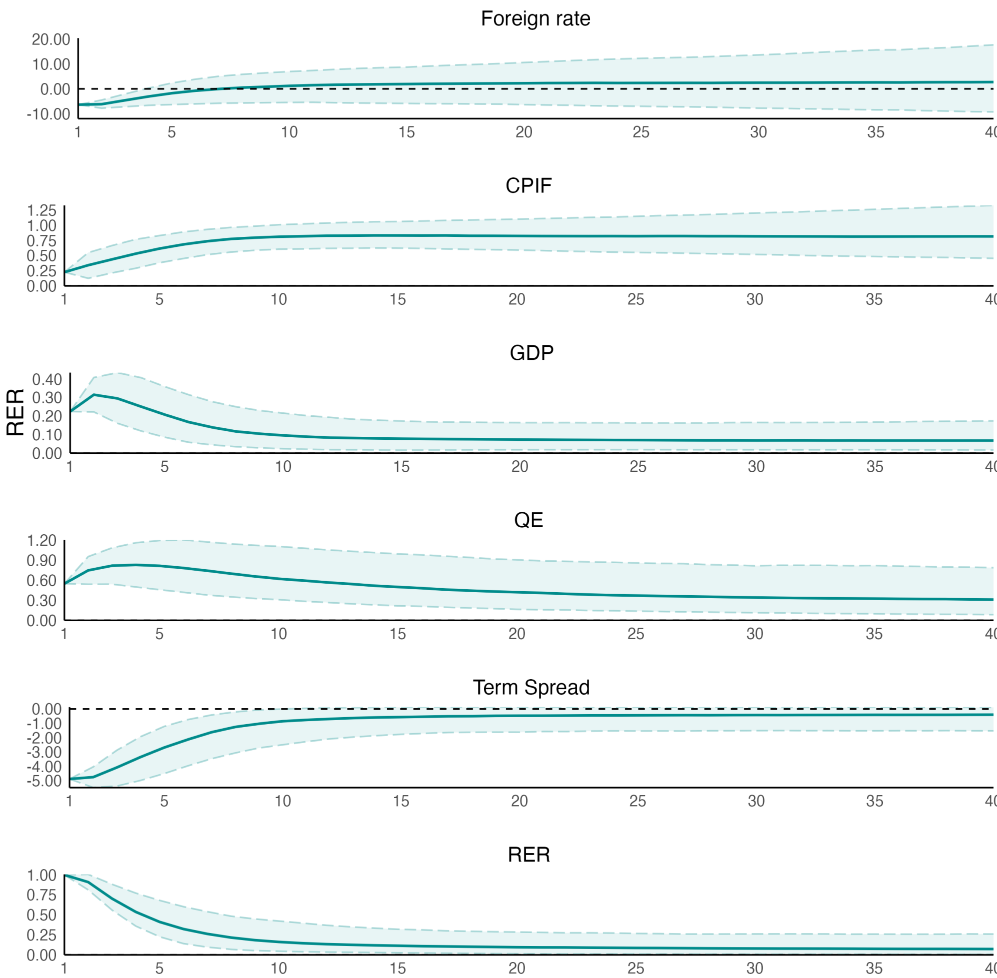

Figure 5: Impulse response functions of the responses in the real exchange rate of a one unit shock in each of the system's variables. Solid line represents the median response, and the dashed lines indicate the 68% credibility intervals. Results are computed using the baseline model with triangular factorisation and 2000 draws with 500 burn-ins. Y-axis displays the responses in percentage terms while the dashed line represents the 68% credibility intervals.

If the foreign rate is shocked, real exchange rate appreciates instantaneously with a relatively large magnitude (-6,365). While the results can seem unexpected at first glance, recall that it is the real exchange rate that is impacted. The real exchange rate is as familiar defined as $RER = ER * \frac{P^*}{P}$, where ER is the nominal exchange rate. To rationalise the findings of a large instantaneous appreciation, imagine that the foreign interest rate is raised as a response to high foreign inflation. In line with UIP, this makes the Swedish nominal currency weaker, and as such, inflation is imported through higher prices, both because of a higher foreign inflation but also because of a weak nominal exchange rate. Ultimately, the domestic price level increases more than the foreign one (and more than the impact of the nominal exchange rate), making the real exchange rate appreciate. Looking at the impact over the full 40 months, this effect is only significant in the first five months, reflecting that a shock in the foreign interest translates to a rather short lived response in the exchange rate. The instantaneous magnitude is largest among all the variables in the system, reflecting a considerable dependence of the Swedish currency to Euro and US short rate, in line with small open economy fundamentals, but note that the magnitude might also partly be explained by the high variance of the variance covariance matrix.

A shock in inflation would instantaneously depreciate the real exchange rate (0.226). In line with the definition of RER, an increase in domestic inflation can result in a depreciation in the real exchange rate if the nominal exchange rate also depreciates and/or if foreign prices have increased too. Rationalising these results, imagine that the increase in domestic inflation is triggered by expectations of a higher price level abroad. Expectations of higher foreign inflation raises expectations of a foreign rate increase, which would depreciate the domestic nominal currency of our small open economy. In this case, we rationalise that the domestic price level does not increase to the extent that it overpowers the depreciating effect of the nominal exchange rate (unlike the case above) by that it is reasonably the case as we solely have expectations driving the effects.[56] This effect is significant for all 40 months, indicating a longer term impact on the exchange rate after a shock in inflation. Note that the persistence and magnitude substantially decreases if the US rate is excluded in the model.

The exchange rate depreciates instantly when output is shocked (0.225). These results can reflect that an increased output level is a sign of heightened global economic activity, which raises expectations of future inflation and/or actual inflation, which in turn depreciates the nominal exchange rate following the same reasoning as above. The full period IRF reveal that the effect on aggregate is also positive, (arguably) significant throughout, indicating a longer term depreciation of the currency in response to a shock in output.[57] Quantitative easing is estimated in the model to depreciate the exchange rate upon impact (0.549), in line with theory as motivated in subsection 2.3. Lastly, the instantaneous effect of the term spread represents the second largest relationship in magnitude (-4.874), indicating a large initial appreciation of the currency. By the definition of the real exchange rate, this is the case if the increase in the term spread appreciates the nominal currency, in line with conventional theory. The appreciating effect is present for at least 10 months as seen in Figure 5.

6.2 Transmission channels

The reduced form nature of the VAR-model limits us to decompose the impact on the real exchange rate to the contribution of each transmission channel (Wieladek & Pascual, 2016)[58]. Fortunately, further analysis can still be made by identifying variables that we expect to transmit the effects of quantitative easing to the exchange rate and adding them to the baseline model. The idea is to check if variables that we expect to transmit the effects of QE, also impact the exchange rate. Previous studies with VAR-models have done a similar analysis (E.g. Di Casola & Stockhammar, 2022 and Weale & Wieladek, 2016), but not in this two-step process which we propose here. In essence, to complete this analysis, we must first confirm that the transmission variable indeed is impacted by QE and then in a second step check if this variable as well impacts the real exchange rate. If the transmission variable has a significant impact in QE as well as the exchange rate, then we will define it as support for the potential existence of that channel. Note that this two-step analysis is novel in a BVAR-setting to our knowledge. We solely aim to be able to provide support (or not) for the potential existence of these channels. We do not claim to significantly isolate any magnitude of transmission in any of the potential channels.

6.2.1 Signalling channel

Recall, the signalling channel states that the additional information that the central bank conveys about their intentions for the future path of interest rates when performing QE affects market expectations, and as such, transmits to the economy through lower rate expectations. In line with Di Casola & Stockhammar (2022), Wieladek & Pascual (2016) and Weale & Wieladek (2016), we will include interest rate futures as a proxy for interest rate expectations. In Sweden, these are the RIBA futures contracts and can be interpreted as the short-term interest rate expectations as they hold expectations regarding the future policy rates. The hypothesis is that quantitative easing should reduce the interest rate expectations and the lower interest rate expectations should in turn depreciate the exchange rate. If this is the case, then there is support for an existence of a signalling channel to the exchange rate.

[56] Decomposing the shock in the direct and indirect effects, the direct impact of inflation on the real exchange rate is an appreciation, in line with UIP. The depreciating effect of inflation is thus the total effect, which is a result of the effect travelling through GDP, QE and the term spread.

[57] Again, when decomposing the shock to reveal the direct and indirect effects, GDP has a direct appreciating effect on the real exchange rate, in line with UIP.

[58] For instance, a forecast error variance decomposition can be a valuable tool to decompose the contribution of each variable of a shock to the exchange rate. The aim of this section is however to decompose the contributions of a specific shock (QE), which is not possible in this framework.

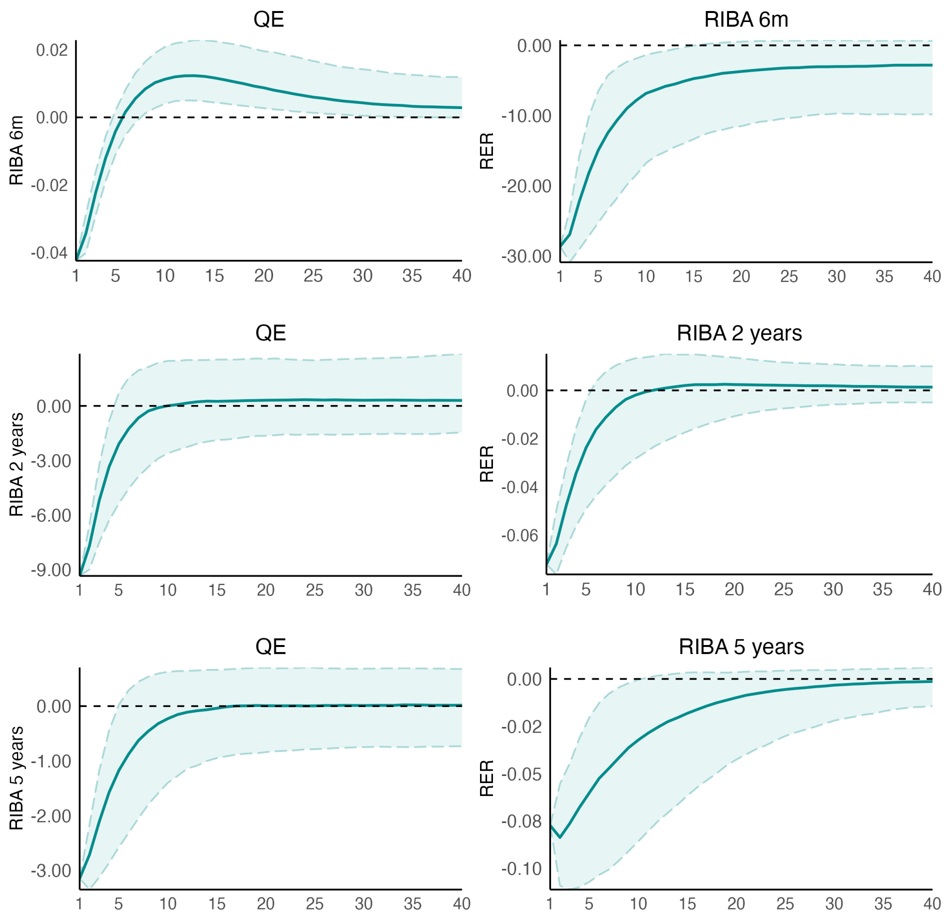

Figure 6: Left panel displays the impact of a one unit shock in quantitative easing on the different maturities of interest rate expectations. Right hand side is the impact of one unit shock in the interest rate expectations, respectively, on the exchange rate. Results are computed with the baseline model, replacing the term spread with the RIBA contracts. Identification is triangular factorisation with 2000 draws with 500 burn-ins. Y-axis displays the responses in percentage terms while the dashed line represents the 68% credibility intervals.

In response to the shock in quantitative easing, interest rate expectations significantly decrease in the short run, reflecting that the market anticipates lower interest rates in the future following a QE announcement. As previous literature notes (e.g. Di Casola & Stockhammar), this is support for the existence of a signalling channel of QE. Extending this analysis by adding the impacts of a shock in interest rate expectations, it becomes clear that these expectations significantly impacts the real exchange rate, at least in the short run (right panel). This result provides support for that QE transmits to the exchange rate through the signalling channel. Providing an attempt of a contextual view of this analysis, this can imply that when the central bank employs quantitative easing as a policy measure, it effectively communicates a credible expectation of a lower future interest rate path. This communication then leads to diminished rate expectations, making the currency less attractive for investors and ultimately resulting in a depreciation of the real exchange rate.

6.2.2 Portfolio channel

The portfolio balance channel proposes that when there are imperfections or frictions in the government bond market, the long-term government bond yield is expected to decrease in response to QE announcement shocks. As asserted in Kirshnamurthy & Vissing-Jorgensen, (2011) this channel can be tested if there is an understanding of which assets investors substitute for when selling the government bonds to the central bank. Accordingly, this requires us to first identify what variables that we expect to be affected if this channel exists. As the portfolio channel theorises that investors would, through a reduce in term premia, reallocate their portfolio to riskier and higher-interest assets in response to lower yields on bonds, we propose to test this channel by analysing the impact of foreign higher-interest assets. Inspired by Di Casola & Stockhammar (2022), along with Weale & Wieladek (2016), an international equity index, S&P 500 is included. Note that the S&P 500 index is in this case seen as a proxy for a common foreign financial asset that Swedish investors turn to[59]. The hypothesis is that if the portfolio channel is one of the channels through which quantitative easing affects the exchange rate, then we would observe a significant impact in the equity index upon a shock in quantitative easing and then a significant effect of a shock in the index on the exchange rate.

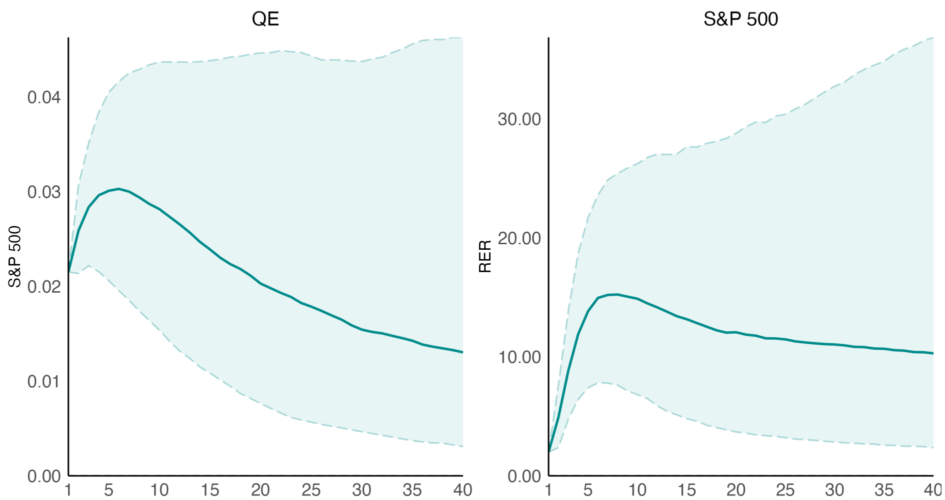

Figure 7: Left panel displays the impact of a one unit shock in quantitative easing on foreign equity prices measured by S&P 500. Right hand side is the impact of one unit shock in the asset variable on the exchange rate. Results are computed with the baseline model, adding the asset as a 6th variable in the model. Identification is triangular factorisation with 2000 draws with 500 burn-ins. Y-axis displays the responses in percentage terms while the dashed line represents the 68% credibility intervals.

In response to a shock in quantitative easing, the equity index is instantly positively affected, reflecting a wealth effect of investors reallocating assets. Equity prices experience a significant persistent effect of a small magnitude, which in itself is evidence of the portfolio channel of QE (See e.g. Weale & Wieladek, 2016). Moreover, a shock in equity prices leads to a significant depreciation of the exchange rate. The effect is positive upon impact and persists throughout all periods. Note that the magnitudes of both shocks however is of high uncertainty, as the credibility intervals are wide. As the asset variable affects QE and in turn significantly impacts the exchange rate, the evidence is consistent with the existence of the portfolio channel. Bringing more context to this analysis, we believe investors could substitute assets in the Swedish long-term bonds with purchases in the foreign stock market when QE brings down the yield on those bonds. Ultimately this drives them to sell the bonds denominated in Swedish kronas and invest abroad, which would depreciate the exchange rate. Note that even though we only claim for the S&P 500 index to be a proxy of foreign financial assets, this analysis requires that we model Swedish fundamentals to be allowed to impact the S&P 500 index, arguably an unconventional assumption for a small economy. When the model is re-estimated with S&P 500 as exogenous, a shock in asset prices still significantly depreciates the Swedish currency. This indicates that an increase in the demand for foreign assets robustly depreciates the krona, although when modelling the index to be exogenous, we cannot confirm a rise in the index can be traced back to Swedish QE.

[59]For this thesis, an extended analysis of the portfolio channel is not done, but it is worth noting that one ideally would also want to test foreign direct investment outflows or the change in Swedish buyers of foreign long-term bonds. To do a valuable analysis of those measures however entails handling various confounding effects and other multifaceted assumptions.

6.2.3 Confidence channel

To test the confidence channel, we follow Weale & Wieladek (2016) along with Wieladek & Pascual (2016) by proxying market uncertainty with the S&P 500 stock market volatility index, VIX. We also add a household confidence index of Swedish household sentiment.[60] In this way, we test the common market's confidence through measures of financial and household (un)certainty. The hypothesis is that the quantitative easing decreases market volatility and increases household confidence through reducing uncertainty in the economy, which in turn affects the exchange rate. To us, a reduced market uncertainty could both translate to a greater risk appetite, leading international investors to Sweden, appreciating the currency, or to a depreciation as Swedish investors feel confident in investing in foreign-currency denominated assets. Like previously, if quantitative easing significantly impacts VIX and the household confidence index and these variables in turn significantly affects the exchange rate, then there is evidence supporting the existence of this channel.

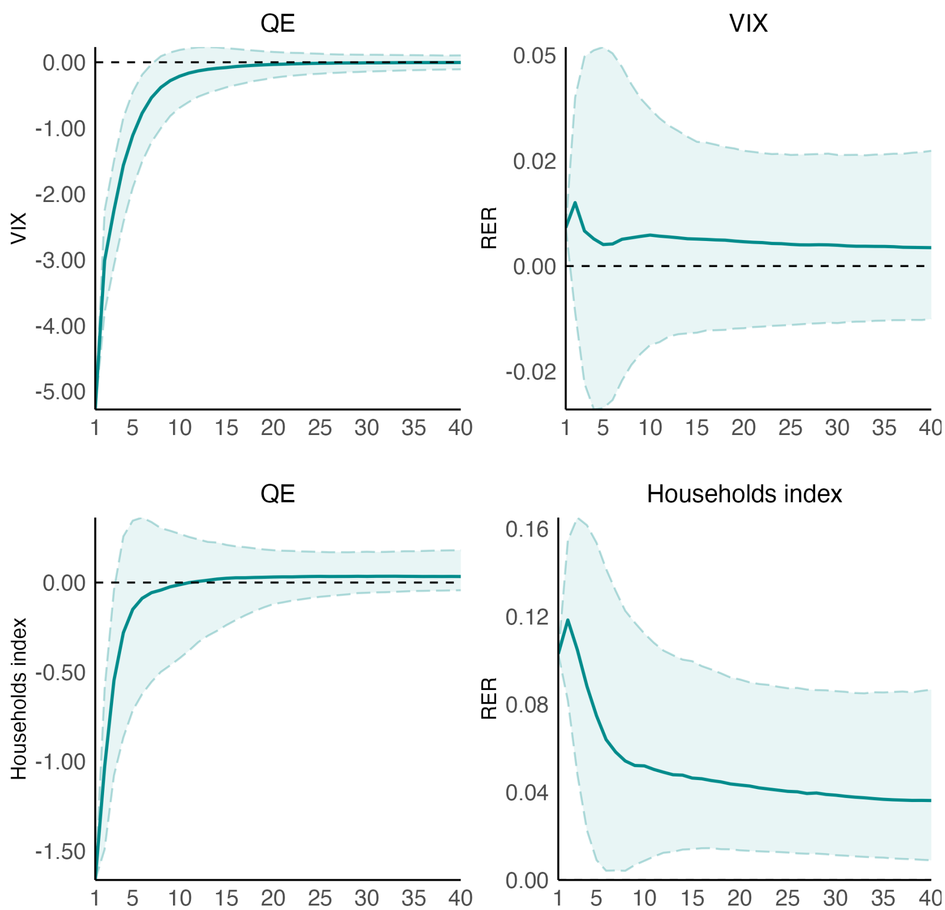

Figure 8: Left graph displays the impact of a one unit shock in quantitative easing on the market volatility index VIX and household's index. Right hand side is the impact of a one unit shock in VIX and households index on the exchange rate, respectively. Results are computed with the baseline model, adding VIX and households confidence index as a 6th variable in the model. Identification is triangular factorisation with 2000 draws with 500 burn-ins. Y-axis displays the responses in percentage terms while the dashed line represents the 68% credibility intervals.

A shock in quantitative easing impacts the financial uncertainty variable negatively, reflecting a decrease in market uncertainty, in line with our previous reasoning. This effect is initially impactful but diminishes after approximately 6-7 months. For the household index, the effect is immediately negative, reflecting a decrease in confidence. It indicates that households may initially have a pessimistic view of the QE announcement, but the effect is only significant for the 2-3 few

[60] The index show how Swedish households view the Swedish economy as well as their private finances. The index includes household's expectations of interest rates and inflation, and future plans for capital purchases and savings.

months. Paring this evidence together with the right panel, representing the shock in these uncertainty measures on the exchange rate, we are not convinced that this channel exists. For VIX, there is support for that quantitative easing transmits to the economy through an effect on financial uncertainty (effect is initially significant), but there is no evidence of that this transmits to the exchange rate. For the household index, we do not feel comfortable with confirming that quantitative easing transmits to the economy through an effect on household uncertainty (significant effect only first few months). While the household index does show to significantly impact the real exchange rate, we cannot confirm the transmission of this through QE. Taken together, the confidence channel seems to not be one of the channels through which QE transmits to the currency. This may not be that surprising either as this channel is only theorised to exist if there are expectations of QE being successfully transmitted throughout the economy. Recall that this channel can only exists if the public expects the Riksbank's QE to successfully integrate in the economy. In this context, it means that the market does not believe the Riksbank's policy will be successful in delivering the promised effects of QE, or that the public are not aware of the (potential) effects a successful QE has.

7 Limitations

VAR based macroeconomic research tends to face a dilemma between a realistic size of the model and accurately estimating its coefficients. One common approach to overcome this is to use shrinkage parameters, for instance, through the use of Bayesian methods and Minnesota priors (Koop & Korobilis, 2010). A common disadvantage with Minnesota priors is however that the variance-covariance matrix, Σ, is assumed to be known, an assumption which can be unrealistic in reality (Koop & Korobilis, 2010; Lütkepohl, 2005). The choice of priors also affect the estimated model's coefficients but in line with Di Casola & Stockhammar (2022), we test for alternative priors, Independent Normal Wishart and Normal Diffuse, and observe that the outcome exhibit little variation. We still find a significant depreciating effect, although with varying persistence and cumulative effects, in line with what is expected when changing priors (see subsection 8.3).

In this thesis, the main approach of analysis is using impulse response functions and although they are (arguably) credibly structured to obtain economically interpretable results, IRF's may still be subject to omitted variable bias. There is therefore a risk that omitted variables may change the behaviour of the dynamic responses (Lütkepohl, 2005). For instance, the shock induced by the quantitative easing has to be exogenous to correctly identify its effects in the economy (Kilian & Lütkepohl, 2017). If the Riksbank's QE decisions are based on a comprehensive analysis of multiple macroeconomic factors (as it is often claimed, see for instance Bernanke & Boivin, 2003), then these considerations end up in the error term if they are not included in the model and will bias the estimated impulse response functions (Stock & Watson, 2001). In the context of this study, the Riksbank probably responds to more variables than those which are endogenised in the model, which means that there is a risk of obtaining biased estimates and incorrect measures (Kilian & Lütkepohl, 2017). In the robustness section, we argue that these effects are probably limited.

Di Casola & Stockhammar (2022), the paper which is followed closely in this thesis, focuses on estimating the impact of foreign and domestic quantitative easing. Between 2015 and 2017, when Sweden implemented QE, the ECB also pursued QE, leading to spillover effects in Sweden as identified by Di Casola & Stockhammar. As this thesis specifically aims to model the Swedish exchange rate and investigate the impacts and transmissions of domestic QE, ECB's quantitative easing is not specifically a variable in the baseline model. As a robustness test we show that when spillovers from ECB are accounted for, a significant depreciating effect is still found, but of a smaller magnitude. The model with ECB asset purchases does not however yield as great model statistics, meaning it doesn't explain the data as well as our baseline model (measured by the DIC value). To account for influences from international macroeconomics, we included a foreign interest rate variable, which we argue encapsulates enough foreign variation for the purpose of the thesis and research question.

Lastly, there is a need to comment on the persistence in effects found in some of the results, e.g. shock of QE in Figure 4 and shock of inflation in Figure 5. Specifically, the variables do not converge back down to zero after the shock, which normally suggests that the variables have shifted to a new long-term equilibrium. While QE has been shown to have large and persistent effect in the economy (See e.g. Johnson et al., 2020) it is not plausible that these persistent results are only observed in some of the variables of the macroeconomic system. As mentioned, the magnitude and persistence in the effects substantially reduces when the Fed rate is removed from the foreign rate index. In general, the impulse response functions excluding the Fed rate exhibit a more pronounced convergence behavior compared to the baseline model, see e.g. Figure A.5. In other words, there are substantially larger effects on the Swedish economy if influence from the US is accounted for in the model. This suggests that the three month interest rate in the US may have a great impact on the Swedish economy, and may therefore be an important decision variable when modelling a small open economy. Di Casola & Stockhammar (2022) included the Fed funds (overnight rate) to make sure their results are not confounded by US monetary policy. Whilst this is a good exercise, we believe our results show that the three month yield, often interpreted as signals of investor sentiment and economic conditions, might be a crucial influence to Swedish macroeconomy, and should be regarded in some way when modelling a small open economy. One alternative explanation for the persistent effects is model misspecification, but as the robustness check show, this is probably not the case.

8 Robustness

8.1 Coherence in the full model responses

In this section, we conduct a saliency check by examining the baseline model's responses to a quantitative easing shock across the entire macroeconomy. As depicted in Figure 9, inflation and GDP is positively affected by a shock in quantitative easing, whilst the term spread is negatively affected, reflecting an increase in aggregate demand and economic activity and a reduction in interest rates[61]. This is indeed what quantitative easing also did in the actual economy (See e.g. Andersson et al., 2022). Note that these results are also in line with previous empirical contributions (e.g. Di Casola & Stockhammar, 2022 and Weale & Wieladek, 2016).

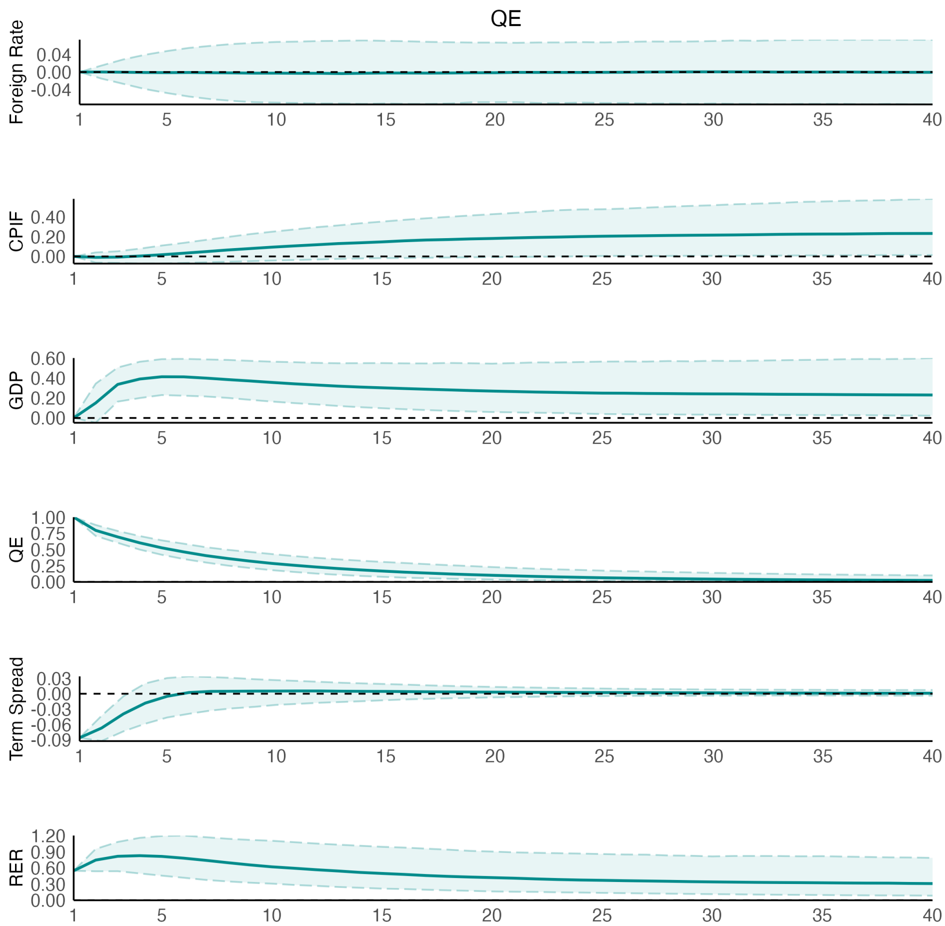

Figure 9: Impulse response functions of a one unit shock in quantitative easing on all the variables in the baseline model. Solid line represents the median response, and the dashed lines indicate the 68% credibility intervals. Results are computed with the BEAR toolbox using the baseline model with triangular factorisation and 2000 draws with 500 burn-ins.Y-axis displays the responses in percentage terms while the dashed line represents the 68% credibility intervals.

8.2 Omitted Variable Bias and Alternative Measures

For the scope of the thesis, the following robustness tests will focus on the impact of quantitative easing on the real exchange rate[62]. The model is limited by the short sample period, but adding additional variables to make sure the results are not confounded by other economic events is still a valuable exercise. Particularly, the domestic asset purchase shock which

[61]Note that there is no impact of foreign interest rate as it is modelled as exogenous.

[62]Note that all the variables in the model are interconnected, e.g. through lag effects. Checking the robustness of one variable is hence one way of defending the entire model, but further analysis of the complete macro variables in the model is not done here.

depreciates the exchange rate may reflect the reaction to a coincident development, either nationally or internationally. Examples of this is the parallel asset purchase programme by the ECB, other domestic policy measures, or commodity price shocks. To explore this, the baseline model is extended to include a variable of ECB asset purchases, the domestic to foreign trade balance, and oil prices[63]. As the results are sensitive to the composition of the foreign interest rate variable, two other proposals of weights are tested. The chosen weights are first the ECB short rate contributing 100% to the foreign interest rate variable and the other is 60% ECB rate and 40% Fed. Additionally, one model with the first difference of the foreign interest rate variable is tested to make sure it is not issues in stationarity that is confounding the persistence in the effects when US is included. Lastly, the model also inherently assumes the market reacts to the announcements of the Riksbank rather than the actual purchases. Thus, it is here checked if the results are robust to this fact, adding actual holdings[64] of the Riksbank, rather than the announcements as a QE variable. Importantly, we expect a lower magnitude in the results when using the holdings as a proxy for QE as we believe the market reacts stronger to announcements than actual purchases.

Table 2: Omitted Variable Bias and Alternative Measures

Model	Peak effect RER	Months with significant effect	Cumulative effect RER
Baseline Model	0.83*	40	19
with ECB asset purchases	0.80*	10	7
with Trade balance	0.88*	40	21
with Oil prices	1.13*	35	14
with i^* 100% ECB	0.60*	6	9
with i^* 60% ECB, 40% Fed	0.73*	40	15
with F.D foreign interest rate	0.69*	40	15
with effective RB purchases	0.24*	40	4

NOTES. Baseline model is extended to check for omitted variable bias. The effects are defined as significant if the 68% credibility intervals do not contain zero, cumulative effect includes both significant and non significant effects. Significant peak effects are denoted by *.

When introducing the ECB asset purchase programme in the model, the peak effect is slightly smaller and the cumulative effect is less than half. The impact also only lasts for 10 months (compared to 40 months in baseline case). As expansionary policy abroad is associated with an appreciation of the krona, (See Di Casola & Stockhammar, 2022), it is not surprising that the depreciating effect is overall lower when adding the ECB assets. Importantly, albeit Euro area spillovers, a deprecating effect is still there.[65] When adding oil prices, trade balance and the two alternative weightings for the foreign interest rate variable, the impact on the real exchange rate does not deviate dramatically from the baseline results, if anything, we find support for that the depreciating effect found in the baseline model may be underestimated. As expected, the effect is smaller when using the Riksbank holdings as a proxy for QE but the effect is still significant for all 40 months. As the baseline model shows a similar effect, but slightly larger, we feel comfortable with that the announcement variable credibly captures the reaction of the market on these announcements. It also highlights the importance of announcements rather than the actual purchases, showing that the Riksbank has a large responsibility for the economic effects when announcing QE.

Overall, the comparison in Table 2 shows that the baseline model effects are robust to additional variables and alternative measures. This conclusion can be drawn as the impact of the exchange rate still shows a significant depreciation, although with varying peak effects and amount of significant months. Note that all results in Table 2 are of higher persistence and magnitude than what previous research has found (Di Casola & Stockhammar, 2022).

[63]The variables are added as the second variable in the model (respectively), allowed to be impacted by the foreign rate but exogenous to the Swedish variables.

[64]Proxy for effective purchases.

[65]Note that when looking at model statistics such as the Deviance Information Criterion (DIC), the baseline model fits the data better, meaning it is a more parsimonious model. This is also the case if we replace the foreign interest rate variable with ECB asset purchases (as the baseline model in Di Casola & Stockhammar, 2022).

8.3 Alternative priors

To test the robustness of using the Minnesota priors, specifically the assumption of a known variance covariance matrix, Σ, the baseline model is re-estimated using the Independent Normal Wishart and the Normal-diffuse prior. Independent Normal-Wishart[66] priors treats Σ as an unknown variable and lets Ω_0 consider an arbitrary structure, while the Normal-diffuse prior relies on an uninformative prior for the variance covariance matrix Σ. Evidently, these differences influence the estimation process and, consequently, the results of the model may change. To compare the models, two Bayesian performance metrics, Bayes factor and the Deviance Information Criteria (DIC), are used. For Bayes factor, Jeffery's guidelines[67] are used to evaluate the support in favor of the baseline model with Minnesota priors, where the strongest support is *Decisive support* (Dieppe et al., 2018). A smaller DIC value indicates a better compromise between data fit and model complexity (Van der Linde, 2005).

As Table 3 reveals, when applicable, there is decisive support in favor of the baseline model with Minnesota priors. This indicates that the baseline model is more likely to be true given the information in the data (Dieppe et al., 2018). The baseline model is also superior in terms of the DIC value, indicating that the Minnesota prior yields a better compromise between data fit and model complexity. Although all models find a depreciation of the real exchange rate, Table 4 reveals that the magnitude and duration of the significant effects is reduced with other priors, indicating that the persistent effects found with in the baseline model is dependent on priors. Additionally, the importance of the Fed rate, argued to be the reason for the persistent effects in the baseline model, does not seem to be dependent on priors. This conclusion can be drawn as the depreciating effects of QE on the exchange rate, independent of the choice of prior, greatly reduces if the Fed rate is excluded, in line with previous reasoning.

Table 3: Alternative Priors

Model prior	Jeffrey's guideline	DIC
Minnesota		83.62
Normal-Wishart with Univariate AR	Decisive support in favor of the model with Minnesota priors	117.85
Normal-Wishart with Identity	Decisive support in favor of the model with Minnesota priors	212.25
Normal-diffuse	Not applicable	123.02

NOTES. Comparison between the baseline model with Minnesota priors along with two alternative priors. Jeffrey's guideline interprets the ratio of two models posterior probabilities, decisive support is the strongest support in favor of the baseline model with Minnesota priors. A small DIC value indicates a better compromise between model fit and complexity.

Table 4: Effect Comparison and Fed Importance

Model	Peak effect RER	Months with significant effect	Cumulative effect RER
Baseline with Minnesota	0.66*	40	16
with i^* 100% ECB	0.60*	6	9
Baseline with Univariate (INW)	0.49*	36	12
with i^* 100% ECB	0.24	0	3
Baseline with Identity (INW)	0.41*	9	9
with i^* 100% ECB	0.47	0	11
Baseline with Normal-diffuse	0.47*	26	12
with i 100% ECB	0.25	0	4

NOTES. Comparison of excluding the Fed rate from the baseline model when using different priors. INW denotes Independent Normal-Wishart. Significant effects are denoted by *, cumulative effect includes both significant and non significant effects.

[66] Two specifications of the Independent Normal-Wishart prior are included in the robustness test, for a thorough review see (Dieppe et al., 2018).

[67] Jeffrey's (1961) propose guidelines to compare models with each other using Bayes factor, the ratio of the two model's marginal likelihood. In Table 3, the baseline model with Minnesota priors is compared with a new model in every row. The results of this calculation is then interpreted by using Jeffrey's guidelines, see Dieppe et al., (2018) for full details. Unfortunately, Bayes factor cannot be calculated using the Normal-diffuse prior.

9 Conclusions

Modelling the macroeconomy is complex. Ideally, one would want a model which can incorporate all relevant variables and enough observations without loss of predictive power. Even if that part is successful, it would still not fit every economy or every research question. In this thesis, the purpose is to model the Swedish real exchange rate, with the aim to provide insights into the quantitative easing period undertaken by the Riksbank from 2015 to 2017. The motivation is that quantitative easing is an unconventional policy measure where there are still unknowns about the effect on the exchange rate, particularly in a small open economy such as Sweden. While it is widely acknowledged that domestic currencies are likely to depreciate in response to quantitative easing, both independent scholars and the Riksbank call for further research to improve the certainty regarding the mechanics, obtain more precise estimates of the magnitude, and identify the transmission channels of this depreciating effect. Among all the considerations that must be accounted for when undertaking this task - navigating the most prudent estimation method for the available data and the choice of relevant variables - we ultimately opted for a Bayesian VAR model, combining the small open economy approach of Bjørnland (2009) and the QE specific model in Di Casola & Stockhammar (2022). To achieve this, we utilize monthly data between 2015 and 2018, incorporating the following variables: foreign short interest rate, inflation, GDP, quantitative easing, term spread and the real exchange rate.

Using impulse response functions, we find that the real exchange rate depreciates throughout all 40 months in response to quantitative easing. This persistent result is partly due to the inclusion of the Fed rate in the foreign interest rate variable, suggesting that the US short-term sentiment has a considerable effect on Swedish economy. In fact, even when accounting for spillover effects from the ECB's quantitative easing programme, this model reveal a stronger depreciation than previous Swedish BVAR research has shown (Di Casola & Stockhammar, 2022). The depreciation is also robust to various other potential omitted variables and priors, suggesting the Riksbank's QE may have had greater consequences for the domestic exchange rate than initially thought. The results also reveal it is the announcement and not the effective purchases that affect the market the most, evidently underlining the responsibility the Riksbank has when announcing policy measures. To our knowledge, this is the first paper to analyse through which transmission channels QE depreciates the exchange rate in Sweden. By employing a two-step approach, we find support of a signalling and a portfolio channel transmission to the domestic currency. The reasoning is that quantitative easing brings down interest rate expectations and encourages speculators to invest in foreign currency denominated assets, which depreciates the currency. No support for the confidence channel indicates however that QE did not affect the exchange rate through increased confidence in the common market. Overall, our results indicate that the unconventional policy measure quantitative easing may have larger effects on the economy than previously thought.

Given the significance of the exchange rate in a small open economy like Sweden, we think conducting additional empirical research on how the currency responds to unconventional monetary policy is a valuable exercise. Particularly, we believe there is room for further exploration of how the US short rate impacts the Swedish macroeconomy and an in-depth analysis of the transmission channels of quantitative easing to the exchange rate. Additionally, as the effects of QE primarily translates to the economy through announcements and not the effective purchases, it would be interesting to explore the effects of a broader or more extensive communication from the Riksbank to the market. As purchasing bonds increases the liabilities of the Riksbank, far-reaching communication that convinces the public of the effects of QE to a greater extent may be a cost-effective alternative in times when unconventional monetary policy is needed, maybe particularly to help avoid unintended consequences. Considering the current economic landscape where Sweden is conducting quantitative tightening (QT) yet experiencing a weak krona, an investigation into how QT influences the exchange rate could be interesting.

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A Appendix

A.1 Variables

Table 5: Full Description of Variables.

Variables	Transformation	Source
GDP	Natural Logarithm	Statistics Sweden
CPIF	Natural Logarithm	Statistics Sweden
Quantitative easing	Natural Logarithm	Di Casola & Stockhammar (2022)
Swedish 3-month maturity Government bond		Riksbank
Swedish 10-month maturity Government bond		Riksbank
Euro area 3-month maturity Government bond		ECB Data portal
US 3-month Treasury bill		Fred Database
Swedish Real Exchange Rate	Natural Logarithm	Di Casola & Stockhammar (2022)
S&P 500	Natural Logarithm	Nasdaq
CBOE Volatility Index (VIX)		Fred Database
Crude Oil Prices: Brent Europe		Fred Database
RIBA contracts		Di Casola & Stockhammar (2022)
ECB Quantitative easning		Di Casola & Stockhammar (2022)
Riksbank effective holdings		Riksbank
Net trade balance Sweden		Statistics Sweden

Table 6: Quantitative Easing Announcements of the Riksbank 2015-2018.

Date	Purchase Announcement
February 2015	SEK 10 billions
March 2015	SEK 30 billions
April 2015	SEK 40-50 billions
July 2015	SEK 45 billions
October 2015	SEK 65 billions
April 2016	SEK 45 billions
December 2016	SEK 30 billions
April 2017	SEK 15 billions

A.2 Baseline model posterior estimates: VAR coefficients

Table 7: Baseline model posterior estimates: VAR coefficients for RER

Variable	Median
Foreign_rate(-1)	1.029
Foreign_rate(-2)	0.248
CPIF(-1)	0.091
CPIF(-2)	0.032
GDP(-1)	0.098
GDP(-2)	-0.013
RBQE(-1)	0.213
RBQE(-2)	-0.019
Term_spread(-1)	-0.260
Term_spread(-2)	-0.212
RER(-1)	0.915
RER(-2)	-0.124
Constant	-4.043

NOTES. Table shows the median values of the estimated coefficients for the real exchange rate in the baseline model. The coefficients represent the historical relationship between the real exchange rate and the first and second lag of the rest of the variables. The magnitudes reveal that the foreign rate and the term spread have the strongest relationship with the exchange rate. The directions are also in line with what is expected from economic theory, e.g., UIP.

A.3 Baseline model posterior estimates: Structural Decomposition Matrix

Table 8: Structural Decomposition Matrix: Posterior Estimates.

	Foreign rate	CPIF	GDP	RBQE	Term spread	RER
Foreign rate	1	0	0	0	0	0
CPIF	-3.290	1	0	0	0	0
GDP	-3.153	0.041	1	0	0	0
QE	-2.040	0.284	0.004	1	0	0
Term spread	0.925	0.096	-0.027	-0.087	1	0
RER	-6.365	0.226	0.225	0.549	-4.874	1

NOTES. The structural decomposition matrix is an economically interpretable extension of the IRF analysis, allowing investigation of the structural form behind the impulse response functions. For the scope of the thesis, the matrix will not be analysed further than the intercept magnitude discussion in the Results, subsection 6.1. Note that the matrix only displays the instantaneous reactions, the full IRF functions are 40 months, see Figure 5. Below, the row values in the matrix are interpreted as the impact upon a shock in the column variables. For instance, the values of the rows in column 1 represents the impact a one unit increase in the foreign rate variable would have on the rest of the variables in the model, where each row represents a different variable. The response in the real exchange rate (RER), row 6, if highlighted in grey.

A.4 Baseline model posterior estimates: Structural Disturbances Covariance Matrix

Table 9: Structural Disturbances Covariance Matrix: Posterior Estimates.

	Foreign rate	CPIF	GDP	QE	Term spread	RER
Foreign rate	0.002	0.000	0.000	0.000	0.000	0.000
CPIF	0.000	0.060	0.000	0.000	0.000	0.000
GDP	0.000	0.000	0.848	0.000	0.000	0.000
QE	0.000	0.000	0.000	0.079	0.000	0.000
Term spread	0.000	0.000	0.000	0.000	0.013	0.000
RER	0.000	0.000	0.000	0.000	0.000	0.913

NOTES. Matrix represents the estimated covariance matrix of the structural disturbances in the baseline model, providing insights into the relationships and uncertainties among the shocks.

A.5 Baseline model without US short rate: Impacts of RER

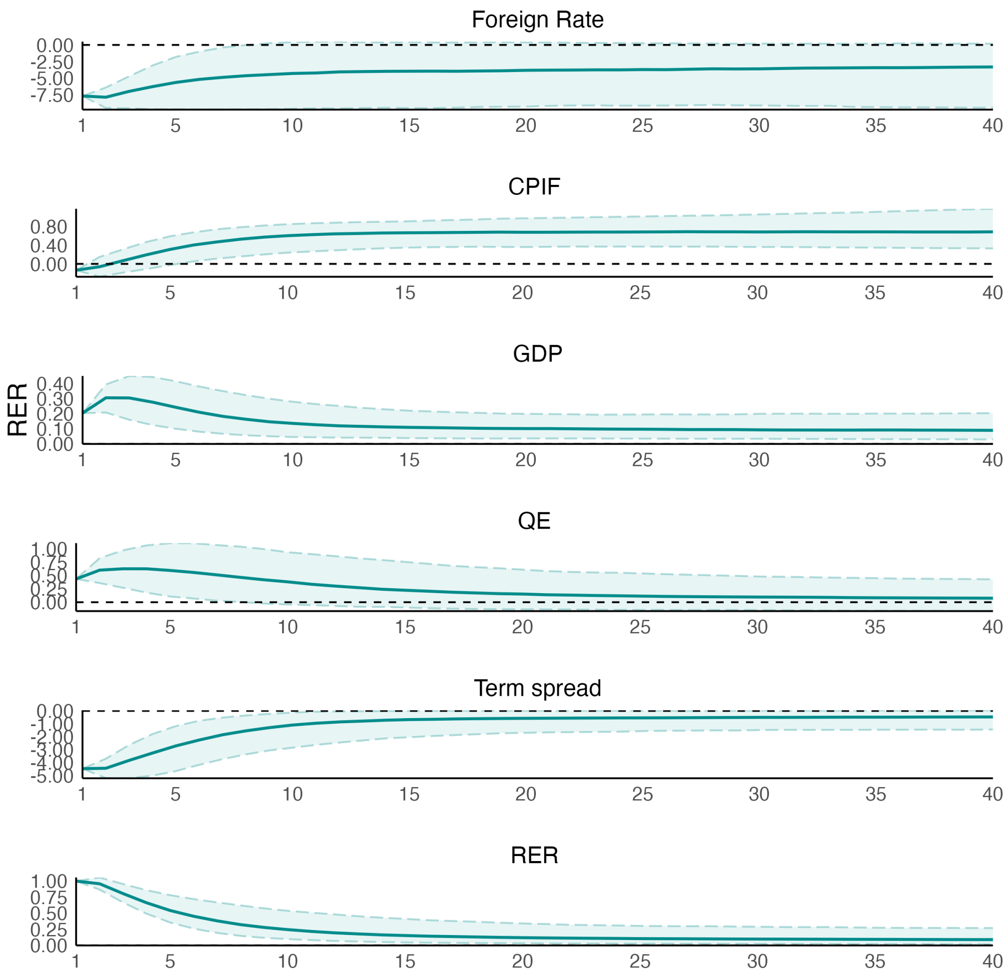

Figure 10: Impulse response function of the response in the real exchange rate of a one unit shock in each of the system's variables. Solid line represents the median response, and the dashed lines indicate the 68% credibility intervals. Results are computed using the BVAR baseline model with triangular factorisation and 2000 draws with 500 burn-ins. Y-axis displays the responses in percentage terms while the dashed line represents the 68% credibility intervals. Foreign rate variable is 100% weighted to the ECB short rate.

A.6 Baseline model without US short rate: Impacts in response to QE

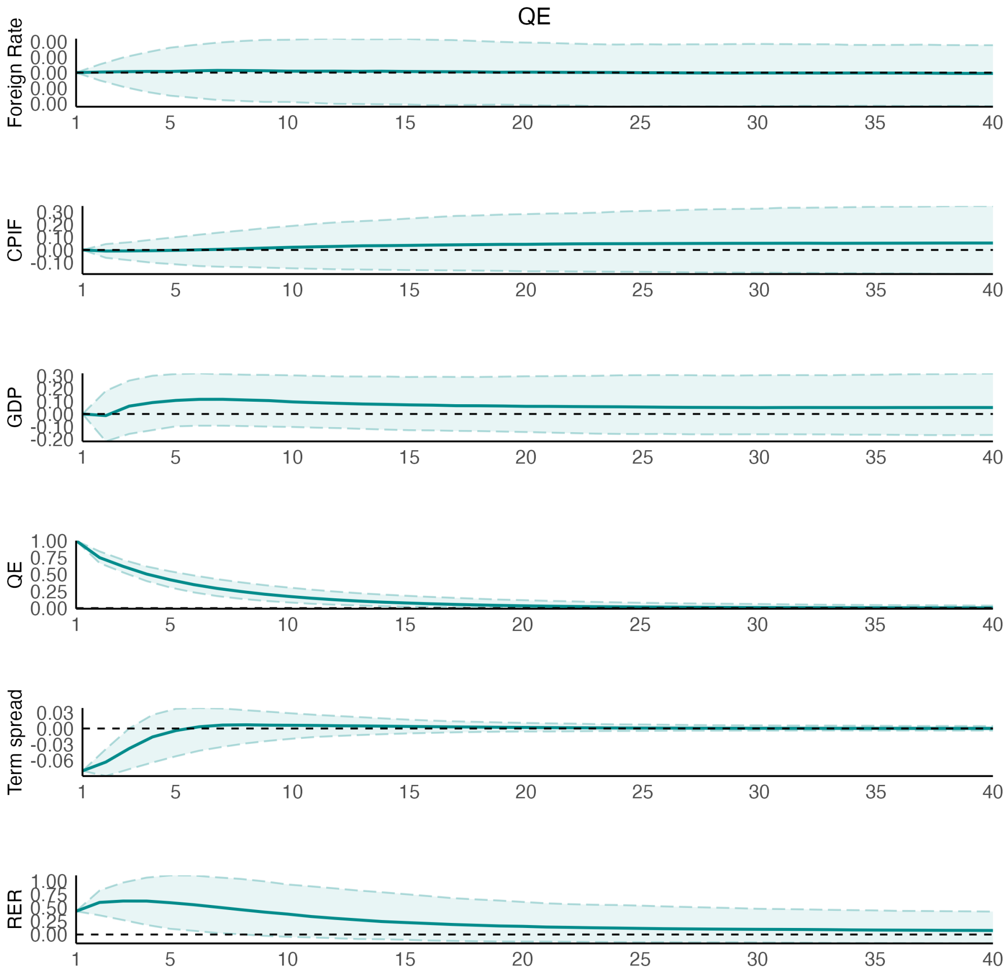

Figure 11: Impulse response functions of a one unit shock in quantitative easing on all the variables in the baseline model. Solid line represents the median response, and the dashed lines indicate the 68% credibility intervals. Results are computed with the BEAR toolbox using the baseline model with triangular factorisation and 2000 draws with 500 burn-ins.Y-axis displays the responses in percentage terms while the dashed line represents the 68% credibility intervals. Foreign rate variable is 100% weighted to the ECB short rate.

A.7 Baseline model without US short rate: Signalling channel

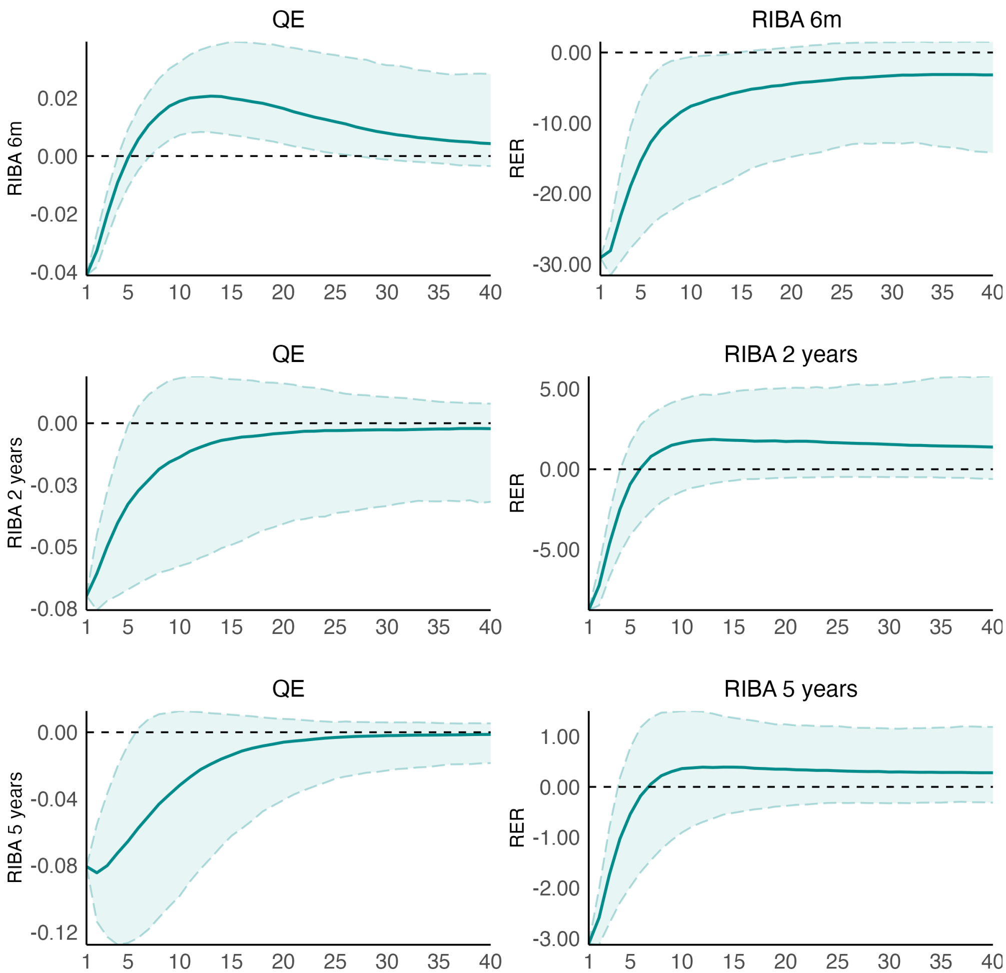

Figure 12: Left panel displays the impact of a one unit shock in quantitative easing on the different maturities of interest rate expectations. Right hand side is the impact of one unit shock in the interest rate expectations, respectively, on the exchange rate. Results are computed with the BVAR baseline model, replacing the term spread with the RIBA contracts. Identification is triangular factorisation with 2000 draws with 500 burn-ins. Y-axis displays the responses in percentage terms while the dashed line represents the 68% credibility intervals. Foreign rate variable is 100% weighted to the ECB short rate.

A.8 Baseline model without US short rate: Portfolio rebalancing channel

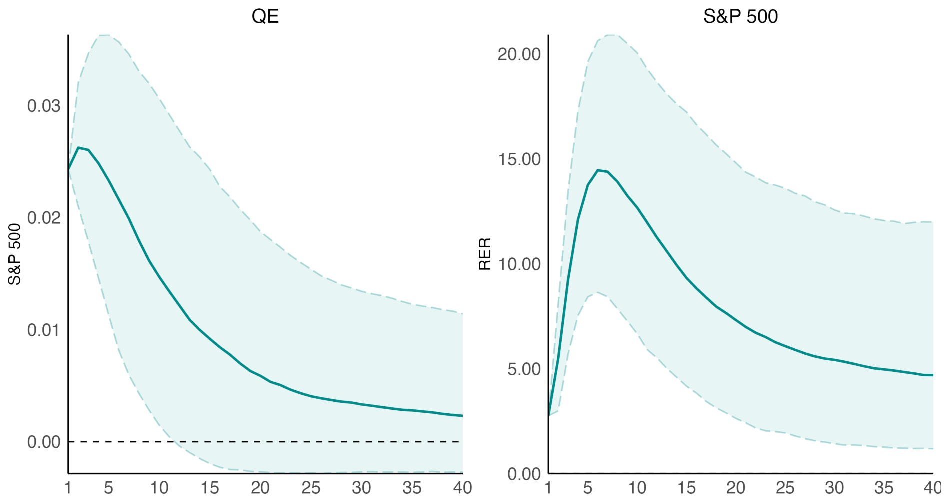

Figure 13: Left panel displays the impact of a one unit shock in quantitative easing on equity prices measured by S&P 500. Right hand side is the impact of one unit shock in the asset variable on the exchange rate. Results are computed with the BVAR baseline model, adding the asset as a 6th variable in the model. Identification is triangular factorisation with 2000 draws with 500 burn-ins. Y-axis displays the responses in percentage terms while the dashed line represents the 68% credibility intervals. Foreign rate variable is 100% weighted to the ECB short rate.

A.9 Baseline model without US short rate: Confidence channel

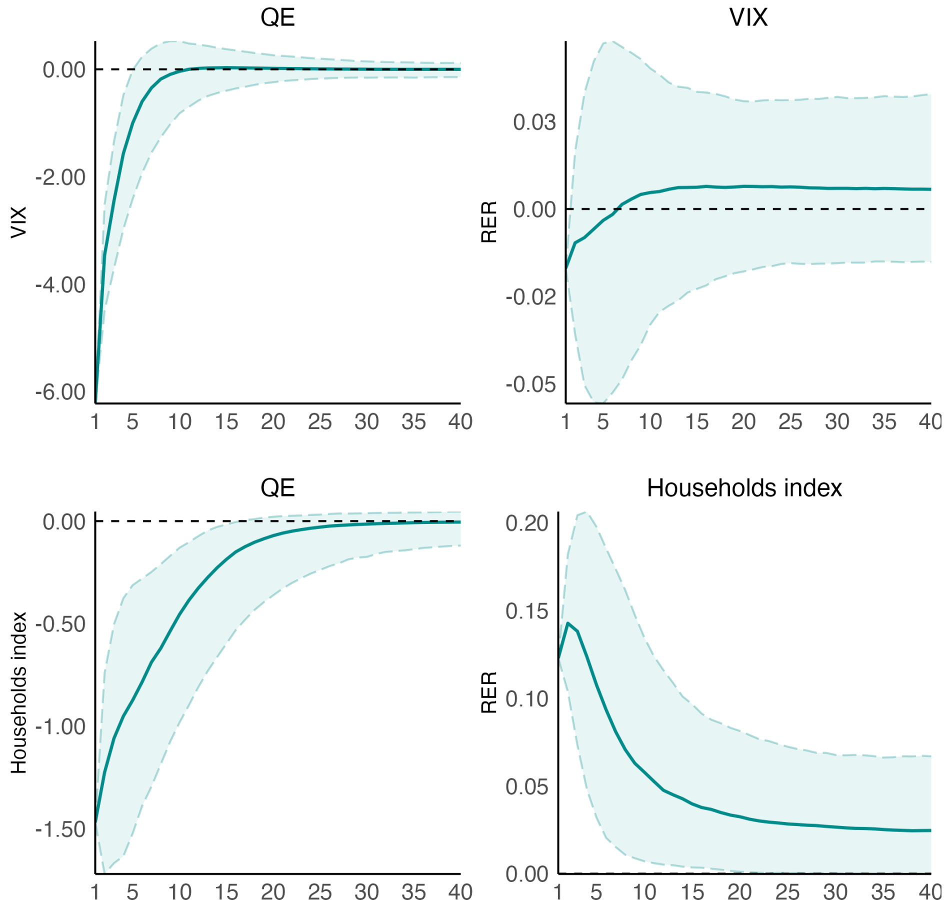

Figure 14: Left graph displays the impact of a one unit shock in quantitative easing on the market volatility index VIX and household's index. Right hand side is the impact of a one unit shock in VIX and households index on the exchange rate, respectively. Results are computed with the BVAR baseline model, adding VIX and households confidence index as a 6th variable in the model. Identification is triangular factorisation with 2000 draws with 500 burn-ins. Y-axis displays the responses in percentage terms while the dashed line represents the 68% credibility intervals.

A.10 Technical estimation

For the actual estimation of the model, the Gibbs sampling method is used, with 2000 iterations and 500 burn-ins. By using the Gibbs sampling method it is possible to obtain random draws from the unconditional posterior distribution of the parameters of interest. Essentially, the Gibbs sampling method relies on that iterative samples from the known conditional distribution gradually converges towards the unknown unconditional distribution of the parameters (Dieppe et al., 2018). Following Greenberg (2007), the notations used in the Gibbs sampling algorithm denotes random variables as x. For instance, the parameters in the RVAR model, and the conditional densities from which random draws can be generated from, are denoted by $f(x_i \mid x_{-i})$, where x_{-i} are all the variables in the joint distribution but x_i.

Gibbs algorithm with d blocks:
Step 1: Choose $x_2^{(0)}, ..., x_d^{(0)}$,.

Step 2: Draw,
$x_1^{(1)}$ from $f(x_1 \mid x_2^{(0)}, ..., x_d^{(0)})$,
$x_2^{(1)}$ from $f(x_2 \mid, x_1^{(1)}, x_3^{(0)} ..., x_d^{(0)})$,
.
.
.
$x_d^{(1)}$ from $f(x_d \mid x_1^{(1)}, ..., x_{d-1}^{(1)})$.

Step 3: At the nth iteration draw,

$x_1^{(g)}$ from $f(x_1 \mid x_2^{(g-1)}, ..., x_d^{(g-1)})$,
$x_2^{(g)}$ from $f(x_2 \mid x_1^{(g)}, x_3^{(g-1)} ..., x_d^{(g-1)})$,
.
.
.
$x_d^{(g)}$ from $f(x_d \mid x_1^{(g)}, ..., x_{d-1}^{(g)})$.

Because the Gibbs sampling process initiates from an arbitrary value which then converges to the distribution of interest, the first iterations has to be discarded, or burned-in. In most cases, the only distribution left is the unconditional distribution, which is the basis of the empirical posterior distribution later used. The Gibbs sampler algorithm is flexible because it only requires that the conditional posterior distribution of the model is known. Note, there is a slight difference between how the Gibbs sampling methods are used in the BEAR toolbox calculation. The Gibbs sampling algorithm used for estimating the RVAR model with Minnesota priors is done by fixing the value of Σ, and then at iteration n draw theβ estimate conditioned on Σ with mean and covariance matrix defined in equation (6) and (7) such that $\beta \sim \mathcal{N}(\overline{\beta}, \overline{\Omega})$. This process is then repeated until all iterations are realized. (Dieppe et al., 2018)

The impulse response function of the RVAR model is estimated by obtaining the posterior predictive distribution and adopting a repeating algorithm based on the Gibbs sampler. The posterior predictive distribution takes the following form:

$$f(y_{t+1:t+h} \mid y_t) \tag{14}$$

$f(y_{t+1:t+h} \mid y_t)$ is the distribution of data points from y_{t+1} to y_{t+h}, where h is chosen to be 40 time periods (months), conditioned on the information set y_t. The information set is defined as:

$y_{t-1}, y_{t-2} ... = 0$
$y_{it} = 1$, for $i \in 1, 2...n$ and $y_{i,t} = 0$ for $j \neq i$
$\epsilon_{t+1}, \epsilon_{t+2} ... = 0$
$x_t, x_{t+1}, x_{t+2} ... = 0$

By using this posterior predictive distribution one can fix $i = 1$ and set $y_{i,T} = 1$ and then at iteration n draw β_n from its posterior distribution. Next, one can generate the simulated values recursively by using equation (1), where A_1 and A_2 comes from β_n. The original β_n can then be discarded to attain the draws from the predictive distribution, this is done for all iterations. To generate the impulse response function, repeat the process for $i = 2, ...n$ (Dieppe et al., 2018).

To translate the RVAR estimates into the SVAR estimates, both D_n^{-1} and Γ_n needs to be estimated and the following Gibbs algorithm is used. The $\Sigma_{(n)}$ is drawn at iteration n from its posterior distribution, $\Sigma_{(n)}$ is then used for calculating the Choleski factor (H). From the choleski factor, D_n^{-1} can be obtained directly by dividing each column by its diagonal entry. Once H and D_n^{-1} is known, Γ_n is calculated by using the $D_0^{-1}\Gamma^{1/2} = H$ formulae. The impulse response estimates of our SVAR model is recovered by multiplying the RVAR IRF estimates derived earlier with D_0^{-1}. Note that the first time period SVAR IRF is equal to D_0^{-1}. By repeating this process through all iterations, a sample of independent posterior draws has been computed which can be used for point estimates and credibility intervals. (Dieppe et al., 2018).