Eirik Rønningstad Olsen

An empirical study of monetary policy shocks in Norway

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Supervisor: Knut Anton Mork
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Norwegian University of Science and Technology
Faculty of Economics and Management
Department of Economics

NTNU
Norwegian University of
Science and Technology

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Abstract

This paper aims to investigate the transmission mechanism of monetary policy under inflation targeting regime in Norway with a vector autoregression (VAR). I exploit monetary policy shocks to ensure a causal relationship between the macroeconomic variables. These structural shocks are identified through Cholesky decomposition of the variance/covariance matrix in a reduced form VAR after imposing short run restrictions. The intertemporal relationships are illustrated with impulse responses. I find that a contractionary monetary policy shock lead to a sluggish decrease in production, an immediate appreciation in the exchange rate and a temporary rise in inflation. The results indicate that monetary policy has statistically significant effect on macroeconomic variables.

Abstrakt

Denne artikkelen undersøker effekten av pengepolitikk under inflasjonsstyring i Norge med en vektor-autoregressiv modell (VAR). For å undersøke kausale forhold mellom pengepolitikk og makroøkonomiske variabler, anvender jeg pengepolitiske sjokk. De strukturelle sjokkene er identifisert gjennom Cholesky dekomposisjon av varians/kovariansmatrisen i en VAR definert på redusert form, etter å ha påført kortsiktige restriksjoner. De intertempolare forholdene er illustrert ved hjelp av impulsresponser. Jeg finner at et kontraktivt pengepolitisk sjokk fører til en gradvis nedgang i produksjon, en umiddelbar appresiering av kronekursen og en midlertidig økning i inflasjon. Resultatet indikerer at pengepolitikk har statistisk signifikant effekt på de makroøkonomiske variablene.

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1. Introduction

Monetary policy has been practiced for decades purposely to achieve monetary and financial stability. Maintaining a robust economy with modest fluctuations contributes to sustainable growth and averts depression. For a long time, implementation of monetary policy aimed on a fixed exchange rate, but a gradually change towards inflation targeting was initiated in the late 1990s. The transition became official in March 2001 when a new framework for monetary policy was presented. The annual inflation target was set to 2.5 percent with intention to stabilize the exchange rate, hence employment and output. As a central bank, Norges Bank is mandatory to follow guidelines for the monetary policy given by the government. This is primarily accomplished by adjusting the key policy rate to regulate money supply. However, the effect of monetary policy is debated by numerous macroeconomists. While most of them agree that an increase in interest rate will slow down the economy, there is no consensus to what extent monetary policy influence macroeconomic factors.

Identifying the effects of monetary policy is complicated. Bernanke and Kuttner (2005) stated that households and companies base their consumption, investment, wages and prices on expectations about forthcoming monetary policy, not on today's policy alone. Thus, the economy will continuously adapt depending on its outlook while the interest rate will adjust to the current state of the economy. To get around this simultaneity issue, macroeconomists exploit shocks to analyze the implications of monetary policy. A monetary policy shock is an unexpected change in the interest rate. Since the shock is unexpected the economy will react to it rapidly, which permits for detection of a causal relationship.

There are different ways to extract and measure monetary policy shocks. Most strategies are rooted in an interest rate feedback rule proposed by Taylor (1993). The rule estimates expected interest rate based on inflation and output gap. Thus, deviations from the expected interest rate can be considered as monetary policy shocks. A modification of the rule was implemented by Stock and Watson (2001) who replaced past values with forecasted values. Romer and Romer (2004) took it further and used Federal Reserve's internal forecast from FOMC meetings to eliminate systematic response of future expectations. The similarities between these methods is that they all relies on time series techniques. In this paper the shocks are measured using a vector autoregression (VAR). More specifically, one of the equations in the vector approximate the interest rate based on macroeconomic variables and the structural shocks of this equation are considered as monetary policy shocks. This procedure gets close to the feedback rule calibrated in a backward-looking manner. One drawback with this approach is that Norges Bank apply a forward-looking perspective when conducting monetary policy (Gjedrem, 2001). Thus, the structural shocks in the VAR may not reflect the true shocks. However, to identify the structural shocks it’s necessary to impose restrictions. In this paper, the structural shocks are identified with a Cholesky decomposition of the variance/covariance matrix after imposing zero restrictions in a recursive order. This is known as Cholesky identification. After the shocks are identified, the effect of a contractionary monetary policy shock is interpreted via impulse responses.

This paper intent to widen the Norwegian macroeconomy literature regarding monetary policy shocks. It provides a VAR analysis aided by econometrics and empirical data of essential macroeconomic variables. A deeper understanding of monetary policy shocks may contribute to a more efficient monetary policy. The results should however not be viewed as evidence since they strongly rely on identification approach and model specification.

The next part will discuss related literature both national and abroad. The third part explains the VAR and the Cholesky identification, followed by a brief on the data and a model calibration in the fourth part. The results will be presented subsequently and interpreted in the fifth part while the sixth and final part will conclude.

2. Related literature

The vector autoregressive model was advocated by Sims (1980). In contrast to regular autoregressions, it can seek out intertemporal relationships among multiple time series. As a result, several macroeconomists have applied VAR models to analyze the monetary transmission mechanism. Sims (1986) studied monetary policy shocks in the U.S with a VAR including GNP, real business fixed investment, inflation, M1 measure of money, unemployment and Treasury-bill. To identify the shock he applied Cholesky identification. Interest rate was ordered last, meaning monetary policy is contemporaneously affected by the other variables, while the other variables are affected by monetary policy with a lag. Sims found that a contractionary monetary policy shock led to a reduction in output, an increase in unemployment and a temporary rise in inflation. Although the response of output and unemployment comply, the response of inflation violates economic theory. In fact, this is a common phenomenon in VAR analysis and is referred to as the price puzzle. Christiano, Eichenbaum and Evans (1994) solved this puzzle by including a variable for commodity prices besides GDP, the GDP deflator, total reserves and the federal funds rate. They noticed that contractionary monetary policy shocks tend to cause a rise in the price level. The reason for this is widely discussed. One explanation is that the VAR is missing a variable which is included in the reaction function of the policymakers. However, by including a variable for commodity prices the abnormal response of inflation disappeared. In line with Sims, they identified the shocks with a Cholesky decomposition of the variance/covariance matrix. The response of inflation was flat for six quarters before it started to decline. Meanwhile, unemployment increased while GDP and commodity prices decreased after the shock. Furthermore, Stock and Watson (2001) inspected monetary policy in U.S based on quarterly data from 1960-2000. They applied a Cholesky identified VAR containing three variables namely inflation, unemployment and federal funds rate, sorted in the mentioned order. Despite fewer variables, their results were consistent with Sims'. A contractionary monetary policy shock led to decreased output, increased unemployment and increased inflation. Instead of using the actual federal funds rate, Romer and Romer (2004) estimated a variable based on Federal Reserve's intentions for the federal funds rate controlled for Greenbook forecasts. As a result, the monetary policy shocks were measured relatively isolated from future expectations. In line with the others, they identified the shocks with a Cholesky approach. Romer and Romer concluded that monetary policy has large and statistically significant effect on output and inflation. The former responded with a sluggish decrease, while the latter responded with a persistent decrease after two years of flat movement.

Meanwhile, literature regarding monetary policy shocks in Norway is narrow. Some research on the subject has been conducted by Bjørnland (2008) who studied monetary policy and exchange rate interactions using a structural VAR comprising GDP, inflation, three-month domestic interest rate, trade-weighted foreign interest rate and real exchange rate. She applied two identification procedures, namely the Cholesky decomposition and a structural VAR with both short-run and long-run restrictions. In the former, two approaches were performed. One where interest rate was ordered prior to exchange rate, meaning exchange rate affect monetary policy with a lag, and one in the reverse order. In both orders, a contractionary monetary policy shock led to an immediate rise in interest rate and a delayed appreciation of the exchange rate. Meanwhile, the structural VAR allowed for a contemporaneous relationship between interest rate and exchange rate by imposing a restriction assuming no long-run effect of interest rate on the exchange rate. As a result, the shock caused exchange rate to appreciate immediately before it gradually depreciated back to baseline. In addition, output and inflation declined after the shock leaving all responses in line with economic theory. Other studies have included financial variables. For example, Bjørnland and Jacobsen (2010) examined the effect of monetary policy on house prices in Norway, Sweden and UK. They applied the same identification procedures as Bjørnland (2008). In the Cholesky identified VAR, monetary policy affected exchange rate and house prices with a lag. In contrast did the structural VAR allow for contemporaneous relationship between these variables by imposing restrictions assuming no long-run effect of interest rate on both exchange rate and GDP. They found that a contractionary shock generated an immediate rise in interest rate, a sluggish decrease in GDP, a rise in inflation and a decrease in house prices. However, the price puzzle was larger in the Cholesky approach. Robstad (2014) extended their study by including household credit in the model. In addition to the Cholesky decomposition and the short- and long run restrictions on the SVAR, he identified the parameters using sign restrictions. This procedure is applied by putting restrictions on the sign of the contemporaneous effect of impulse responses. He found that a contractionary shock lead to an immediate rise in interest rate, an appreciation of the exchange rate and a decrease in GDP, house prices and household credit. The price puzzle appears in all identification procedures except sign restrictions where it’s moved by construction. As in the original study, the price puzzle was larger in the Cholesky approach. Overall, Cholesky identification usually lead to a price puzzle, a sluggish decrease in production/employment and an immediate appreciation in the exchange rate.

3. Model specification

Theory relating the models are obtained from Enders (2014) and Schenck (2016).

The reduced form VAR can be expressed in matrix notation as

$$y_t = A_0 + A_1 y_{t-1} + \cdots + A_l y_{t-l} + e_t \qquad (1)$$

y_t denotes a $(n \times 1)$ vector of endogenous variables, A_0 is a $(n \times 1)$ vector of constants, A_l is the $(n \times n)$ coefficient matrix on the l'th lag of y and e_t is a $(n \times 1)$ vector of error terms assumed to be white noise.

The variance/covariance matrix of e_t can be expressed as

$$\Omega_e = \begin{pmatrix} \omega_{11} & \cdots & \omega_{1k} \\ \vdots & \ddots & \vdots \\ \omega_{k1} & \cdots & \omega_{kk} \end{pmatrix}$$

where the diagonal contains all variances while the upper and lower triangle contains all covariances. The matrix indicates that the reduced form VAR allows for correlation across the error terms. Thus, a monetary policy shock can affect other endogenous variables in the same period which may be unreasonable considering some delay of monetary policy.

To remove correlation among the error terms and allow for contemporaneous effect between the variables one can rewrite (1) to a structural vector autoregressions (SVAR).

$$B_0 y_t = C_0 + B_1 y_{t-1} + \ldots + B_l y_{t-l} + \varepsilon_t \qquad (2)$$

where B_0 is a matrix of contemporaneous restrictions and assumed invertible, ${B_0}^{-1} C_0 = A_0$, ${B_0}^{-1} B_l = A_l$, ${B_0}^{-1} \varepsilon_t = e_t$ and $\Omega_e = {B_0}^{-1} \Sigma ({B_0}^{-1})'$. The structural shocks, ε_t, are assumed to be independent and identically distributed with a variance/covariance matrix, Σ, containing nonzero values only on the diagonal which is normalized to unity. Thus, the variance/covariance matrix of the reduced form VAR is $\Omega_e = {B_0}^{-1} ({B_0}^{-1})'$.

Because each endogenous variable of y_t depends on all variables and their structural shocks simultaneously, general estimation procedures can't be performed on (2). Therefore, one must benefit from the reduced form VAR to identify the parameters in the SVAR. However, it is not possible to uniquely pin down B_0, C_0, B_l and ε_t from A_0, A_l, e_t and Ω_e without imposing sufficient zero restrictions on elements of ${B_0}^{-1}$ (or equivalently on B_0). Because every variance/covariance matrix is symmetric about the diagonal, $n(n+1)/2$ is the maximum number of parameters in B_0 that can be uniquely identified by exploiting Ω_e. Thus, zero restrictions must be placed on the remaining elements.

3.1 Cholesky identification

Ramey (2016) stated that a Cholesky decomposition of the variance/covariance matrix is the most usual approach to identify structural shocks. The method can be implemented by placing restrictions in a recursive order so that B_0 becomes a lower triangular matrix. In this way B_0 contain $n(n+1)/2$ unknown parameters and exact identification is ensured. As a result, the parameters of B_0 can be obtained with a Cholesky decomposition of the variance/covariance matrix Ω_e, given by $\Omega_e = {B_0}^{-1}({B_0}^{-1})'$. Hence, all parameters in the SVAR can be identified including the structural shocks.

$$B_0 = \begin{pmatrix} b_{11} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ b_{k1} & \cdots & b_{kk} \end{pmatrix}$$

The restrictions provide uncorrelated structural shocks and the possibility to decide which of the endogenous variables that gets contemporaneously affected by other variables and implicitly their structural shocks. The first endogenous variable, $y_{1,t}$, is only affected by lagged variables and its own structural shock, $\varepsilon_{1,t}$. The second endogenous variable, $y_{2,t}$, is affected by lagged variables and its own structural shock, $\varepsilon_{2,t}$. Besides that, its contemporaneously affected by $y_{1,t}$ and accordingly $\varepsilon_{1,t}$. The n'th endogenous variable, $y_{n,t}$, is affected by lagged variables and its own structural shock, $\varepsilon_{n,t}$. In addition, it is contemporaneously affected by all variables and accordingly their structural shocks. Note that the ordering determines which of the endogenous variables that is contemporaneously affected. Sims (1986) proposed to select the order based on economic theory. A common approach in monetary policy studies is to order interest rate last such that monetary policy responds to all variables contemporaneously, while the other variables is affected by monetary policy with a lag. In that case, the structural shocks of the last equation, $\varepsilon_{n,t}$, characterizes the monetary policy shocks. More specifically, monetary policy shocks are the structural shocks of the equation where interest rate is the endogenous variable.

3.2 Exogenous variables

To control for additional effect, exogenous variables can be included. The exogenous variables are independent of other variables in the model and helps explain the endogenous variables.

$$B_0 y_t = C_0 + B_1 y_{t-1} + \ldots + B_l y_{t-l} + \Psi x_t + \varepsilon_t$$

The extension of the general SVAR introduce a $(k \times 1)$ vector, x_t, with k exogenous variables and a $(n \times k)$ coefficient matrix, Ψ, capturing their effect on the endogenous variables. Note that the exogenous variables are inserted without any lags, meaning they will only affect the endogenous variables contemporaneously.

4. Data

The sample period spans from Q1 1999 to Q4 2017 with quarterly observations. Even though the formal introduction of inflation targeting took place in 2001, the transition had already started when Svein Gjedrem became the governor of Norges Bank first of January 1999 (see Kleivset (2012)).

The endogenous variables in the model includes short term interest rate (r), core inflation (CPI), gross domestic product (GDP) and import weighted exchange rate (I44). The selection is based on a comparison of various models represented in Appendix B. In addition, I estimate a model where the oil price is included as an exogenous variable due to its impact on the Norwegian economy. To remove exponential growth, all series except interest rate are transformed to natural logarithms.

The augmented Dickey-Fuller test is applied on each variable to determine the order of integration. The test is conducted without trends. A constant is included if substantial and significant at 5% level. I use the conventional 4 lags but reduce the length if the last lag is insignificant. Based on the test results, all variables are integrated of order 1 which mean they contain one unit root. However, there is no consensus regarding the necessity of stationary variables in VAR analysis. Even if there exist a unit root, Sims (1980), Sims, Stock and Watson (1990), Gospodinov, Herrera and Pesavento (2013) and Stock and Watson (2016) argued against differencing because it can lead to loss of important information regarding comovements in the data. On the other hand, non-stationary variables can lead to invalid estimation results. For level-specified variables to be an option, cointegration is essential to ensure an unbiased analysis. Both Engle-Granger test and Johansen test were conducted. The former is testing for stationary residuals in each equation of the reduced form VAR while the latter is testing for joint cointegration in the VAR model based on eigenvalues. Both tests indicate cointegration. Considering that this paper aims to investigate interrelationships and not the exact value of coefficients, I decide to specify the VAR in levels. The conducted tests are described thoroughly in Appendix B. Regardless of stationary variables, Lütkepohl (2006) remarks the importance of a stationary system for result robustness. This requires all characteristic roots to have moduli less than one which is satisfied in the modelled VAR.

The ordering of the endogenous variables is based on priori beliefs. Normally GDP or CPI are ordered first due to sluggish responsiveness. This implies that they effect interest rate and exchange rate contemporaneously while they get affected with a lag. However, because of interrelationship, the sequence between them varies across studies. In this paper GDP is ordered prior to CPI but as a robustness check I estimate the reverse order in Appendix B. Meanwhile the interest rate is ordered prior to exchange rate which is ordered last. This implies that exchange rate reacts instantaneous to a change in interest rate, while monetary policy responds to changes in exchange rate with a delay. The ordering is supported by the fact that exchange rate is very sensitive to changes in interest rate. However, if exchange rate affects the real economy, theory suggest that monetary policy should respond to it contemporaneously. This simultaneity issue is another drawback with the Cholesky approach and is discussed in Bjørnland and Jacobsen (2008).

I chose the lag length based on information criteria to obtain as much information as possible without consuming too many degrees of freedom. Both Akaike and Schwarz suggests two lags. Even though 2 lags won't capture potential seasonal effects, I decide to follow the suggestion since both CPI and GDP are seasonally adjusted.

5. Results

The identified shocks and impulse responses are interpreted below. All figures are presented in Appendix D

5.1 Identified shocks

The identified monetary policy shocks are plotted next to the interest rate in Figure 1. A visual inspection reveals particularly large shocks during the early 2000s recession, mostly contractionary. This implies an unexpectedly tight monetary policy based on the development of production, inflation and exchange rate. There is also a large contractionary shock in the wake of the financial crisis. The shock may confirm that Norges Bank apply a forward-looking perspective when conducting monetary policy, considering the unanticipated onset of the crisis and the recent economic growth. In the aftermath of the crisis, a large expansionary monetary policy shocks can be observed. This indicates that the interest rate cut was exaggerated as an attempt to mitigate the recession. Consequently, some contractionary shocks appear afterwards. The subsequent shocks are relatively modest whereas the interest rate declines steadily.

5.2 Impulse responses

The impulse response function characterizes how each endogenous variable reacts to a shock, in this case an unexpected increase in interest rate equivalent to one standard deviation. The solid line represents the estimated response while the dashed lines illustrate the corresponding 95 percent confidence interval. The vertical axis displays the magnitude and the horizontal axis displays number of quarters after the initial shock with a maximum of five years. Note that the magnitude of impulse responses of different models should not be compared directly because the underlying shocks are different. However, in the estimated models the differences are small.

As illustrated in Figure 2, the interest rate increases immediately with almost 30 basis points, followed by a peak, before it starts to normalize. The response is statistical significant for five quarters and in line with related literature. It indicates that Norges Bank conduct a predictable and smooth monetary policy subsequent to a shock. Meanwhile, the response of consumer price index is relatively small with an initial increase reaching 0.06 percent at its maximum which is equivalent to an increase of 6 basis points in inflation. After two years it returns to the original level and starts to decline consistently. The reduction is equal to 14 basis points the fifth year. Including the oil price generates an even smoother response of interest rate which seems to increase the magnitude of CPI. Given that CPI is adjusted for energy prices, the oil price itself should not affect it directly, but it may do so through production and exchange rate. The decrease of inflation is significant and equal to 24 basis points after 5 years. Regarding Galí (2015), the delayed decline of CPI can be interpreted as evidence of price rigidities. In fact, several studies on the subject experiences this delay in the response of inflation. Due to appearance of the price puzzle, I followed the suggestion of Christiano, Eichenbaum and Evans (1994) and included a variable for commodity prices in the model. The variable is placed prior to interest rate so that monetary policy reacts to it contemporaneously while it affects GDP and CPI with a lag. Although the increase of CPI was moderated, the price puzzle still appeared. The maximum increase of inflation was reduced from 6 basis points to 4.5 basis points. However, the underlying shock was reduced with 0.5 basis points which may has been a leading cause to the lower magnitude of the response. The result indicates that Norges Bank don't emphasize industrial production when conducting monetary policy. The impulse responses of the adjusted model are illustrated in Figure 3.

The response of output and exchange rate is in line with economic theory besides the initial increase in the former. A contractionary shock generates a sluggish decrease in output reaching a trough after two years at nearly 0.5 percent, after which it reverts to normal. The response is statistical significant between the fourth and twelfth quarter. Meanwhile, the exchange rate appreciates instantaneously with 0.6 percent before it loses power as interest rate declines. However, the corresponding confidence interval is large, hence the appreciation is barely significant for the first quarter. When the oil price is included, the uncertainty in the response of exchange rate is reduced. The impulse response illustrates an immediate appreciation of 0.35 percent. Afterwards it depreciates for half a year before it appreciates for two years reaching a maximum of 0.6 percent, equivalent to the magnitude of the initial response in the original model. This pattern is referred to as a delayed overshooting puzzle, an occasional phenomenon in the Cholesky approach with exchange rate ordered last (see Cushman and Zha (1997)). As a robustness check I estimated a VAR with exchange rate ordered prior to interest rate as in Bjørnland (2008). Consequently, monetary policy responds to exchange rate contemporaneously while it affects exchange rate with a lag. Although this contradict with the fact that exchange rate reacts fast to changes in interest rate, it allows monetary policy to respond immediately to movements in exchange rate which is reasonable considering that exchange rate affect the real economy. Despite the reverse ordering, the response to a contractionary monetary policy shock was pretty much the same except for the initial magnitude which is constructed by the ordering itself. Hence, the alternative ordering does not solve the delayed overshooting puzzle. The impulse response of the alternative ordering is illustrated in Figure 4.

To briefly summarize, a contractionary monetary policy shock lead to an immediate increase in interest rate, a reduction in GDP, an immediate appreciation in exchange rate and a temporary increase in CPI. Considering Norges Bank targets inflation to implicitly stabilize exchange rate and output, the response of CPI lowers the validity of the results. Including the oil price as exogenous variable lead to smoother movements and increased uncertainty in interest rate and GDP. Meanwhile, the confidence interval of exchange rate becomes smaller, but at the cost of a delayed overshooting puzzle. Regarding Bjørnland (2008), the exchange rate is supposed to appreciate rapidly and reverse soon after which is the case in the original model. Overall, the results of the original model are in line with research on monetary policy shocks where Cholesky identification is applied.

6. Conclusion

This paper provides an empirical study of monetary policy shocks in Norway. The shocks are identified through Cholesky decomposition and the dynamic effects are illustrated with impulse responses. Based on interpretation of the latter, monetary transmission mechanism has a significant effect on production and exchange rate. Although the response of inflation questions the validity of the results.

The incorporation of oil price did not contribute much to the analysis. Less uncertainty in the response of exchange rate is of little use when a new puzzle is introduced. Both the price puzzle and the delayed overshooting puzzle may imply that Cholesky decomposition is unable to identify a pure monetary policy shock. An eventual extension of this paper should include another identification procedure as a robustness check.

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Appendix A: Data

Three-month money market rate (NIBOR). Source: OECD.

Gross domestic product (GDP) mainland adjusted for population growth, seasonally adjusted. Source: Macrobond.

Unemployment, 15-74 years. Source: Macrobond. *

Consumer price index (CPI), seasonally adjusted. Source: OECD. *

Consumer price index adjusted for tax changes and excluding energy prices (CPI-ATE), seasonally adjusted. Source: Macrobond.

Import-weighted nominal exchange rate index (I-44). Source: Norges Bank.

Exchange rate for Euro, NOK per 1 EUR. Source: Macrobond. *

Brent oil price index. Source: Macrobond.

Commodity price index. Source: Macrobond. *

*Only used in robustness check.

Appendix B: Robustness

As stated by Todd (1990) small changes in the VAR may have crucial effect on the results. To ensure a good combination of variables, different VAR models were estimated. Each model includes short term interest rate, inflation, exchange rate and a variable related to output. The quality of each model is based on its ability to explain the endogenous variables, measured by the root mean square error (RMSE). All models are estimated with two lags. The results are reported in table 1.

Table 1: Alternative models.

Ranking	**Variables**
1	Interest rate, GDP, CPI adjusted for taxes and energy prices and import weighted exchange rate
2	Interest rate, GDP, CPI and import weighted exchange rate
3	Interest rate, GDP, CPI adjusted for taxes and energy prices and spot exchange rate NOK/EUR
4	Interest rate, GDP, CPI and spot exchange rate NOK/EUR
5	Interest rate, unemployment, CPI and import weighted exchange rate
6	Interest rate, unemployment, CPI adjusted for taxes and energy prices and import weighted
7	Interest rate, unemployment, CPI adjusted for taxes and energy prices and spot exchange rate NOK/EUR
8	Interest rate, unemployment, CPI and spot exchange rate NOK/EUR

I also estimated a VAR with CPI prior to GDP. The change had minimal impact on the impulse responses.

Appendix C: Statistical tests

The theory is obtained from Enders (2014).

Dickey-Fuller test.

Given the AR(1) process without any constant or trend:

$$y_t = \beta_1 y_{t-1} + \varepsilon_t$$

For y_t to be stationary, the modulus of β_1 is required to be less than unity.

The autoregression can be written in first order difference:

$$\Delta y_t = p y_{t-1} + \varepsilon_t$$

where $p = (\beta_1 - 1)$. For the modulus of $\beta_1$to be less than unity, the coefficient p must be negative. This can be examined by performing a t-test on p.

$$H_0: p = 0, integrated\ of\ order\ k\ where\ k > 0$$

$$H_1: p < 0, integrated\ of\ order\ zero$$

The null hypothesis indicates that the series contain at least one unit root. The alternative hypothesis indicates that y_t is stationary. If the null hypothesis is kept, one can take the second order difference of y_t and repeat the test to find the exact order of integration.

$$\Delta\Delta y_t = \varphi \Delta y_{t-1} + \varepsilon_t$$

$$H_0: \varphi = 0, integrated\ of\ order\ 2$$

$$H_1: \varphi < 0, integrated\ of\ order\ 1$$

The augmented dickey-fuller test includes more lags of y_t to ensure the residuals are white noise. An AR(4) process without any drift or trend can be written as:

$$\Delta y_t = \alpha_1 y_{t-1} + \alpha_2 \Delta y_{t-1} + \alpha_3 \Delta y_{t-2} + \alpha_4 \Delta y_{t-3} + \alpha_5 \Delta y_{t-4}$$

The approach is the same. If $\alpha_1 < 0$, y_t are integrated of order 0, if not it contains at least one unit root.

Note 1: The test result is invalid if p is positive.
Note 2: The test-statistics in Dickey-Fuller does not follow a normal t-distribution. The critical values were simulated using Stata.

<u>Johansen test.</u>
Johansens trace test is a test for cointegration based on eigenvalues. The general formula for the test is:

$$\lambda_{trace}(r) = -T \sum_{i=r+1}^{g} \ln(1 - \lambda_i)$$

The null hypothesis is zero ranks which indicates no cointegration. The alternative hypothesis indicates that there exist cointegration between two variables or more.

$$H_0: \lambda_1 = \lambda_2 = \cdots = \lambda_g, r(\pi) = 0$$

$$H_1: At\ least\ 1\ eigenvalue\ is\ different\ from\ zero, r(\pi) \neq 0$$

If the null hypothesis is rejected, the test is repeated without the first eigenvalue. This process goes on until the null hypothesis is kept.

<u>Information criteria.</u>
Information criteria is applied to choose the optimal lag length. The estimator measures the quality of models with different lag lengths based on the trade-off between goodness of fit and complexity. Since the goodness of fit usually increase when including new parameters, there is a penalty that discourage overfitting. The way to apply the criteria is simply to measure the estimator for each model and pick the model with the lowest value. Note that the results don’t tell the absolute quality of each model, just the quality relative to models with different lag lengths. In this paper both Akaike criterion and Schwarz criterion is applied. The estimators are calculated with the following formulas:

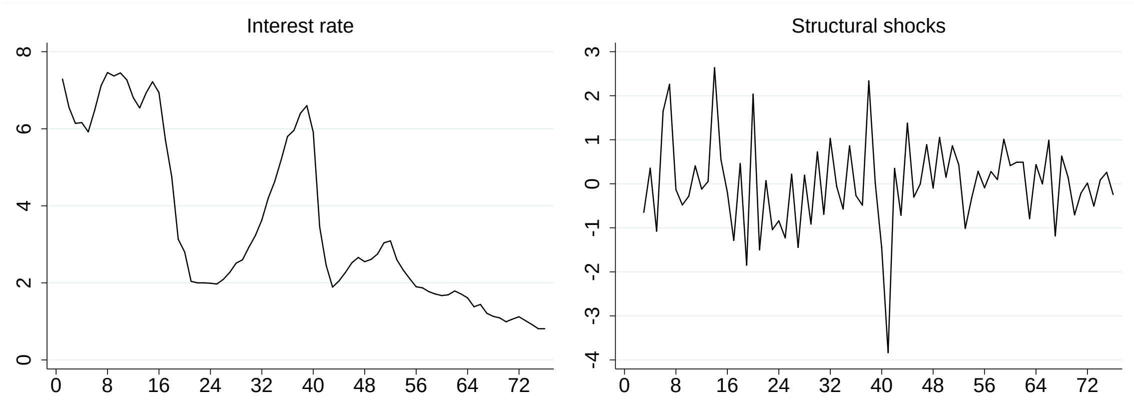
$$AIC = \ln|\Omega| + \frac{2N}{T}$$

$$SBC = \ln|\Omega| + \frac{N * lnT}{T}$$

Where Ω is the variance/covariance matrix of the error term and $N = n + pn^2$ is the number of parameters in the VAR. Note that the penalty term is larger in SBC.

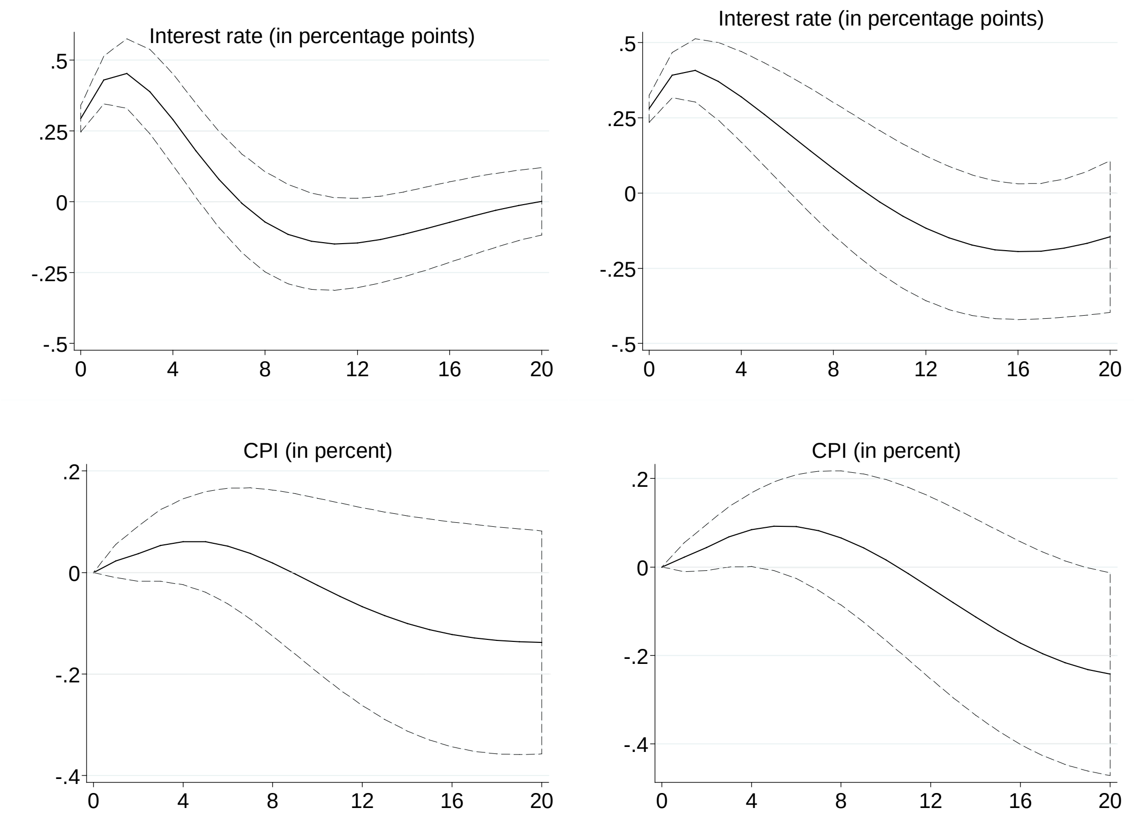
Appendix D: Figures

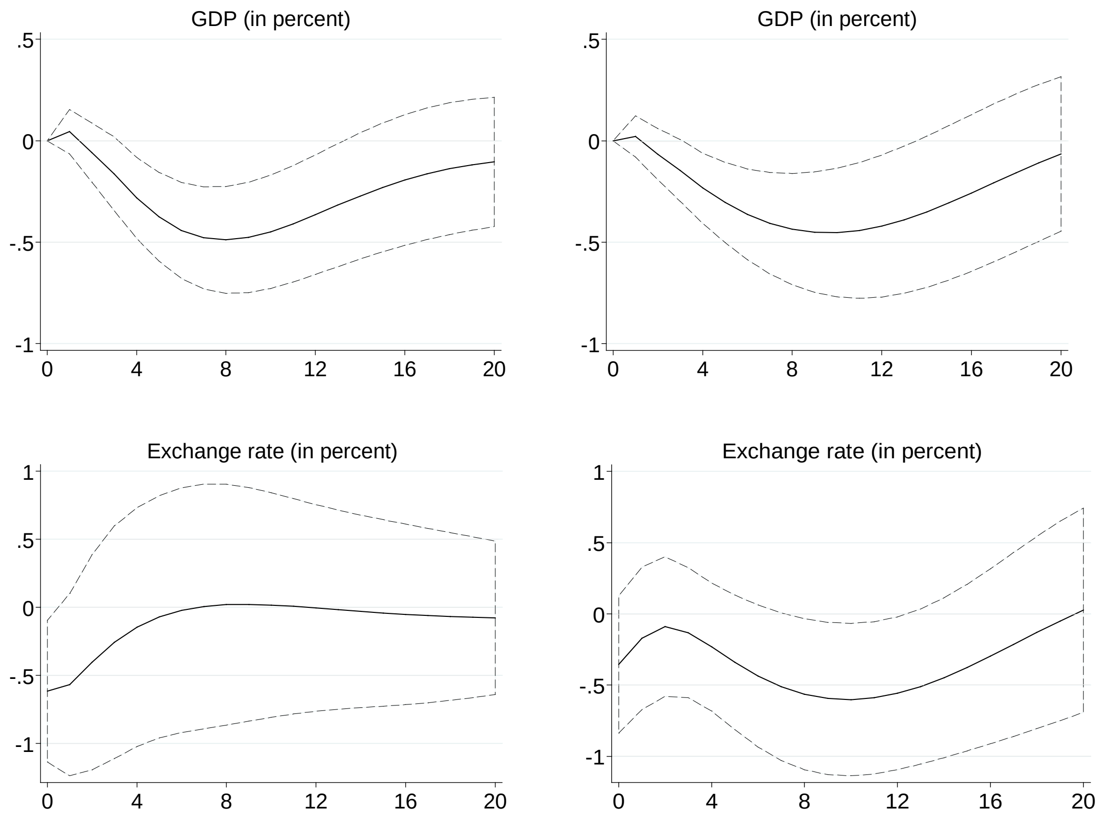
Figure 1: Quarterly data of interest rate and monetary policy shocks



Positive values represent contractionary shocks, while negative values represent expansionary shocks.

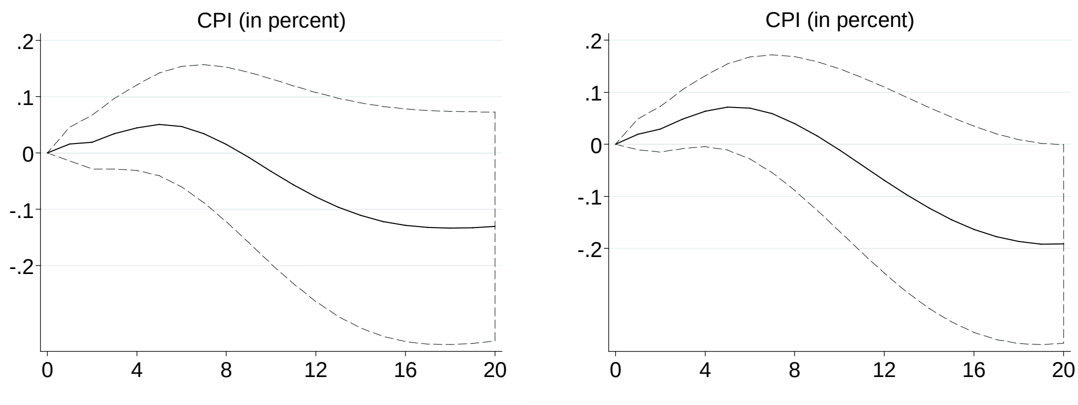
Figure 2: Impulse responses after a contractionary monetary policy shock.





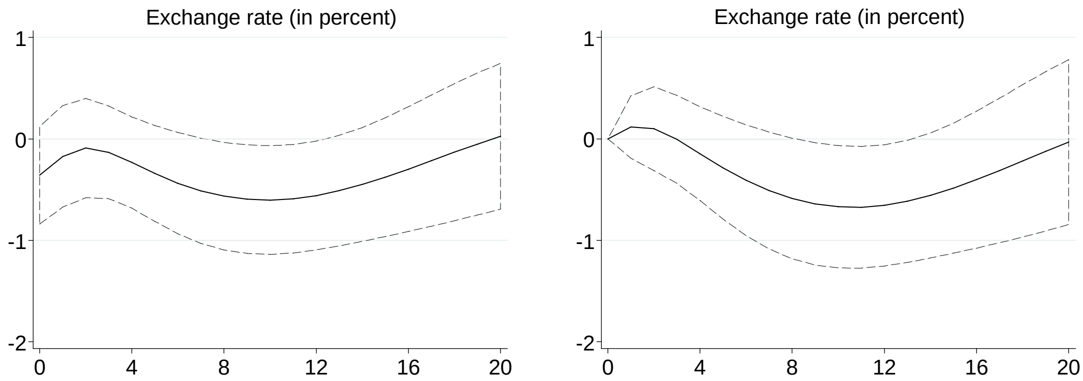
The impulse responses on the right-hand side include oil price as exogenous variable.

Figure 3: Commodity price index included as endogenous variable.



The impulse response on the right-hand side include oil price as exogenous variable.

Figure 4: Different orderings of exchange rate in the model including oil price.



The impulse response to the left represents the original ordering, while the impulse response to the right represents the alternative ordering.