UNIVERSITAT AUTÒNOMA DE BARCELONA

IDEA
DEPARTAMENT D'ECONOMIA I D'HISTÒRIA ECONÒMICA

Essays on the Transmission Mechanism of Monetary Policy

Julius Moschitz

June 2004

Supervisors: Dr. Hugo Rodríguez Mendizábal and Dr. Gabriel Pérez Quirós

You can know the name of a bird in all the languages of the world, but when you're finished, you'll know absolutely nothing whatever about the bird... So let's look at the bird and see what it's doing - that's what counts. I learned very early the difference between knowing the name of something and knowing something.

Richard Feynman *(Nobel Prize in Physics 1965)*

Contents

List of Figures

List of Tables

Acknowledgments

Many, many people contributed to the success of this dissertation. Some have been involved directly, as supervisors or teachers. Others added value by creating an intellectually stimulating environment, providing support or putting things into context. I want to thank all of them!

I am heavily indebted to my supervisors Hugo Rodríguez Mendizábal and Gabriel Pérez Quirós. Their dedication and enthusiasm for pushing forward our understanding of economics is probably the best motivation one can get to keep on track and to overcome the - alas, they do exist - difficult times in the process of writing a dissertation. The aim of writing a dissertation is not only to discover some new insights and to present them well. Perhaps even more important is to develop and foster a critical mind. To be critical - also in the positive sense - about one's own research, but also about other people's findings. There is no better teacher than the one who lives up to his sermons! I had precisely this luxury of not only learning through words, but through examples. Last, but not least, I want to thank you for opening me doors, supporting my goal to work in international organizations as well as your help in finding a challenging job as economist.

What would a dissertation on monetary policy be without knowing a central bank, *the* monetary policy institution, from inside? I had two magnificent opportunities to work at the European Central Bank (ECB). However, it was not the mere fact to be at a central bank, but rather to work at the Monetary Policy Implementation Unit, which made the experience so special. I want to thank in particular Nuno Cassola for motivating part of this dissertation, for many helpful discussions and detailed comments. Nuno and his unit - Steen, Clara, Natacha, Livio and Stefano - provided a warm and very stimulating environment. I would not want to miss the chance to thank ECB seminar participants, both in October 2002 and March 2004, for their comments.

Gunther Tichy and Nick Baigent, from Karl-Franzens Universität Graz (Austria), guided my first steps into economics. Especially Nick has his share of "responsibility" that I ended up in a Ph.D. program. In this particular Ph.D. program, IDEA, at Universitat Autònoma de Barcelona. Among other people, Clara Ponsatí, Carmen Beviá, Jordi Massó, Inés Macho and David Pérez have been leading and developing the program during the last six years. It is a very international program and highly competitive, although in a friendly manner. In particular I appreciate the openness of the faculty. It has never been easier to meet a professor! This is especially true for Michael Creel, who supervised my Master thesis and introduced me to econometrics. I benefited enormously from some Ph.D. courses. Both, from their content but also from the way how they were taught. I want to mention explicitly the classes by

Juan Enríque Martínez, David Pérez, Carmen Beviá, Jordi Galí, Fabio Canova and Giles Saint-Paul. Mercè Vicente, Sira Mora, Mario Jiménez and Maite Nuñez have provided invaluable support for dealing with all kinds of bureaucratic hurdles. Without the financial support from both Universitat Autònoma de Barcelona and the Spanish Ministry of Education this dissertation would not have been written!

A big hug and thousand thanks to my colleagues and classmates for their support and friendship. At the end of the day it is them who create a motivating atmosphere and environment, both to work and to relax. *Autònoma* would not have been the same without you, Jo, Albert, Debrah, Jernej, Laura, Carmelo and Mathias! Working and studying at other institutions did not only enhance my professional skills, but also started some wonderful friendships with Thomas (Universitat Pompeu Fabra); Ditte and Anike (ECB); and Yolanda (Asian Development Bank). I feel very fortunate for having been able to share an office, have a coffee, or solve an economic problem with so many unforgettable people at *Autònoma*, the ECB, the Asian Development Bank and Banc Sabadell. Not to forget Jochen and Michael for testing my *theoretical* knowledge of economics on its applicability to *real* world issues while guiding me through the Austrian mountains.

Last, but not least, I want to thank my family! My parents for transmitting me the will to explore the unknown, the benefits from fighting for one's convictions, their generosity, trust and sense of responsibility. My brothers and my sister for opening my eyes to new challenges and to challenge the common wisdom. And of course Ester, for sharing; for sharing the good and the not so good things in life.

Barcelona, June 2004 Julius Moschitz

Chapter 1

Introduction

This thesis studies the effects and effectiveness of monetary policy. In a stylized way, the central bank changes the short-term interest rate and, via the term structure, long-term interest rates are affected. Long-term rates are the relevant variables for firms' investment and households' saving decisions, which influence output and prices and, as a consequence, the final objectives of a central bank, e.g. price stability. This thesis looks carefully at some particular, and widely overlooked, issues along the above described transmission mechanism of monetary policy.

In chapter 2 the transmission of monetary policy in open economies is analyzed. Chapter 3 looks at the determinants of a particular short-term interest rate, the overnight interest rate, which is the rate most strongly related to the conduct of monetary policy. Chapter 4 studies the effects of monetary policy implementation on the euro area money market.

Chapter 2 analyzes the effects of a monetary policy shock in several European countries. The focus is on the 20 years before the European Monetary Union (EMU) and changes within this period are investigated. These changes are documented and interpreted. Furthermore, it is shown how the effects of a shock vary across countries. There are several reasons why this analysis is interesting and worthwhile undertaking.

Firstly, with the, sometimes turbulent, events experienced in Europe in the 1980's and 1990's the transmission mechanism of monetary policy is expected to have changed. This chapter looks in great detail at these possible changes. In particular, it studies how the creation (more exactly the credible announcement of the creation) of the EMU affected these dynamics.

Secondly, for a monetary authority it is very important to know the dynamic effects of its actions. Accordingly, a good understanding of these effects can help in policy making. Since countries differ in various aspects, these effects might vary considerably among countries. Therefore, an in-depth analysis for each country is necessary. However, the creation of the common monetary policy could be a major structural break for European economies. Nevertheless, the proposed analysis is useful, because although some dynamic relationships might have changed with the creation of a common European currency, it is very unlikely that all country differences have changed immediately, as well. Consequently the results presented here should be good enough to give some hints on the country specific effects of a common monetary policy. Besides that, it is interesting to learn more about the historical behavior of some countries.

Thirdly, robustness of the results with respect to different estimation methods is intensively discussed. Several different treatments will be applied to a given problem in order to see if and how the results change. The relevant issues are unit roots and co-integration versus level specification, seasonal adjusted versus seasonal unadjusted data and how to deal with the German unification.

Finally, it should be stressed that investigating the effects of policy *shocks*, in contrast to policy actions, does not imply the reaction to shocks to be important or interesting per se. Rather it allows to assess competing theories according to their reactions to a shock or, going one step further, to trace the effects of policy changes.

Chapter 3 studies the determinants of the overnight interest rate and quantifies them. The overnight interest rate is at the short end of the yield curve and the equilibrium outcome of supply and demand for bank reserves. The structural model of both supply and demand for reserves developed here allows an in-depth analysis of the interaction between the central bank, as the sole net supplier of reserves, and commercial banks, on the demand side. The precise set-up of this market, i.e. the institutional details of the reserve market, has important implications for the behavior of the overnight rate, both for the conditional mean and variance. These implications are derived from a theoretical model and their magnitudes are estimated for the euro area overnight rate.

The behavior of the overnight interest rate is important for several reasons. Firstly, in most monetary models the central bank is assumed to have perfect control over the interest rate. The transmission mechanism of monetary policy in these models starts at the short-term interest rate. A change in the short-term rate works through to long-term interest rates. These long-term rates are the relevant variables for firms' investment and households' savings decisions. Investment and saving then influence output and prices and, as a consequence, the final objectives of a central bank, e.g. price stability. However, the control of the short-term interest rate is far from perfect in practice. Interest rates are determined on markets, being influenced by both supply and demand side factors. The central bank has a strong influence on the supply side, but is not able to control it perfectly. This chapter studies the, widely overlooked, first step in the monetary transmission mechanism, the relation between reserves and the overnight rate. In particular, the assumption made in many models that the central bank has perfect control over the interest rate is analyzed. The ways in which the details of monetary policy implementation affect the behavior of the interest rate are documented.

Secondly, the short-term rate is an important explanatory variable for long-term interest rates. According to the expectation hypothesis the N-period yield is the average of expected future one-period yields, possibly adjusted for a risk premium. Therefore, understanding better the behavior of the short end of the yield curve - the overnight rate - helps explaining other interest rates further out the term structure as well.

Thirdly, in efficient markets there are no (long-lasting) arbitrage opportunities. Predictable patterns usually provide such arbitrage opportunities. Both mean and volatility of the overnight rate are tested for predictable patterns and implications for market efficiency are investigated.

Finally, central banks have a natural interest in studying the determinants of the overnight rate. This is particularly true nowadays as the operating target of many central banks is a short-term interest rate. The behavior of the overnight rate depends on reserve supply, but equally important on the institutional framework for the reserve market.

With these issues in mind the overnight rate is analyzed and the reserve market is discussed with respect to market efficiency, the importance of institutional features, and the ability of the central bank to control the interest rate.

As mentioned above, nowadays most central banks target a short-term interest rate in order to achieve their primary objectives, like price stability. By signalling its target rate and managing the liquidity situation in the money market a central bank steers short-term money market rates. Chapter 4 describes how the European Central Bank manages the liquidity situation in the money market and its implications for interest rates of various maturities. In particular, volatility of interest rates and its transmission along the yield curve is discussed extensively.

Central banks differ substantially in how they manage the liquidity situation in the money market. These differences in the operational framework may have implications for the behavior of interest rates, in particular for their volatility. Central banks are eager to avoid high volatility, especially for interest rates with long maturities. Firstly, high volatility of money market rates may give market participants confusing signals on the monetary policy stance. However, the central bank wants to communicate its monetary policy stance clearly, without unnecessary noise, and, therefore, avoid high volatility. Secondly, and maybe even more important, long-term interest rates are relevant for firms' investment and households' consumption decisions. High volatility of an asset's price requires, in general, higher returns on this asset and, therefore, increases the costs of an investment. Again, there are benefits of avoiding high volatility.

High volatility of interest rates at the short end of the yield curve is less of a concern. Volatility at the short end - as long as it is not transmitted along the yield curve - is mainly interpreted as money market noise, without affecting the real side of the economy. This chapter analyses volatility in money market rates and its transmission from the short to the long end of the yield curve. It provides insights into the operational framework of the European Central Bank and the effects of this framework on money market rates.

This analysis is not only important for the conduct of monetary policy, but also to understand better the term structure of interest rates. It is widely accepted that short-term rates explain a large part of the movements in longer term rates. In this chapter money market rates of various maturities are modeled carefully and the linkages between them are explored. The empirical model specifications for both, conditional mean and volatility are tested extensively for misspecification, especially for omitted variables. The models presented here also allow a detailed discussion of the expectation hypothesis, comovements of interest rates of different maturities and the adjustment of interest rates to their long-run equilibria.

Chapter 2

The changing effects of a monetary policy shock

2.1 Introduction

In this chapter the effects of a monetary policy shock in several European countries are analyzed. The focus is on the 20 years before the European Monetary Union (EMU) and changes within this period are investigated. These changes are documented and interpreted. Furthermore, it is shown how the effects of a shock vary across countries. There are several reasons why this analysis is interesting and worthwhile undertaking.

Firstly, with the, sometimes turbulent, events experienced in Europe in the 1980's and 1990's the transmission mechanism of monetary policy is expected to have changed.[1] This chapter looks in great detail at these possible changes. In particular, it is studied how the creation (more exactly the credible announcement of the creation) of the EMU affected these dynamics.

Secondly, for a monetary authority it is very important to know the dynamic effects of its actions. Accordingly, a good understanding of these effects can help in policy making. Since countries differ in various aspects, these effects might vary considerably among countries. Therefore, an in-depth analysis for each country is necessary. However, the creation of the common monetary policy could be a major structural break for European economies. Nevertheless, the proposed analysis is useful, because although some dynamic relationships might have changed with the creation of a common European currency, it is very unlikely that all country differences have changed immediately, as well. Consequently the results presented here should be good enough to give some hints on the country specific effects of a common monetary

[1] Examples are the crisis of the European Monetary System, the independence of the Italian central bank and the German unification.

policy. Besides that, it is interesting to learn more about the historical behavior of some countries.

Thirdly, robustness of the results with respect to different estimation methods is intensively discussed. Several different treatments will be applied to a given problem in order to see if and how the results change. The relevant issues are unit roots and co-integration versus level specification, seasonal adjusted versus seasonal unadjusted data and how to deal with the German unification.

Finally, it should be stressed that investigating the effects of policy *shocks*, in contrast to policy actions, does not imply the reaction to shocks to be important or interesting per se.[2] Rather it allows to assess competing theories according to their reactions to a shock (what Christiano et al. (1998) call the Lucas program) or, going one step further, to trace the effects of policy changes (Bernanke and Mihov, 1998a).

There are many papers analyzing the transmission mechanism of monetary policy. This is especially true for the United States, but recently European countries have been investigated more intensively as well (for an overview see e.g. Angeloni et al., 2002). However, most of the early contributions apply a system of equations with a very limited amount of variables, which is to say they might omit relevant variables. Furthermore, the assumptions made for identifying the structural model are in many cases not very convincing. Two recent studies, Mojon and Peersman (2001) and Kim and Roubini (2000), are exceptions and the present analysis follows them quite closely in the choice of variables and the identification restrictions. Nevertheless, most studies rely on one specific methodology without even mentioning the others. In contrast, results in this chapter are checked for robustness with respect to several methodological issues.

It is very important to look carefully on each country and set up the model which represents it best. Country specific information can be found in thorough single country studies like Bernanke and Mihov (1997) and Clarida and Gertler (1996), which concentrate on Germany. This and other institutional information is used when setting up the econometric models for the different countries analyzed in this chapter.

Concerning the changing effects of a monetary policy shock over time and the importance of the creation of the EMU for these effects, we are not aware of any work directly related to ours. There are some recent papers applying alternative

[2] Various interpretations can be given to these policy shocks (see e.g. Christiano et al, 1998). They might reflect exogenous shocks to the preferences of the monetary authority, either as shocks to the preferences of the decision making members of the central bank or to the weights how their preferences are aggregated. Secondly, shocks may arise from the central bank's desire to avoid the cost of disappointing private agents' expectations. Thirdly, measurement errors in the preliminary data available to the central bank or technical factors are other possible sources.

methodologies.[3] However, we prefer to improve on a widely used and fairly simply approach by taking into account the criticism raised on earlier studies.

In the next section the econometric model is set up. In section 2.3 data sources are provided. Furthermore, identification and specification issues are discussed extensively, it is explained why seven variables are included into the system of equations and the choice of the specific variables used is defended. In section 2.4 a range of tests is performed to investigate the stability of parameters. Section 2.5 takes results on instability into account and discusses their effects on the dynamics of the system. In section 2.6 sensitivity analyses are performed and, finally, section 2.7 concludes and outlines further research. The appendix explains how the German unification has been modeled. Additionally it contains all test results on parameter stability and all impulse response functions.

2.2 The econometric model

The present analysis is based on a simple model of an open economy, which is represented by a system of equations:

$$A_0 x_t = a + A_1 x_{t-1} + A_2 x_{t-2} + ... + A_p x_{t-p} + e_t \tag{2.1}$$

or equally

$$x_t = b + B_1 x_{t-1} + B_2 x_{t-2} + ... + B_p x_{t-p} + u_t. \tag{2.2}$$

Equation (2.1) is called the structural vector autoregression (structural VAR) and equation (2.2) the reduced form VAR. Since some of the variables might be integrated and even co-integrated, the concept of a vector error correction model (VECM), which is represented in equation (2.3), is also introduced:

$$\Delta x_t = d + D_1 \Delta x_{t-1} + D_2 \Delta x_{t-2} + ... + D_{p-1} \Delta x_{t-p+1} + \Pi x_{t-1} + v_t, \tag{2.3}$$

with $\Delta x_t \equiv (x_t - x_{t-1})$. This system of equations is assumed to be complete enough to represent the economy and, thus, its dynamic effects. The main interest lies in the dynamic effects of a shock to the policy equation. One of the equations in the system is the policy equation and it is assumed that this equation represents the reaction function of the central bank. It is analyzed what happens if the central bank deviates from this rule, in other words, if there occurs a shock to the policy equation, or in short, a policy shock.[4]

[3] E.g. Ciccarelli and Rebucci (2002).

[4] For a general discussion of this kind of analysis see e.g. Christiano et al (1998).

2.3 Data and model specification

2.3.1 Data

Monthly data on oil price, federal funds rate, industrial production, consumer price index, monetary aggregate (M1 in most specifications), domestic interest rate (three months LIBOR in most specifications) and an exchange rate (in most specifications the Domestic-currency/US-Dollar exchange rate, monthly averages) is used. All variables, except the interest rates, enter in logs into the system of equations. If not otherwise stated, the data begin in 1979 and go up to 1998. Both seasonally unadjusted and seasonally adjusted data are used, either, if available, the series quoted as such, or seasonally adjusted by ourselves using X-11, multiplicative, from Eviews. The data are from OECD and IMF as quoted in the International Statistical Yearbook 2000.

The following abbreviations are used in tables and graphs: if not otherwise stated, OP represents oil price, FFR the federal funds rate, Y industrial production, P the consumer price index, M the monetary aggregate M1, SR the three months interest rate and EXC the exchange rate. These symbols might follow two letters identifying a particular country. GE stands for Germany, FR for France and IT for Italy. For example, $GESR$ means German interest rate.

2.3.2 Empirical model

For analyzing the effects of monetary shocks on output and prices at least three variables are needed, namely the ones mentioned before and a policy instrument. In the present model the policy instrument is a short-term interest rate. However, as will be discussed later on, many countries were either targeting (officially or actually) a monetary aggregate or watching it carefully, consequently this variable should be included as well. Since European countries are studied, which are economies with a high degree of openness, it seems necessary to include an exchange rate. In order to extract correctly a policy shock, there is need for a variable which captures supply shocks. In the present system of equations the oil price plays this role. Furthermore, it is a variable which contains information on future inflation and, therefore, is likely to be watched closely by a central bank. Finally, interest rates in one country are not independent of interest rates in other countries. This fact is controlled for by including the federal funds rate, or in some sections, for France and Italy, the German interest rate.

Theory tells something about the relationship between e.g. money and interest rate. But there are many monetary aggregates and even more interest rates, thus, the econometrician has to make a choice which one to take. Since the main purpose is to specify correctly the policy function of the central bank the variables which are most likely to enter it are used. For example, Germany had a clear commitment to target a monetary aggregate and, therefore, one should include it.[5] Although the targeted monetary aggregate was M3, the monetary aggregate M1 is included into the empirical model, because both aggregates are strongly correlated and the formulation of a money demand equation for M1 is more straightforward than for M3.[6]

In table 2.7, in the appendix, correlation coefficients of different interest rates across countries are provided. The interest rates are the federal funds rate, three months LIBOR rates for Germany and France and the three months interbank rate for Italy. Simply looking at correlation coefficients does not support a follower-leader relationship among Germany and the other European countries. Indeed, the coefficients among, e.g., the federal funds rate and the French short-term rate are as high as among the German and the French short-term rate.[7] Thus, the federal funds rate is used as the foreign interest rate. Nevertheless, in section 2.6.3 the German interest rate is used as foreign interest rate, as well. Furthermore one could argue to use, for example, the treasury bill rate and not the three months LIBOR rate. The various interest rates are highly correlated, therefore the precise choice of the short-term interest rate should not matter too much.

The interest rate equation is assumed to represent the policy equation. This is by now a widely used assumption, but it may be controversial, thus, this issue is discussed in more detail. Although the Bundesbank was officially targeting M3 as a monetary aggregate, there are several papers intending to show that the Bundesbank was effectively targeting other variables.[8] Clarida and Gertler (1996) found that it was *de facto* managing short-term interest rates. Similarly, Bernanke and Mihov (1997) argue that the German monetary authority was targeting inflation and that the call rate as a policy variable does almost as good as modelling a market of reserves, especially from 1980 onwards. Walsh (1998) states that central banks in both France and Germany started targeting a monetary aggregate in the mid 1970's (1977 and 1975, respectively), but from the mid 1980's onwards it is sensible to assume interest rate targeting. According to Gaiotti (1999) the treasury bill rate can be used as a policy instrument for the Italian central bank from 1981 onwards, whereas the overnight rates starts to become useful from 1988 onwards (De Arcangelis, 1999). Taking into account

[5] See e.g. Issing (1997).

[6] A money demand equation should include, among other things, the opportunity costs of holding money (see e.g. Ericsson (1998)). For M1 this would be a short-term interest rate and possibly the inflation rate. However, for M3, the adequate opportunity costs would additionally involve a long-term interest rate. Since we do not want to blow up the system unnecessarily and because of the high correlation between M1 and M3, M1 is included.

[7] For this comparison to be completely valid one might have to use a 3 months rate for the US as well.

[8] See Issing (1997) or Deutsche Bundesbank (1997).

this evidence, it seems reasonable to use the interest rate equation as policy equation.

2.3.3 Identification

The main interest of this chapter lies in studying impulse response functions to orthogonal shocks, that is to the shocks in equation (2.1). To identify the model, which is to obtain equation (2.1) from equation (2.2), some assumptions have to be made on the matrix A_0. Variables are divided into policy and non-policy variables. The policy variables are the monetary aggregate, the domestic interest rate and the exchange rate. The non-policy equations, which are oil price, federal funds rate, output and prices, are identified in a lower triangular fashion, with an additional assumption on the output equation, namely that the foreign interest rate does not affect it contemporaneously. The exchange rate equation serves as an information equation, which is to say, it depends on all variables in the system, contemporaneous and lagged ones. On the interest rate and the monetary aggregate equation more structure is put, in a way such that they represent a policy and a money demand equation, respectively. The policy variable is assumed to depend contemporaneously only on the oil price, money and exchange rate. This involves the assumptions that information on prices and output is not available in the current month and that the home country is not going to react immediately to changes in the foreign interest rate. Money demand is assumed to depend contemporaneously on the interest rate; consumer prices, as opportunity costs; and output, as scale variable. These are commonly made assumptions for a money demand equation.[9] The above described identification is based heavily on Kim and Roubini (2000) and is used in all other subsections unless otherwise stated. Many times the identification scheme is judged whether it leads to *credible* impulse responses.[10] Identification schemes which do not produce credible impulse responses show e.g. a liquidity, price or exchange rate puzzle. The *liquidity puzzle* denotes a situation where a positive change in a monetary aggregate (e.g. M1) is associated with a positive interest rate reaction. The *price puzzle* is called for whenever a positive interest rate change is related to a positive price reaction. Finally, the *exchange rate puzzle* relates to an impact depreciation of the exchange rate, expressed as home vs. foreign currency, associated with a positive change in the home interest rate. These terms are used throughout this chapter, as well.

[9] See e.g. Saikkonen and Lütkepohl (2000) or Ericsson (1998).

[10] Credible impulse responses means that they are in line with what most monetary theories predict (see e.g. Kim and Roubini (2000) for a discussion of this issue).

2.3.4 VAR, VECM and seasonal adjustment

In the following analysis a VAR in levels is the benchmark specification.[11] The reasoning for doing so is that even if some, or all, time series are integrated one gets consistent parameter estimates from a level specification. What is more, the usual estimates of the standard errors are also consistent.[12] The alternative is a VECM, which is labelled specification 1. This involves testing for unit roots and co-integration.[13]

Seasonal adjustment of the series leads to a similar methodological discussion. There are good reasons for using seasonally adjusted data. Usually the goal of the analysis is to study the responses to a typical shock, which means taking out seasonal influences. By deseasonalising a series with a procedure like X-11 one gets a series which is largely free of seasonal effects.[14] This advantage is at the same time a disadvantage. Procedures like X-11 might not only deseasonalise the data, but take away more information. They might smooth the data and, as a consequence, make it more difficult to detect breaks in the series. In short, they might adjust the series "too much". Strictly speaking, the usual unit root tests are not valid if applied to seasonally adjusted data.[15] If seasonally unadjusted data is used, seasonal dummies are included in the model.[16] Seasonally unadjusted data with a VAR in levels is called a variant of the benchmark, whereas with a VECM is labelled specification 2.

It is very likely that these methodological questions are not solved theoretically in a satisfactory manner and, furthermore, because this is an applied analysis, a practical

[11] Authors analysing the transmission mechanism of monetary policy differ in at least two issues. There are those, which take into account integration and co-integration and there are the others, which use a VAR in levels. Furthermore, some use seasonally adjusted data, others do not adjust the series. Usually little space is spent on explaining why one or the other approach is followed. Of course, results could be sensitive to the exact specification.

[12] However, in some cases the limiting distribution might be non-normal and, hence, test statistics will have a non-standard form. Furthermore, in small samples it might be preferable to impose co-integration if it is actually satisfied (see for example Lütkepohl (1993), pp. 369). Since we do not know with certainty if it is satisfied, we follow Hamilton's (1994, pp. 651) advice of using both methodologies and check the results for differences.

[13] For Germany there is a known break date, thus, one might want to use unit root tests, which take this into account, e.g. Perron (1989) and Perron (1990). These tests are not performed at the moment, because the usual unit root tests are considered as a first approximation. Furthermore, using different tests for different countries might lead to results interpretable as country specific, but are rather due to a specific test procedure.

[14] Or using seasonally adjusted data which is often obtained by applying X-11.

[15] Ghysels (1990) and Ghysels and Perron (1993) discuss unit root tests for different types of seasonal adjustment. However, as argued in Hatanaka (1996, p. 70), the conclusions of tests on unit roots should not be too different whether applied to seasonally adjusted or unadjusted data. Since one has to control for seasonal effects in some way, the minimalist version is to use seasonally unadjusted data and include seasonal dummies in the model (see Diebold (1993)).

[16] In general results are for uncentered dummies. However, co-integration tests are performed with centered seasonal dummies. This is a necessary step for correct inference as argued in Johansen and Juselius (1990). (However, interestingly, the test statistics are identical for centered and uncentered dummies.)

approach is taken: All specifications will be used along with the benchmark and it is checked if results differ.[17]

2.4 Stability tests

Maybe the biggest advantage of using a VECM is that standard tests on the estimated parameters, for example also on stability, can be applied. One of the central questions of this chapter is if and how the dynamics changed. These changes of dynamics come from changes in the parameters. Consequently, the natural way to proceed is to test for parameter stability.

For both specifications, tests on lag length, integration and co-integration are performed.[18] It turns out that three lags are sufficient for all countries and specifications. For specification 1 all series in all countries are integrated of order one. The VECM is thus estimated by using one co-integrating vector for Germany and France and two for Italy.

Similarly for specification 2 the null hypothesis of a unit root is accepted for almost all series and countries at 5%. In order to make results comparable across specifications all series are assumed to be integrated of order one. The results on co-integration are also very similar and in what follows, one co-integration vector for Germany and France and two for Italy are used.

2.4.1 Graphical analysis

A first approach to assess instability is the CUSUM and CUSUMSQ test. It is assumed that the co-integration vector is correctly estimated in a first step and then, in a second step, recursive estimates of the single equations of a VECM (specification 1) are preformed and these tests are obtained. Plots are not provided here, rather the results are summarized. The CUSUM test, which can be interpreted as a test on a changing mean (see Hansen 1992), rejects stability in almost all equations and countries. The CUSUMSQ test, which can be thought of a test on a changing variance, rejects stability for the oil price and interest rate equations.

[17] The focus of this paper is on instabilities and changing effects. However, for completeness, the results on a comparison of impulse responses to a monetary shock performed at the full sample are given here as well:

1) Using seasonally unadjusted data leads to very similar impulse response functions for both a VAR in levels and a VECM. Using adjusted data, the VAR in levels and the VECM lead to some different impulse response functions for France and Italy, however, impulses to the variables of main interest are largely unchanged. The responses for Germany do not change.

2) Estimating a VAR in levels gives the same impulse responses for seasonally adjusted and unadjusted data. However, estimating a VECM for France or Italy, using seasonally unadjusted data results in slightly more credible impulse responses. The responses for Germany do not change.

[18] Detailed test results are available from the author.

As said before, it is checked if using seasonal dummies affects the results. Recall that a seasonal adjustment procedure might smooth breaks and so make it more difficult to detect them. Using specification 2, the results on the CUSUM test do not change dramatically. However, for the CUSUMSQ test additionally to the rejection of stability of the interest rates also indications of instabilities in the price and money equation are found. These results are not discussed further, because the idea of performing these tests is to get a quick assessment of instabilities. In the next subsections a more detailed picture of parameter instabilities is drawn.

2.4.2 Nyblom (1989) test

As can be seen in table 2.8, in the appendix, there is evidence of instabilities in specification 1.[19] Confirming our intuition the interest rate equations are unstable and this is mainly because of a changing variance. Not too surprisingly the money equation in Germany is unstable and this is due to the constant. What is maybe more surprising is the instability in the output and money equation in France and Italy. And again it is the variance and not the constant for which stability is rejected. For specification 2, not at all contrary to our conjectures, even more instabilities are found in the system (for details see table 2.8 in the appendix).

If stability is rejected for one equation as a whole that does not mean that all parameters are moving. Rather it could be that only some parameters are driving this result. Thus, the solution seems to test individual parameters for stability. However, if there is a large number of parameters, tests on a single parameter are not very powerful (see Hansen, 1992).[20] Before taking a decision on how to model instabilities some more tests are applied. In the next subsection break dates for unstable equations and also for the whole system are estimated. Splitting the sample at some, endogenously determined, break date may very well induce a stable model.

2.4.3 Andrews (1993) and Harvey-Collier (1977) tests

For the single equations the heteroskedasticity consistent version of the test is applied. For the whole system both the basic and the heteroskedasticity consistent versions are computed.[21] For detailed test results see tables 2.9 and 2.10 in the appendix.

[19] All test statistics are asymptotically robust to heteroskedasticity.

[20] In our case each equation has 22 parameters, not counting possible seasonal dummies.

[21] The heteroskedasticity consistent test-statistic is based on weighted least squares. This has been performed by dividing all series by the foreign interest rate (usually the federal funds rate, but, e.g. in section 2.6.3 the German interest rate), because as seen before, the heteroskedasticity is likely to be driven by one, or both, of the interest rates. The critical values are computed from extrapolating Andrews's (1993) table 1. For 20 parameters, $\pi = 0.15$ and 5% we have a critical value of 43. The increments for one more parameter are around 1.6. We have 154 parameters, hence, 43+134*1.6 gives

Probably the most striking result for specification 1 is that the test statistics for the whole system are very close or above the critical value. This indicates that splitting the sample in two parts might improve the estimation considerably. This issue is taken up in detail in the next section. Test results include a stable German money equation and Italy as the most unstable country. Since it turns out that there are some substantial differences in using seasonal dummies[22] the results from specification 2 are shown, as well.[23] The Harvey-Collier (1977) test finds instabilities in the interest rate and money equations.

Two obvious extensions to the tests performed here could be undertaken. The first one is to look on single parameters and check if some striking results on instabilities are found. The second one is to perform these tests directly on the structural equations. If there are instabilities in the reduced form equations, there will also be some instabilities in the structural equations. It can be interesting to perform these tests, because it might allow to pin down more exactly the sources of instabilities. Suppose only the matrix of contemporaneous coefficients, matrix A_0 in equation (2.1), is unstable and all the other structural parameters, i.e. all other parameters of equation (2.1), are stable. Then, the reduced form parameters, from equation (2.2), will be unstable as well. Performing stability tests simply on the reduced form parameters will not reveal that only A_0 is unstable. Nevertheless, these tests have not been performed, because it is unlikely that only contemporaneous parameters are unstable and lagged parameters are stable. What is more, letting only some parameters change complicates the estimation considerably and estimating structural equations in the present set-up involves instrumental variables.[24] For an identification like the one used here it is not obvious which instrument to choose for the contemporaneous exchange rate in the policy equation. Furthermore the calculations of test statistics would have to be modified.

2.4.4 Conclusions

In table 2.1 the results from a range of tests on stability are summarized. All the unstable equations according to different tests are listed. As already mentioned above, by using seasonally unadjusted data (specification 2) some additional equations turn unstable (as compared to specification 1).

approximately 257. All p-values shown are computed by Hansen's GAUSS code, following Hansen (1997).

[22] Uncentered seasonal dummies are used.

[23] The critical values are computed again from extrapolating Andrews's (1993) table 1. For 20 parameters, $\pi = 0.15$ and 5% we have a critical value of 43. The increments for one more parameter are around 1.6. We have 231 parameters, hence 43+211*1.6 gives approximately 380.

[24] See Shapiro and Watson (1988).

Table 2.1: Stability tests.

Test type	Specification 1			Specification 2		
	Germany	France	Italy	Germany	France	Italy
Nyblom (all parameters)	FFR, M, SR	FFR, Y, P, M, SR	FFR, Y, P, M	OP, FFR, Y, P, M, SR, EXC	OP, FFR, Y, P, M, SR	OP, FFR, Y, P, M, SR, EXC
Nyblom (variance)	FFR, SR	FFR, Y, M, SR	FFR, Y, P, M	FFR, Y, M, SR	FFR, Y, P, M, SR	FFR, P, M, SR
Andrews	FFR, M, SR	P	Y, P	Y, P, M, SR	Y, P, M	Y, P, M
Harvey-Collier	M, SR	FFR	M, SR	SR	FFR	Y

NOTE: Equations for which stability is rejected at 10%. See the detailed tables or the text for information on the tests.

In specification 1 and for Germany the different tests tell almost the same story, namely that the equations for the two interest rates and the money aggregate fail to be stable. It looks like that the instability of the interest rates comes from the variance. This possibility will be checked later. Furthermore, the instability in the monetary aggregate seems to come from a changing mean. Two possible explanations arise. The first one is that the adjustment undertaken for the German unification is not good enough, or worse, introduces some more instability. The second one is that the money equation indeed is unstable. This could be explained by the shift from monetary targeting to interest rate targeting in the mid or late 1980's as discussed above. However, Wolters et al. (1998), analyzing a smaller system, find their money demand equation to be stable after including a shift dummy and an impulse dummy in the third quarter of 1990. So far there is no good explanation for the instability found, but it might be that it comes from including the federal funds rate. This can be checked by analyzing the system without the federal funds rate, by simply looking on the stability tests for single parameters on the lagged federal funds rate, or by starting the sample in 1983, that is to say, leaving out a highly unstable period, the so-called Volcker period. These issues are explored below.

For France, the conclusions are not so obvious. The only equation, which is found to be unstable with the Andrews (1993) test is the price equation. For the other tests interest rates are unstable and the Nyblom (1989) test also indicates output and money to be unstable. Again, it has to be checked if this comes from the instability of the federal funds rate, and especially its variance.

Similar conclusions can be drawn for Italy. The Andrews (1993) test finds only the output and the price equation to be unstable, whereas the Nyblom (1989) test indicates instability in some more equations. The above remarks also apply here.

Looking at specification 2, the main difference to specification 1 is the result on the output equation. Now in all countries, and by almost all tests, except Harvey-Collier (1977) for Germany and France, stability for it is rejected.

Table 2.2: Break dates.

	Specification 1			Specification 2		
Equation	Germany	France	Italy	Germany	France	Italy
OP	09/1982	08/1986	09/1992	09/1986	03/1988	07/1986
FFR	04/1988*	09/1982	10/1982	03/1983	11/1982	10/1982
Y	08/1991	02/1989	12/1989*	11/1990*	01/1989*	06/1989*
P	05/1990	12/1986*	06/1984*	07/1989*	05/1990*	12/1985*
M	04/1991*	08/1995	11/1992	01/1989*	08/1987*	10/1988*
SR	02/1989*	04/1984	05/1984	06/1990*	11/1985	05/1992
EXC	01/1985	09/1982	07/1982	08/1984	11/1982	02/1991
SYSTEM	08/1982*	09/1982*	07/1982*	08/1982*	09/1982*	07/1982*
SYSTEM (hc)	09/1992	01/1990	09/1992*	08/1992*	01/1990*	12/1991*

NOTE: * denotes significance at 10%. hc means heteroskedasticity consistent test. See the detailed tables or the text for information on the tests.

Table 2.2 shows the estimated break dates. For output, break dates are in 1989 for France and Italy and in 1991 for Germany. The price equation for Italy breaks around 1984, for France in 1986 (specification 1) and 1990 (specification 2). The German money equation breaks in 1991 (specification 1) and in the beginning of 1989 (specification 2). Roughly the same break date is estimated for the Italian money equation, the French one breaks a year earlier. For Germany both interest rates (FFR and SR) break around 1989 (specification 1), and in 1990 (only SR, for specification 2). The system test without heteroskedasticity consistency shows breaks at the very beginning of the sample.[25] If the volatility of the federal funds rate is taken into account, the German and the Italian system break in 1992, the French system in the beginning of 1990.

Result 1: For every country and every specification some unstable equations are found. The interest rate equations are almost always unstable, but in same cases also prices, money demand and output equations are found to be unstable. These results hold for various different tests. Break dates are estimated to be in the second half of the 1980's and early 1990's.

Several reasons might account for these instabilities in the parameters. As already mentioned above, it can be argued that European central banks switched from money targeting to interest rate targeting, somewhere in the late 1980's. Perhaps they did so, because the money equation became unstable, or its instability was then realized. Similarly, this switch may explain the instability of the interest rate equation. By stretching this argument further, a changing monetary policy instrument may be responsible for changing price and output equations, as well. However, another

[25] Possibly again due to the huge volatility in the federal funds rate or to an agreement among countries of the European monetary system in March 1983 which put a stop to previously frequent realignments. See e.g. Juselius (1998).

possibility is the liberalization of financial markets and its impact on the economy. Although investigating further the causes of instabilities is a very interesting topic, it is left for future research. The present work rather studies the implications of the above documented instabilities for the dynamic effects of monetary policy.

2.5 Instabilities and dynamics

Firstly, the sample is split at some, endogenously determined, break date and the resulting dynamic effects of a monetary policy shock are analyzed. Secondly, country differences in the transmission mechanism of monetary policy shocks are studied. Thirdly, one particular possible structural break is closely looked at, namely the creation of the common currency. Finally, the possibility of letting only some equations, or parameters, change over time is explored.

2.5.1 The changing transmission mechanism

Starting with the benchmark specification, impulse responses to a one-unit increase in the domestic interest rate are discussed.[26] For Germany the sample is split at the end of 1991. Comparing the first and second sub-sample some striking, and significant, differences can be seen. The most important ones are that in the second sub-sample output and prices fall considerably more in response to a monetary shock. On the other hand, the exchange rate falls less (appreciates less), but does so for a longer period. Similar results hold for France, which is split in the middle of 1989. Prices decrease much more in the second sub-sample and what is more the decrease is significant. However, the reaction of the exchange rate changes completely. In the first sub-period, the impulse response function is similar to the one for Germany, in the second sub-period there is an initial depreciation. Italy is split at the end of 1991, but it is not possible to identify the second sub-sample with the same assumptions made for the other countries. Therefore, results are not discussed here.

The complete set of impulse responses for the variant of the benchmark specification is shown in the appendix, in figures 2.1 to 2.6, whereas a comparison of significant differences across sub-samples is provided in figures 2.7 to 2.13. Due to the inclusion of seasonal dummies, now the samples are split at the beginning of a year. The January closest to the estimated split date is chosen. For Germany, basically the same as before holds, namely that the reaction of output, prices and exchange rate is stronger in the second sub-sample. But now, additionally, the reaction of money is stronger, too. For France, again, the output reaction is stronger in the second sub-sample. Addition-

[26] Plots of impulse response functions are available from the author.

ally, money reacts stronger and the exchange rate decreases (appreciates) slower, but increases (depreciates) faster. For Italy, in the second sub-sample the liquidity and the exchange rate puzzle are found, so results are not interpreted since the monetary shock might not have been identified correctly.[27]

Concerning the other specifications it has to be noted that for the second sub-sample the standard identification does not work for Italy and France.[28] Therefore only Germany is discussed here. For specification 1, output and money decrease significantly more in the second sub-sample, although the exchange rate increases insignificantly. In specification 2 output, prices and money react stronger in the second sub-sample, however, the exchange rate decreases more in the first sub-sample. The following lines summarize what is robust across specifications.

Result 2: For Germany and France, the reactions to a monetary shock have in general increased over time, being stronger in the second sub-sample, which corresponds roughly to the 1990's.

The impulse responses discussed so far show the effects of a one-unit increase in interest rates. These effects have increased over time. One explanation might be that a typical monetary policy shock was larger in the 1980's than in the 1990's, and in consequence a one-unit increase had a bigger impact in the later period. If this is the case and coming back to the interpretation of a policy shock, as described in the introduction, one can conclude that in the 1990's a) there were fewer preference shifts within the monetary authority, or b) private agents understood better the central banks' behavior, which implied fewer incentives to avoid the costs of disappointing them, or c) more accurate preliminary data were available implying smaller measurement errors. Alternatively, it could be that only in the second sub-sample the interest rate equation represents the monetary policy equation and, accordingly, an increase in the interest rate in the first sub-sample reflects something else than a policy shock. This is clearly a possibility, however, as argued above, it seems reasonable to use the interest rate as policy instrument throughout the full sample period.

To get an idea if splitting the sample at endogenously determined break dates produces a stable system, the stability of sub-samples for specification 1 for France is checked. In the first sub-sample only the price equation and the variance of the federal funds rate equation are found to be unstable, whereas in the second sub-sample the

[27] In a later section a sub-sample comparison for Italy is performed, as well. Including the German interest rate in the Italian system seems to identify correctly the monetary shock for the second sub-sample.

[28] Recall that in this section samples are simply split and a separate estimation of each sub-sample is performed. However, using co-integration and assuming that the co-integration relationship is not subject to a break, it might be much better to estimate the co-integration relationship over the whole sample. In the present analysis one co-integration relationship is estimated for each sub-sample, which might explain why we get very imprecise estimates for these two specifications.

only instabilities found are the variances of the output and oil price equation. In short there are almost no instabilities left. For completeness sub-sample stability should be checked for all other countries, too.

2.5.2 Country differences in the transmission mechanism

Different countries do not react in the same way to a monetary policy shock. These differences are documented by computing, for all countries, the effects of a one-unit increase in the interest rate (see figures 2.14 to 2.19). In the first sub-sample, which corresponds roughly to the 1980's, output decreases slowly in Germany and Italy, whereas the reaction is insignificant in France. Germany and Italy show a similar pattern for the price reaction, as well. After an initial decrease, prices increase, however, not significantly for Italy. France shows an increase in prices, but it is hardly significant. The exchange rate appreciates significantly on impact and is followed by a depreciation for Germany and Italy. The reaction of the French exchange rate is hardly significant. In the second sub-sample, roughly the 1990's, output decreases rapidly in response to a shock for France and Germany. The output reaction for Germany is stronger than for France. The same holds for prices. The exchange rate reaction differs, too. For Germany only a long lasting appreciation can be observed and France shows a relatively quick appreciation followed by a deprecation.

Result 3: Responses to a monetary policy shock differ across countries. Usually Germany shows the largest effects.

Responses to a monetary policy shock may differ across countries due to differences in financial systems and institutions in general. It seems intuitive that a one-unit increase in interest rates has a bigger effect in Germany than in other countries. The Bundesbank has gained a reputation of fighting inflation fiercely and indeed was very successful in it. Probably a relatively small change in the interest rate was already a sufficient signal for private agents to react, whereas in other countries a larger change was necessary.

2.5.3 EMU – what changed?

There is one event which might have changed completely the structure of the economy, namely the creation of a common monetary policy. This step was announced in December 1995 and came into being in 1999. During these three years, the transition period, could one observe some changes in the transmission mechanism? In other words, did agents prepare for this upcoming event and, in consequence change their actions, or did nothing happen until the end of 1998? This subsection sheds some light on this question. Impulse responses are estimated for a sub-sample, excluding these three years, and are then compared to the results from the full sample. Furthermore, the effect of having a different number of observations is also checked for. Since impulse responses between specifications do not seem to change much and the benchmark shows the results clearest, the benchmark specification will be used as a first approximation.[29]

Comparing the impulse responses from the full sample to those excluding the last three years it can be seen that for Germany the full sample has a weaker price and output reaction than the one excluding the transition period.[30] For France, the full sample has a stronger output, money and exchange rate reaction, but a weaker price reaction. Especially the reaction of the money aggregate changes dramatically by switching its sign. For Italy, basically only the output reaction changes and it is stronger in the full sample.

In order to compare impulse responses from estimations which have the same sample size, the full sample including the transition period starts at 1982:1, and the subsample excluding the transition period, starts at 1979:1. For Germany, including the transition period leads to slower output, stronger money and exchange rate and weaker price reaction. For France, including this pre-EMU period leads to stronger output and exchange rate reaction. Additionally money reactions switch sign. For Italy, including the transition period weakens output and money reaction and changes the sign of the exchange rate reaction.

Nevertheless, the beginning of the 1980's was a turbulent time concerning monetary policy, especially monetary policy in the US. By comparing two sub-samples, for which this period is included in only one, different results might reflect precisely this fact. However, if one wants to see what changed in Europe, one cannot be sure, where possible changes came from. Therefore, as a last exercise, two sub-samples are compared for which both start in 1982:1 and one ends in 1995:12, and the other ends in 1998:12. For Germany, including the transition period weakens the output reaction and strengthens the money and exchange rate reaction. For France, the output, money and exchange rate reaction became stronger. For Italy, basically nothing changes.

Summarizing all this information, it can said that, in the case of Germany, the transition period made price reaction weaker, output reaction weaker or slower, and money and exchange rate reaction stronger. Although not all of these effects are observed in any single estimation, they are fairly consistent over different samples. The picture for France is even more uniform across samples. Output, money and exchange rate react stronger when the transition period is included. Also a switch in the sign of the money response is observed. For Italy, conclusions are less clear.

[29] See the last footnote of subsection 2.3.4 "VAR, VECM and seasonal adjustment".

[30] Plots of the impulse response functions are available from the author.

Including the pre-EMU years some changes are found, but different ones for different samples. All in all, there are pronounced changes, especially in Germany and France. One possible explanation is the creation of the monetary union, but, of course, these effects could be independent of it. If it is indeed the creation of EMU is worth studying in more detail.

Result 4: Including the three pre-EMU years (1996-1998) in the sample changes the reaction to a monetary shock. For Germany, output and prices react weaker, but money and exchange rate stronger. For France, output, money and exchange rate react stronger. For Italy, the results depend on the exact specification and so no general conclusion is possible.

The stronger effect of a policy shock in France in the run-up to EMU could be interpreted as the benefit of being in a monetary union with Germany, famous for its success in monetary policy. A similar interpretation could be given for the weaker effects in Germany, when being in the same union as France.

2.5.4 Conclusions

There are several insights, which can be stated with fairly high degree of confidence. They are summarized in results 2 to 4 and say that 1) reactions to a monetary policy shock have changed over time, being stronger in the second sub-sample (1990's) for France and Germany, 2) the transmission mechanism is different across countries and 3) taking pre-EMU years into the sample makes a monetary policy shock less effective on output and prices for Germany, but more effective for France. The reaction of money and exchange rate becomes stronger for both Germany and France.

As has been seen above, only some equations are unstable. Nevertheless, so far sub-sample analysis have been performed, meaning that all parameters and, therefore, equations are allowed to change. It might be a good strategy to allow only the unstable parameters to change. There are several reasons why this analysis has not been undertaken. Firstly, and this is a technical reason, by letting only some parameters change the right hand side variables differ from equation to equation. This implies that the simple way of estimating a VAR, namely performing OLS equation by equation, is no longer equal to the maximum likelihood estimation. Rather one has to set up a system of seemingly unrelated regressions.[31] Secondly, and maybe more important, it is not so clear from the instability tests which equation one would like to restrict to not change over different sub-samples. Some equations, like the interest rate equations, are unstable, no matter which test is applied, but for other equations the result is not so sharp. Thus, in order not to impose false restrictions, the general approach of not

[31] See Hamilton (1994), pp. 315.

imposing any restrictions is taken.

2.6 Sensitivity analysis

2.6.1 Oil price in local currency

It is crucial for the current study to specify a correct model of the economy, which involves including the right variables in the empirical model. So far the oil price in US$ has been used, but this variable might not be the most relevant variable for e.g. the Italian economy. Nevertheless, using the oil price in local currency leads to very similar results for the stability tests and break dates (Italy) and impulse responses (Germany). Therefore, as a first answer to the question, it can be said that the currency in which the oil price is measured does not matter for the present analysis. However, to be completely sure, one should check the results for all countries.

2.6.2 Excluding the Volcker period

Examining the errors of the VAR as estimated above shows that the ones corresponding to the federal funds rate equation are much more volatile in the first three years of the sample.[32] This corresponds to the so-called Volcker period (1979:10 to 1982:10), which was a period of a monetary policy regime in the USA substantially different from the regime in the years afterwards.[33] In the tests above it has been found that the variance of interest rates might be a major reason for instabilities. To assess this intuition these years are excluded from the sample. Another possibility is to exclude the federal funds rate from the system. However, one should note that the federal funds rate is an important variable for several equations, so not including it might result in a misspecified model.

The model uses specification 1 with the sample starting in 1983:1 and ending in 1998:12. Results on lag length, integration and co-integration are very similar to the full sample. The only difference is that now two co-integrating vectors for France are included, as well. To summarize, 3 lags are included for all countries, all series are integrated, and Germany has one co-integrating vector, while France and Italy have two. In tables 2.11 to 2.13, in the appendix, results for various instability tests are provided in detail. A summary of these tests is shown in tables 2.3 and 2.4.

[32] Christiano et al (1998) and Walsh (1998) conclude similar.

[33] In August 1979 Paul A. Volcker became the chairman of the Federal Reserve System. In October 1979 the Fed moved to a nonborrorwed-reserves operating procedure in order to bring down the high inflation of the 1970's. From 1982 onwards the Fed has generally followed a borrowed-reserves operating procedure, which is similar to a federal-funds-rate operating procedure (see e.g. Walsh, 1998).

Table 2.3: Stability tests; excluding the Volcker period.

Test type	Specification 1		
	Germany	France	Italy
Nyblom (all parameters)	-	P, M, SR	FFR,Y, M, SR
Nyblom (variance)	FFR	FFR,Y, M, SR	FFR,Y, M, SR
Andrews	SR, EXC	P	Y, M, SR
Harvey-Collier	-	SR	EXC

NOTE: Equation for which we reject stability at 10%. See the detailed tables or the text for information on the tests.

Table 2.4: Break dates; excluding the Volcker period.

	Specification 1		
Equation	Germany	France	Italy
OP	11/1986	10/1986	07/1992
FFR	04/1988	07/1992	04/1988
Y	09/1990	03/1989	03/1991*
P	09/1990	07/1988*	09/1986
M	02/1987	05/1991	09/1992*
SR	02/1989*	07/1986	10/1992*
EXC	11/1989*	04/1994	07/1986
SYSTEM	03/1989	08/1986*	08/1986
SYSTEM (hc)	07/1993	06/1990	09/1992*

NOTE: * denotes significance at 10%. Sample starts in 1983:4, after adjusting for 3 lags. hc means heteroskedasticity consistent test. See the detailed tables or the text for information on the tests.

Comparing test results with the previous section, it turns out that instabilities are less present, but, however, there are still many unstable equations. Almost all equations, which were unstable before, continue to be so now also. However, there are some more, for example the exchange rate equation for Germany, or the interest rate equation for Italy. Also some break dates change. All in all, it has to be said that the federal funds rate and its variance in the beginning of the 1980's is not the only driving force of instabilities.

Impulse responses from the benchmark specification for the full sample and for the one excluding the Volcker period are compared, too. For Germany, the full sample gives a smaller price and exchange rate reaction. For France, the full sample has a stronger reaction on output. Both the price and the money reaction switch signs. The price reaction becomes less credible while the money and the exchange rate reaction becomes more credible in the reduced sample. For Italy, the output and money reaction becomes stronger in the full sample, whereas the exchange rate reaction switches sign and becomes more credible. The general result on impulse responses is that they are sensitive to including or excluding some more data points. The question is how one decides where to start the sample or equally which results one should believe. One could investigate further why impulse responses change and take the reasons for these changes explicitly into account. One possible reason has been given above, namely the change in the US monetary policy and the implied changes in the behavior of the federal funds rate. However, there might have occurred some particular events in the European economies, which then implied different responses to monetary policy shocks. For example, one can look more carefully on institutional changes (e.g. the independence of the Italian central bank in 1981, EMS crisis or other exchange rate events) and analyze if they explain the discrepancies.

2.6.3 Is Germany or the USA Europe's leader?

So far the federal funds rate has been included as a foreign interest rate in the system of equations. This means that the federal funds rate is considered to be an important variable in explaining macroeconomic variables in Italy and France. But, one might say, the Bundesbank and the German interest rates were by far more important for these countries than the Fed and its target interest rate. This question has already been addressed above by checking for correlations among interest rates. No reason for rejecting a model using the federal funds rate has been found. Indeed, there was slight evidence in favour of it and against using the German interest rate.[34] However, the present subsection presents a more formal analysis of this issue. For specification 1 and the full sample size, 3 lags are sufficient, all variables are found to be integrated and, this is different, two co-integration vectors for France and one for Italy have to be used.[35] In tables 2.5 and 2.6 results from the stability tests are summarized. More details can be found in the appendix, in tables 2.14 to 2.16.

Table 2.5: Stability tests; including the German interest rate.

Test type	Specification 1	
	France	Italy
Nyblom (all parameters)	GESR, P, M, SR	GESR, P, M
Nyblom (variance)	GESR, Y, M, SR	GESR, Y, P, M
Andrews	P	P, M
Harvey-Collier	M	GESR, M

NOTE: Equation for which we reject stability at 10%. See the detailed tables or the text for information on the tests.

Also with this specification instabilities are widely present and in general the same equations as before are found to be unstable. The estimated break dates are in the

[34] This is in line with Uctum (1999) who finds some evidence for German dominance over France and Italy for his full sample, 1982 to 1996, but no evidence for it in a reduced sample involving only the 1990's.

[35] However, the precise number of co-integration vectors does not change the results on instabilities. Using one co-integration vector for France and two for Italy, as in the previous sections, gives the same picture.

late 1980's and early 1990's. Note that a significant break is estimated for the whole system in France and the system for Italy breaks almost significantly at 10% as well.

Table 2.6: Break dates; including the German interest rate.

	Specification 1	
Equation	France	Italy
OP	06/1986	09/1990
GESR	07/1982	05/1993
Y	02/1989	02/1991
P	12/1986*	06/1984*
M	09/1986	11/1992*
SR	03/1984	01/1991
EXC	01/1994	12/1992
SYSTEM	03/1983	07/1982
SYSTEM (hc)	08/1986*	01/1988

NOTE: * denotes significance at 10%. Sample starts in 1979:4, after adjusting for 3 lags. hc means heteroskedasticity consistent test. See the detailed tables or the text for information on the tests.

Impulse response functions of a variant of the benchmark are discussed and compared with a system including the federal funds rate.[36] For France, the impulse response functions are fairly similar, the only striking differences are observed in the exchange rate reaction. In the first sub-sample, including the German interest rate, the exchange rate depreciates on impact. In the second sub-sample, an impact appreciation is followed by a slow depreciation. For Italy both specifications differ considerably. Including the German interest rate leads in the first sub-sample to the liquidity puzzle, to an increase in prices and a weak output reaction. Including the federal funds rate gives a decrease in prices and money as response to a monetary shock. In the second sub-sample just the opposite is true. Including the German interest rate leads to a decrease in prices and in the exchange rate, as well as in output. The price reaction is not significant. On the other hand, including the federal funds rate, leads to the liquidity and exchange rate puzzle as well as to an increase in prices and output.

For France it does not matter much if the federal funds rate or the German interest rate is included as a foreign rate. However, for Italy, the federal funds rate leads to

[36] The sample is split at the same dates as in the previous sections, because results should be comparable. However, the analysis is also performed for the break dates as estimated in this section. It has been seen previously that break dates for the whole systems do not vary much across specifications, hence, one can be confident to discuss results from using seasonally unadjusted data, although one should check break dates for specification 2 as well. For both countries the sample is split at the end of 1985. Results are very similar to the ones from the split at the end of 1989 or 1991, respectively. The differences arise in the price reaction, which is negative for the first sub-sample in Italy and the second sub-sample in France. In the second sub-sample, for Italy, now an increase in prices is observed. Furthermore, money tends to rise on impact for France in the first and for Italy in the second sub-sample. To summarize, some impulse responses gain in credibility by splitting the sample earlier, in particular this is true for Italy in the first and for France in the second sub-sample.

more credible impulse responses in the first sub-sample, whereas the German interest rate does so in the second sub-sample. Therefore, the German interest rate is included only for the second sub-sample for Italy. Doing this makes us more confident that the monetary shock has been identified correctly. A sub-sample analysis for Italy is performed and the responses are compared to other countries. For Italy, in the second sub-sample (1990's) responses to a monetary shock are weaker than in the first sub-sample (1980's). In the first sub-sample, Italy's output and exchange rate reaction is very similar to the one for Germany, whereas its price reaction is similar to the one for France. In the second sub-sample, the exchange rate behaves as in France, whereas the price reaction is between France and Germany, and the output reaction is the weakest of all three countries.

2.6.4 Interdependence among European economies

In addition to the above performed sensitivity analysis there are some other issues, which one could check, for example the use of different exchange rates for different countries. It might be that the relevant exchange rate for France and Italy was against the DM and not against the US$ as previously assumed. Estimating impulse responses for the benchmark specification, which in this case includes the oil price in local currency, the German interest rate and the exchange rate against the DM, supports in general the results presented above. However, the exchange rate puzzle and the liquidity puzzle show up in some sample periods for both countries.

2.7 Conclusions and further research

This chapter analyses, for several European countries, the dynamic effects of an unexpected monetary policy action and how they changed over time. Responses to a monetary policy shock in Germany and France are stronger in the 1990's than in the 1980's, whereas weaker in Italy. Nevertheless, these responses differ substantially across countries. What is more, the effects of a monetary policy shock changed after the creation of the European Monetary Union was announced.

In order to analyze changes in the dynamic effects, stability tests on the estimated parameters are performed. For every country and every specification some unstable equations are found. The interest rate equations are almost always unstable, but in same cases also prices, money demand and output equations are found to be unstable. Besides that especially variances of most equations are unstable. One possible explanation for the instability of the interest rate equation is the switch of European central banks to an interest rate rule in the middle of the 1980's. Money equations are found to be unstable, which might be part of the explanation for this switch, since targeting a monetary aggregate needs a stable equation for it. Break dates are estimated to be in the second half of the 1980's and early 1990's.

Taking these findings into account, it is shown that for Germany and France responses to a monetary shock have increased over time, being stronger in the second sub-sample, which corresponds roughly to the 1990's, whereas for Italy the opposite holds. One explanation can be that a typical monetary policy shock in France and Germany was larger in the 1980's than in the 1990's, and so a one-unit increase in the interest rate had a bigger impact in the later period. If this is the case, depending on the preferred interpretation of a monetary policy shock, one could even draw further conclusions. For example that the monetary authority had fewer preference shifts in the more recent period, measurement errors of preliminary data have decreased over time, or private agents improved in predicting the central banks' actions.

Responses to a monetary policy shock differ across countries. Usually Germany shows the largest effect. Differences in financial systems and institutions are good candidates to explain differences in the transmission mechanism. Probably a relatively small change in the interest rate in Germany was already a sufficient signal for private agents to react, whereas in other countries a larger change was necessary. Therefore, for Germany stronger effects in response to a one-unit increase in interest rates are found.

Including the three pre-EMU years (1996-1998) into the sample changes the reaction to a monetary shock. For Germany, output and prices react weaker, but money and exchange rate stronger. For France, output, money and exchange rate react stronger. For Italy, the results depend on the exact specification and, thus, no general conclusion is possible. One interpretation for these results is the creation of the EMU. That is to say, for implementing a common monetary policy action the EMU countries have to agree on the action in place. Therefore, a common monetary policy will react as an average of national monetary policies, e.g. not being as strict on inflation fighting as Germany, but being stricter than France alone. France might benefit from the credibility of the German monetary policy, while Germany will see itself in a weaker position. Agents anticipated this already and consequently the transmission mechanism changed.

It has been shown that results are fairly robust concerning specification and methodological issues. However, what really makes a difference for dynamic relationships is the sample size. Starting the sample some years later can change impulse responses dramatically. This is in line with our findings that many equations are not stable throughout the sample period.

The present work documents parameter instabilities and estimates implications for the dynamic effects of monetary policy shocks. An interesting area of research is to study explanations for the here found parameter instabilities. Several possible explanations have been mentioned above, however, a more thorough analysis remains to be done. In particular, it seems promising to study further the relation between institutional changes in monetary policy execution and the dynamic effects of policy shocks.

2.8 Appendix

2.8.1 German unification

The only variable in the present system of equations which needs an adjustment for the German unification is the monetary aggregate. Up to 1990:6 the monetary aggregates are for West-Germany only, from that month on, which is the month of the German monetary unification, monetary aggregates are for the unified Germany. In the series a jump is observed in this month and it has to be accounted for in some way. As a first approximation we follow Deutsche Bundesbank (1995). It is supposed that the monetary aggregate can be described by an AR(1) process. The autoregressive coefficient is estimated by OLS, using data from 1979:1 to 1990:5. Then the monetary aggregate is predicted for 1991:1 and compared with the actual value of the monetary aggregate at that time. This difference is the estimated jump of the monetary aggregate due to the German unification. This estimated jump is added to the West-German monetary aggregate and, in consequence, one gets the estimated monetary aggregate for a (hypothetically) unified Germany. The reason for calculating the size of the jump at 1991:1 and not at 1990:6 is that in addition to the jump in 1990:6 one observes a higher than usual jump in December 1990. Although money has in general a peak in December, the unusual high number for that year leads to conclude that this is due to the German unification, and so it is taken into account. As already said, this is seen as an approximation and one could estimate the jump directly from and at the same time with the VAR by either including a step dummy and calculating new critical values for Johansen's (1991) co-integration test, as in Wolters et al. (1998), or by applying the methodology developed by Saikkonen et al. (2000).

2.8.2 Impulse response functions

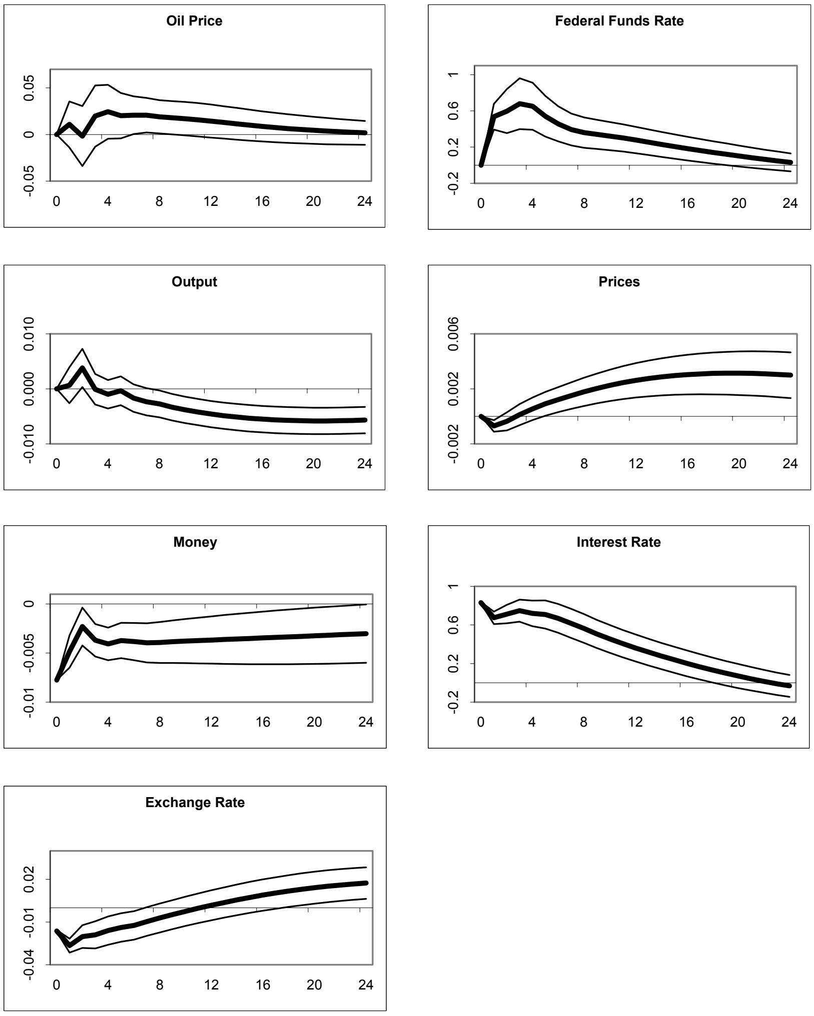

Figure 2.1: Impulse response functions, and one standard error bands, to an orthogonal one-unit shock in the domestic interest rate; for Germany, sub-sample 1979:1 to 1991:12. All impulse responses are from the variant of the benchmark specification, i.e. from a VAR in levels with seasonally unadjusted data. Identification as explained in the text.

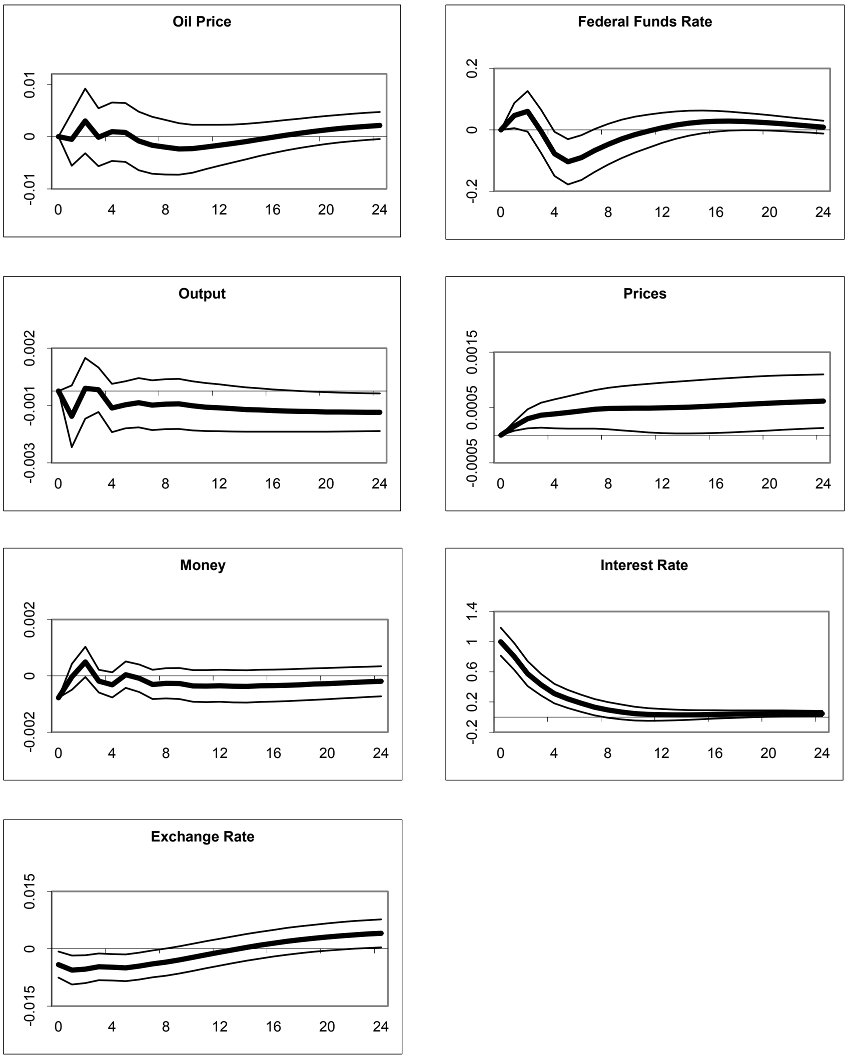

Figure 2.2: Impulse response functions, and one standard error bands, to an orthogonal one-unit shock in the domestic interest rate; for France, sub-sample 1979:1 to 1989:12. All impulse responses are from the variant of the benchmark specification, i.e. from a VAR in levels with seasonally unadjusted data. Identification as explained in the text.

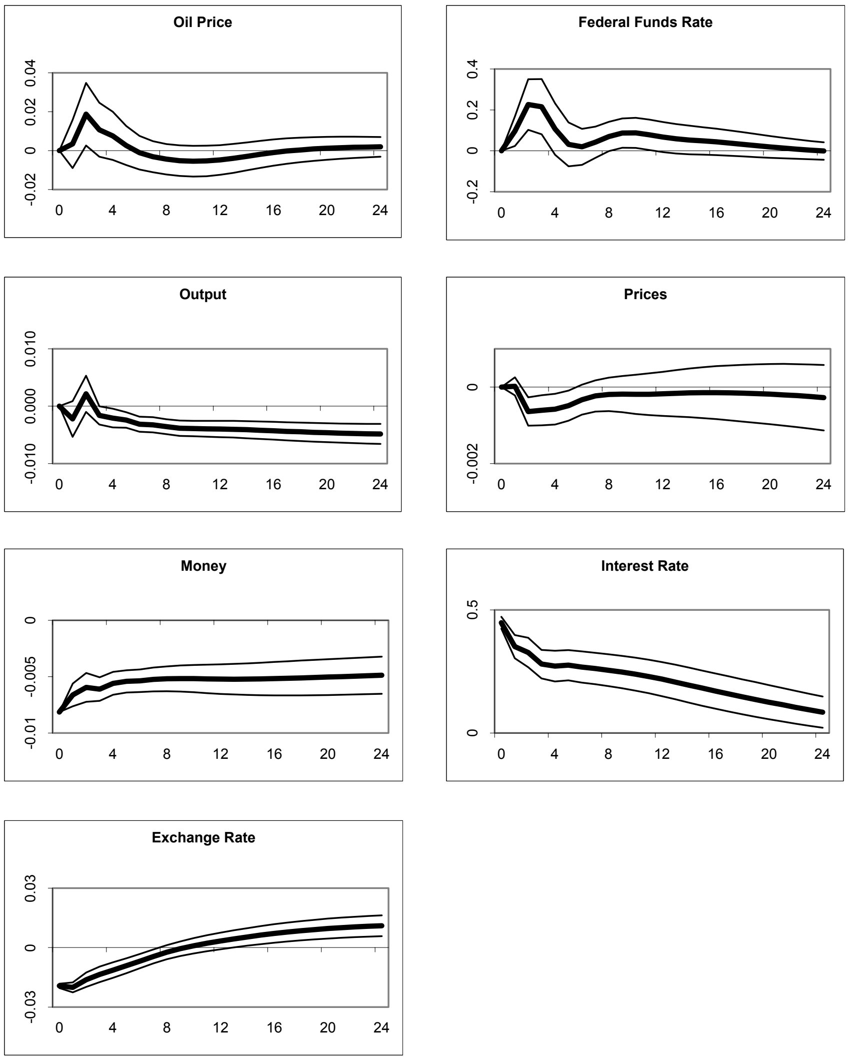

Figure 2.3: Impulse response functions, and one standard error bands, to an orthogonal one-unit shock in the domestic interest rate; for Italy, sub-sample 1979:1 to 1991:12. All impulse responses are from the variant of the benchmark specification, i.e. from a VAR in levels with seasonally unadjusted data. Identification as explained in the text.

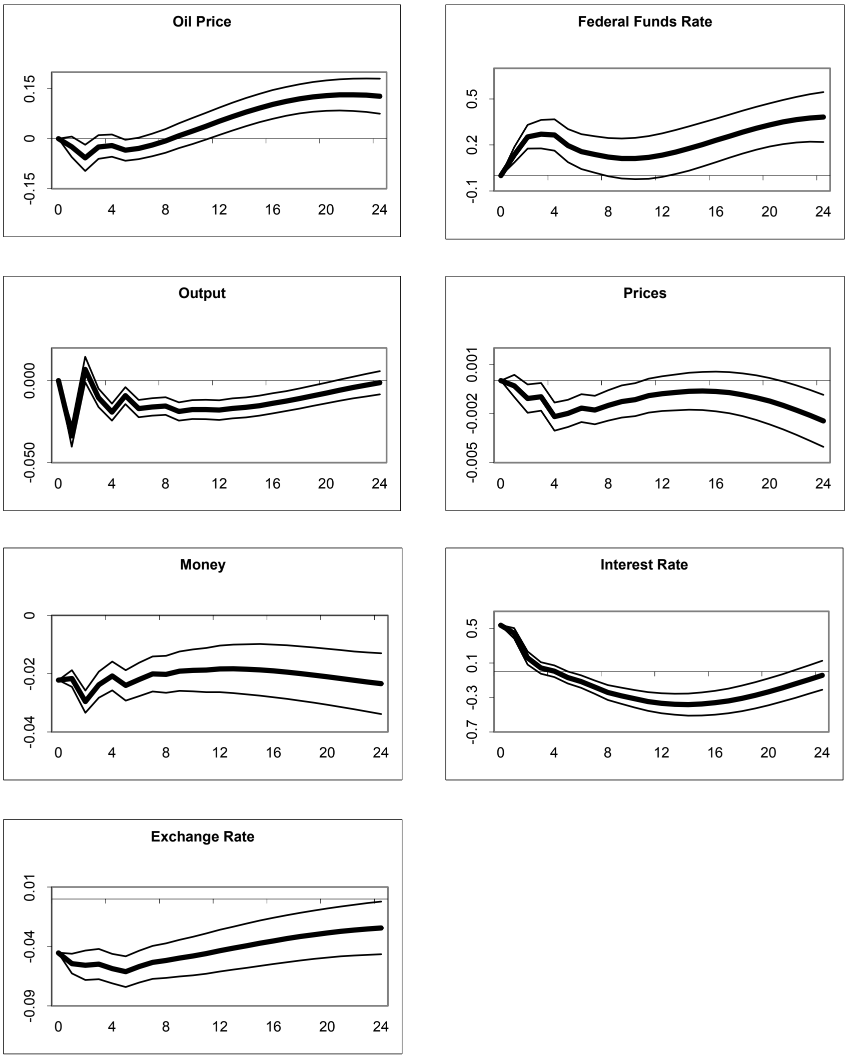

Figure 2.4: Impulse response functions, and one standard error bands, to an orthogonal one-unit shock in the domestic interest rate; for Germany, sub-sample 1992:1 to 1998:12. All impulse responses are from the variant of the benchmark specification, i.e. from a VAR in levels with seasonally unadjusted data. Identification as explained in the text.

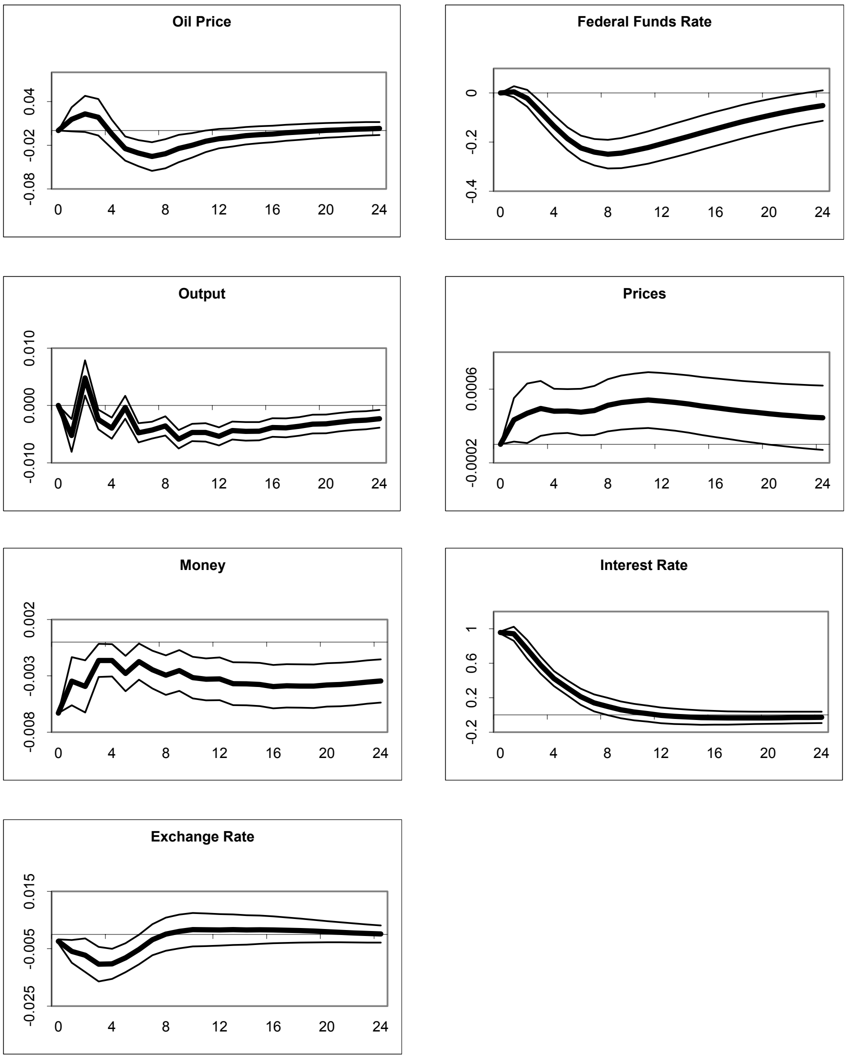

Figure 2.5: Impulse response functions, and one standard error bands, to an orthogonal one-unit shock in the domestic interest rate; for France, sub-sample 1990:1 to 1998:12. All impulse responses are from the variant of the benchmark specification, i.e. from a VAR in levels with seasonally unadjusted data. Identification as explained in the text.

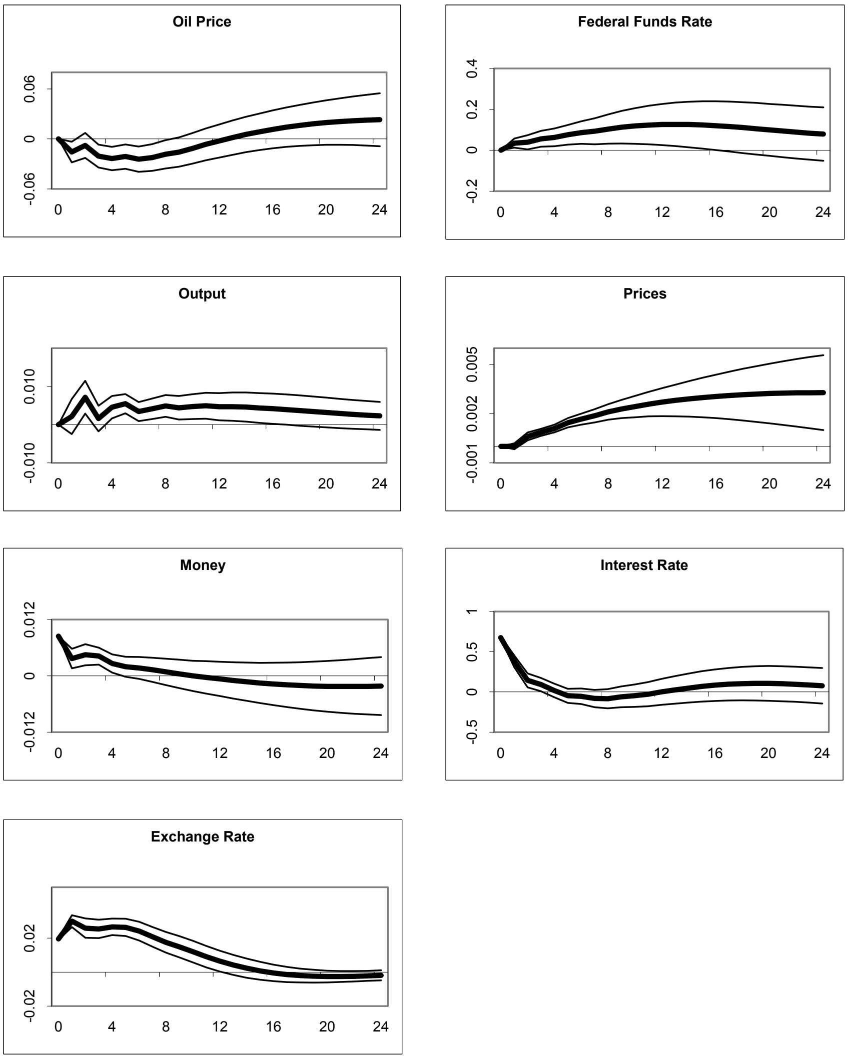

Figure 2.6: Impulse response functions, and one standard error bands, to an orthogonal one-unit shock in the domestic interest rate; for Italy, sub-sample 1992:1 to 1998:12. All impulse responses are from the variant of the benchmark specification, i.e. from a VAR in levels with seasonally unadjusted data. Identification as explained in the text.

2.8.3 Sub-sample and cross-country comparison

Impulse response functions as discussed in section 2.5 "Instabilities and dynamics" (except Italy for the second sub-sample as in section 2.6.3 "Is Germany or the USA Europe's leader"). Comparisons of only such impulse response functions are shown, which, using one-standard error bands, are significantly different from each other for at least several months.

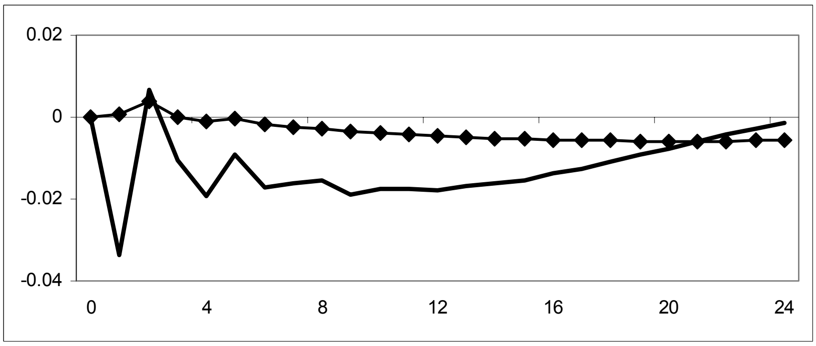

Figure 2.7: Germany: output responses to a monetary shock; sub-sample comparision. First sub-sample from 1979:1 to 1991:12 (with ⧫); second sub-sample from 1992:1 to 1998:12.

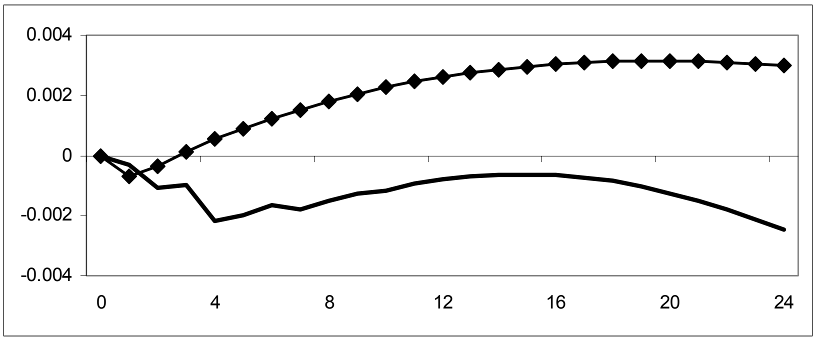

Figure 2.8: Germany: price responses to a monetary shock; sub-sample comparision. First sub-sample from 1979:1 to 1991:12 (with ⧫); second sub-sample from 1992:1 to 1998:12.

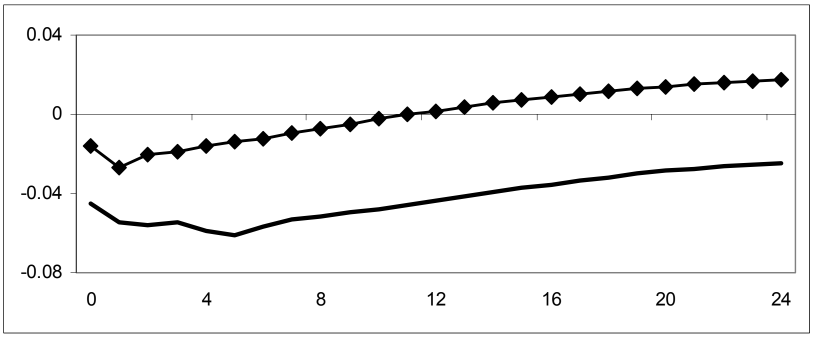

Figure 2.9: Germany: exchange rate responses to a monetary shock; sub-sample comparision. First sub-sample from 1979:1 to 1991:12 (with ⧫); second sub-sample from 1992:1 to 1998:12.

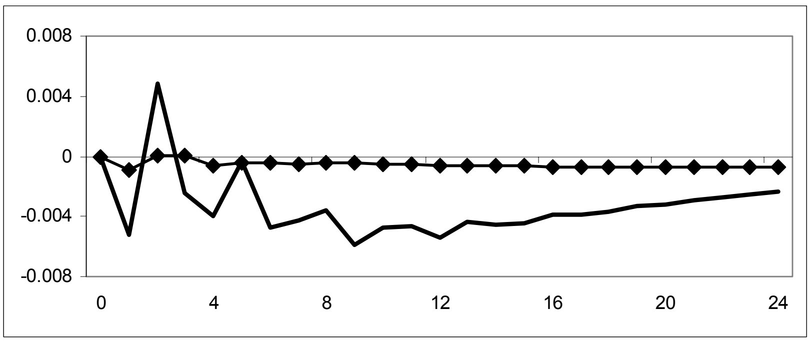

Figure 2.10: France: output responses to a monetary shock; sub-sample comparision. First sub-sample from 1979:1 to 1989:12 (with ⧫); second sub-sample from 1990:1 to 1998:12.

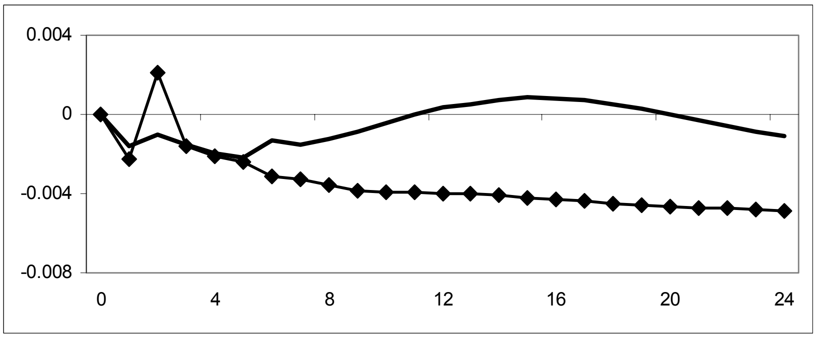

Figure 2.11: Italy: output responses to a monetary shock; sub-sample comparision. First sub-sample from 1979:1 to 1991:12 (with ⧫); second sub-sample from 1992:1 to 1998:12.

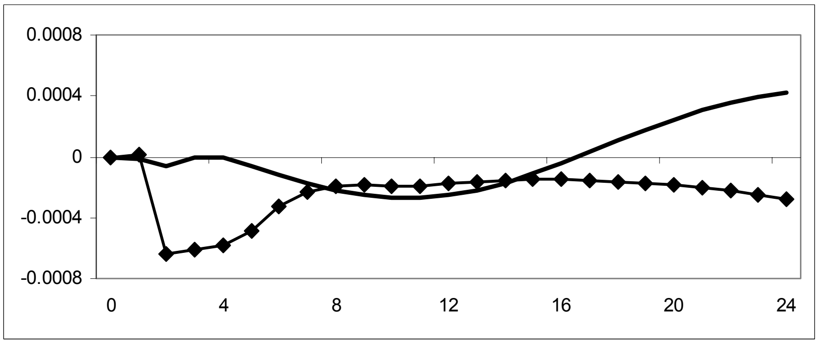

Figure 2.12: Italy: price responses to a monetary shock; sub-sample comparision. First sub-sample from 1979:1 to 1991:12 (with ⧫); second sub-sample from 1992:1 to 1998:12.

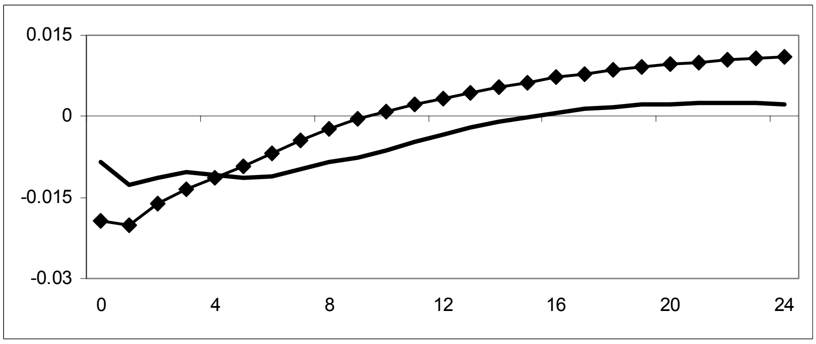

Figure 2.13: Italy: exchange rate responses to a monetary shock; sub-sample comparision. First sub-sample from 1979:1 to 1991:12 (with ⧫); second sub-sample from 1992:1 to 1998:12.

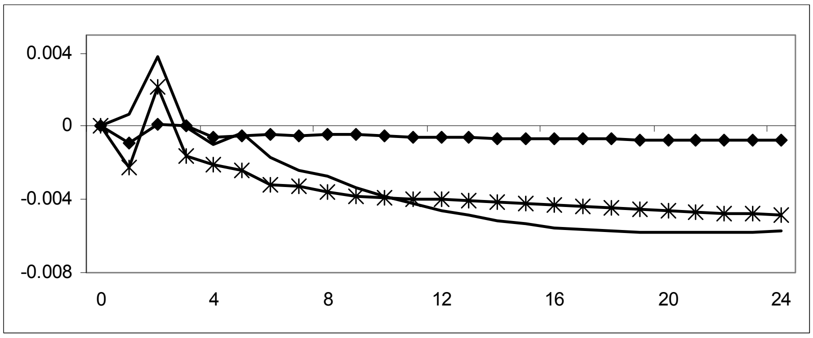

Figure 2.14: Cross-country comparision of output responses to a monetary shock during the first sub-sample; 1979:1 to 1991:12 for Germany and Italy (with ⧫) and 1979:1 to 1989:12 for France (with ★).

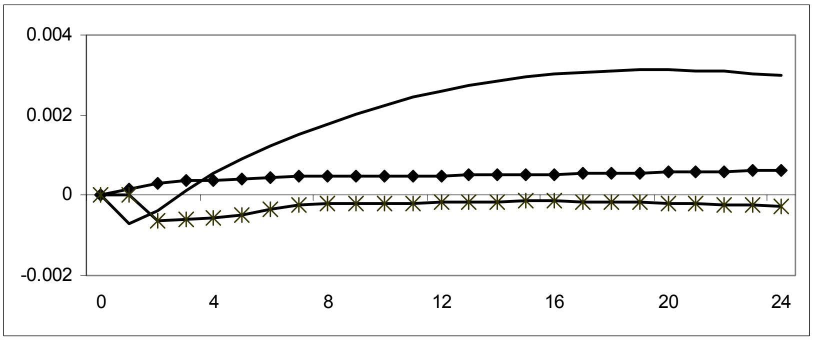

Figure 2.15: Cross-country comparision of price responses to a monetary shock during the first sub-sample; 1979:1 to 1991:12 for Germany and Italy (with ⧫) and 1979:1 to 1989:12 for France (with ★).

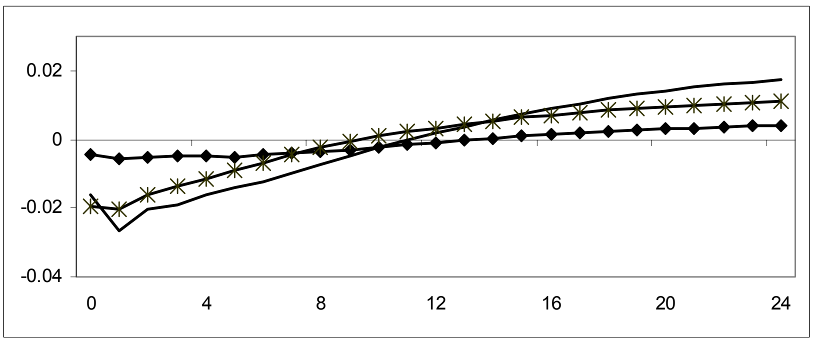

Figure 2.16: Cross-country comparision of exchange rate responses to a monetary shock during the first sub-sample; 1979:1 to 1991:12 for Germany and Italy (with ⧫) and 1979:1 to 1989:12 for France (with ★).

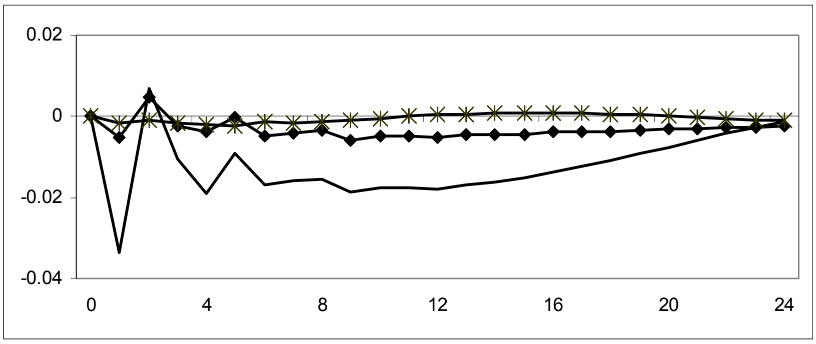

Figure 2.17: Cross-country comparision of output responses to a monetary shock during the second sub-sample; 1992:1 to 1998:12 for Germany and Italy (with ⧫) and 1990:1 to 1998:12 for France (with ★).

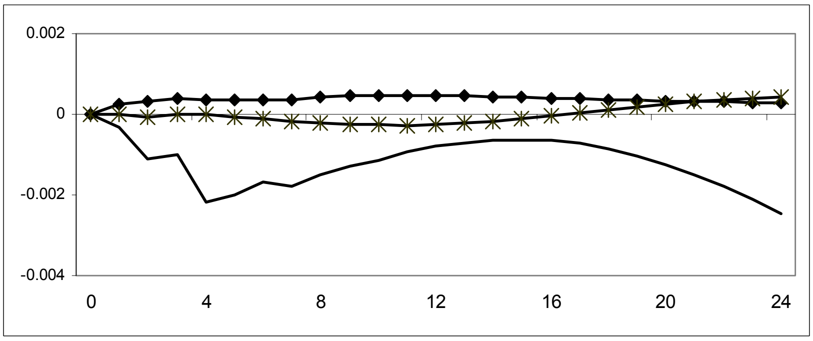

Figure 2.18: Cross-country comparision of price responses to a monetary shock during the second sub-sample; 1992:1 to 1998:12 for Germany and Italy (with ⧫) and 1990:1 to 1998:12 for France (with ★).

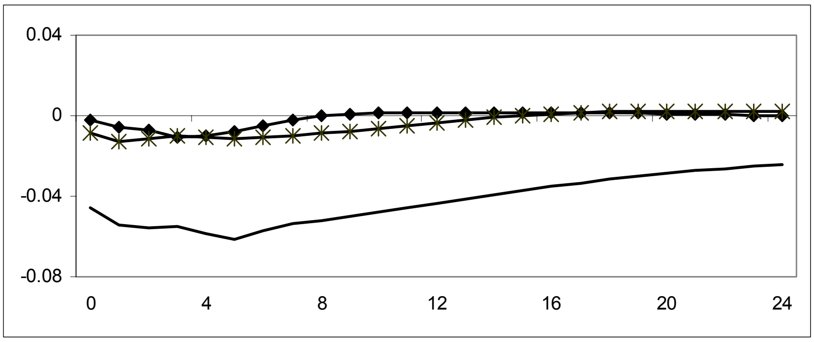

Figure 2.19: Cross-country comparision of the exchange rate responses to a monetary shock during the second sub-sample; 1992:1 to 1998:12 for Germany and Italy (with ⧫) and 1990:1 to 1998:12 for France (with ★).

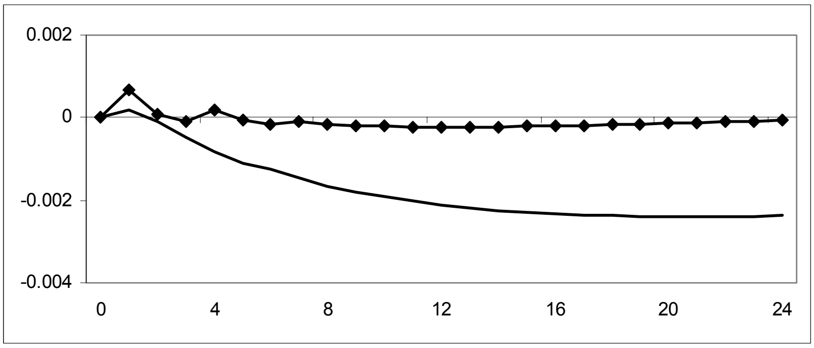

Figure 2.20: France: output response to a monetary shock; pre-EMU (with ⧫) and full sample.

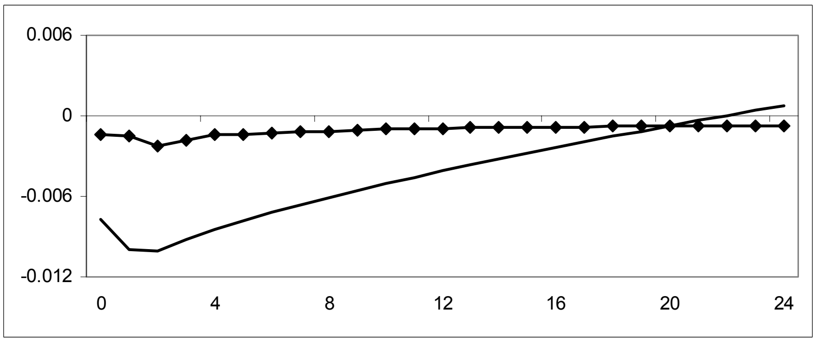

Figure 2.21: France: exchange rate response to a monetary shock; pre-EMU (with ⧫) and full sample.

2.8.4 Tables

Table 2.7: Correlation coefficients of interest rates across countries.

	FFR	GESR	FRSR	ITSR
FFR	1.000	0.484	0.666	0.684
GESR	0.484	1.000	0.621	0.685
FRSR	0.666	0.621	1.000	0.903
ITSR	0.684	0.685	0.903	1.000

NOTE: FFR is the federal funds rate, GESR and FRSR are the 3 months LIBOR for Germany and France, respectively, and ITSR is the 3 months interbank rate. Data from 1979:1 to 1998:12.

Table 2.8: Nyblom (1989) stability tests.

(A) Germany

Equation	Specification 1: All parameters	Specification 1: Constant	Specification 1: Variance	Specification 2: All parameters	Specification 2: Constant	Specification 2: Variance
OP	2.262	0.092	0.088	5.373 **	0.078	0.096
FFR	5.328 **	0.037	1.407 **	6.956 **	0.039	1.404 **
Y	1.740	0.029	0.182	8.293 **	0.023	0.638 **
P	1.974	0.087	0.115	6.190 **	0.092	0.234
M	4.300 **	0.613 **	1.111	7.883 **	0.667 **	1.909 **
SR	5.097 **	0.302	1.816 **	6.105 **	0.340	1.255 **
EXC	1.914	0.083	0.123	3.595	0.088	0.232

(B) France

Equation	Specification 1: All parameters	Specification 1: Constant	Specification 1: Variance	Specification 2: All parameters	Specification 2: Constant	Specification 2: Variance
OP	1.834	0.040	0.100	5.224 **	0.053	0.095
FFR	4.663 **	0.070	1.661 **	6.470 **	0.065	1.472 **
Y	2.446	0.052	0.843 **	13.029 **	0.032	1.064 **
P	4.512 **	0.038	0.181	8.153 **	0.037	0.505 **
M	4.031 **	0.265	0.943 **	5.931 **	0.240	1.112 **
SR	4.378 **	0.032	0.664 **	6.410 **	0.030	0.615 **
EXC	1.633	0.142	0.115	2.895	0.134	0.171

(C) Italy

Equation	Specification 1: All parameters	Specification 1: Constant	Specification 1: Variance	Specification 2: All parameters	Specification 2: Constant	Specification 2: Variance
OP	3.098	0.051	0.085	5.934 **	0.068	0.085
FFR	4.611 **	0.041	1.246 **	7.062 **	0.038	1.265 **
Y	3.773 *	0.073	0.886 **	6.767 **	0.055	0.234
P	5.569 **	0.126	1.641 **	8.652 **	0.062	1.341 **
M	3.484	0.098	1.107 **	7.396 **	0.207	2.279 **
SR	2.302	0.067	0.205	5.932 **	0.061	0.376 *
EXC	2.076	0.060	0.101	4.268 **	0.106	0.201

NOTE: System of seven variables: OP, FFR, Y, P, M, SR, EXC. Data from 1979:1 to 1998:12. Test of each equation in the system separately. See Hansen (1992) for details. Critical values at 10% (5%) for all parameters are 3.64 (3.95) and for one parameter 0.353 (0.470). ** reject H0 (stability) at 5%, * reject H0 (stability) at 10%.

Table 2.9: Andrews (1993) stability tests.

(A) Germany

Equation	P-values Specification 1 Break date	Sup F	Exp	Ave	Specification 2 Break date	Sup F	Exp	Ave
OP	09/1982	0.524	0.489	0.658	09/1986	0.477	0.427	0.344
FFR	04/1988	0.350	0.173	0.080 *	03/1983	0.802	0.700	0.547
Y	08/1991	0.978	0.928	0.863	11/1990	0.014 **	0.005 **	0.001 **
P	05/1990	0.853	0.704	0.484	07/1989	0.257	0.182	0.102
M	04/1991	0.122	0.132	0.061 *	01/1989	0.065 *	0.071 *	0.046 **
SR	02/1989	0.215	0.107	0.021 **	06/1990	0.394	0.242	0.100 *
EXC	01/1985	0.706	0.548	0.283	08/1984	0.717	0.698	0.513
System	**Break date**	**Sup F statistic**	**Critical value**		**Break date**	**Sup F statistic**	**Critical value**	
	08/1982	330.8 **	257		08/1982	556.3 **	380	
het. con.	09/1992	226.0	257		08/1992	373.2	380	

(B) France

Equation	P-values Specification 1 Break date	Sup F	Exp	Ave	Specification 2 Break date	Sup F	Exp	Ave
OP	08/1986	0.804	0.699	0.589	03/1988	0.312	0.260	0.350
FFR	09/1982	0.877	0.935	0.918	11/1982	0.995	0.996	0.997
Y	02/1989	0.500	0.411	0.327	01/1989	0.000 **	0.000 **	0.000 **
P	12/1986	0.038 **	0.018 **	0.005 **	05/1990	0.083 *	0.041 **	0.007 **
M	08/1995	0.756	0.626	0.451	08/1987	0.419	0.313	0.150
SR	04/1984	0.617	0.592	0.762	11/1985	0.259	0.206	0.446
EXC	09/1982	0.742	0.744	0.617	11/1982	0.867	0.825	0.807
System	**Break date**	**Sup F statistic**	**Critical value**		**Break date**	**Sup F statistic**	**Critical value**	
	09/1982	354.3 **	257		09/1982	534.4 **	380	
het. con.	01/1990	238.2	257		01/1990	411.8 **	380	

(C) Italy

Equation	P-values Specification 1 Break date	Sup F	Exp	Ave	Specification 2 Break date	Sup F	Exp	Ave
OP	09/1992	0.788	0.696	0.530	07/1986	0.4550	0.363	0.186
FFR	10/1982	0.497	0.371	0.144	10/1982	0.353	0.439	0.480
Y	12/1989	0.062 *	0.042 **	0.025 **	06/1989	0.056 *	0.026 **	0.011 **
P	06/1984	0.004 **	0.003 **	0.008 **	12/1985	0.018 **	0.014 **	0.007 **
M	11/1992	0.328	0.287	0.334	10/1988	0.396	0.312	0.310
SR	05/1984	0.605	0.459	0.234	05/1992	0.503	0.335	0.128
EXC	07/1982	0.821	0.673	0.490	02/1991	0.835	0.768	0.521
System	**Break date**	**Sup F statistic**	**Critical value**		**Break date**	**Sup F statistic**	**Critical value**	
	07/1982	419.7**	257		07/1982	694.7 **	380	
het. con.	09/1992	289.5 **	257		12/1991	423.6 **	380	1 coint.

NOTE: System of seven variables: OP, FFR, Y, P, M, SR, EXC. Data from 1979:1 to 1998:12. P-values for heteroskedasticity consistent tests on each equation separately are from Hansen (1997). The whole system is tested by a Likelihood Ratio test, where the heteroskedasticity consistent test is based on Weighted Least Squares (all variables divided by FFR). Critical values are computed from Andrews (1993) as explained in the text. ** reject H0 (stability) at 5%, * reject H0 (stability) at 10%.

Table 2.10: Harvey-Collier (1977) stability tests.

Equation	P-values					
	Specification 1			Specification 2		
	Germany	France	Italy	Germany	France	Italy
OP	0.368	0.715	0.952	0.292	0.397	0.852
FFR	0.882	0.005 **	0.316	0.196	0.002 **	0.081 *
Y	0.848	0.576	0.505	0.832	0.950	0.036 **
P	0.269	0.406	0.262	0.397	0.623	0.885
M	0.062 *	0.701	0.095 *	0.086 *	0.922	0.101
SR	0.042 **	0.316	0.095 *	0.032 **	0.526	0.504
EXC	0.735	0.594	0.673	0.577	0.832	0.824

NOTE: System of seven variables: OP, FFR, Y, P, M, SR, EXC. Data from 1979:1 to 1998:12. Tests for each equation individually following Green (1997), pp. 357. ** reject H0 (stability) at 5%, * reject H0 (stability) at 10%.

Table 2.11: Nyblom (1989) stability tests; excluding the Volcker period.

(A) Germany

Equation	Test statistic	Critical value 10% (5%)	Test statistic		Critical value 10% (5%)
	All parameters		Constant	Variance	
OP	1.757		0.054	0.116	
FFR	3.238		0.058	0.958 **	
Y	2.898		0.139	0.452	
P	2.413	3.64 (3.95)	0.171	0.186	0.353 (0.470)
M	2.584		0.142	0.106	
SR	3.379		0.267	0.263	
EXC	3.125		0.066	0.196	

(B) France

Equation	Test statistic	Critical value 10% (5%)	Test statistic		Critical value 10% (5%)
	All parameters		Constant	Variance	
OP	2.361		0.057	0.132	
FFR	2.995		0.059	0.983 **	
Y	2.811		0.054	0.586 **	
P	4.277 **	3.64 (3.95)	0.035	0.171	0.353 (0.470)
M	4.140 **		0.169	0.613 **	
SR	9.647 **		0.705	0.422 *	
EXC	2.915		0.177	0.133	

(C) Italy

Equation	Test statistic	Critical value 10% (5%)	Test statistic		Critical value 10% (5%)
	All parameters		Constant	Variance	
OP	3.095		0.068	0.111	
FFR	3.605 *		0.172	1.080 **	
Y	3.726 *		0.043	0.531 **	
P	2.774	3.64 (3.95)	0.068	0.269	0.353 (0.470)
M	4.539 **		0.254	1.420 **	
SR	3.637 *		0.139	0.491 *	
EXC	2.370		0.145	0.158	

NOTE: System of seven variables: OP, FFR, Y, P, M, SR, EXC. Data from 1983:1 to 1998:12. Test of each equation in the system separately. See Hansen (1992) for details. ** reject H0 (stability) at 5%, * reject H0 (stability) at 10%.

Table 2.12: Andrews (1993) stability tests; excluding the Volcker period.

(A) Germany

Equation	Break date	P-Values Sup F	Exp	Ave
OP	11/1986	0.787	0.754	0.709
FFR	04/1988	0.836	0.699	0.515
Y	09/1990	0.884	0.766	0.638
P	09/1990	0.862	0.723	0.516
M	02/1987	0.564	0.397	0.284
SR	02/1989	0.189	0.154	0.057 *
EXC	11/1989	0.126	0.077 *	0.031 **

Whole system	Break date	Sup F statistic	Critical value
	03/1989	139.499	257
heterosk. cons.	07/1993	206.975	257

(B) France

Equation	Break date	P-Values Sup F	Exp	Ave
OP	10/1986	0.947	0.902	0.840
FFR	07/1992	0.894	0.867	0.841
Y	03/1989	0.757	0.667	0.588
P	07/1988	0.052 *	0.025 **	0.023 **
M	05/1991	0.503	0.426	0.276
SR	07/1986	0.924	0.913	0.812
EXC	04/1994	0.738	0.527	0.314

Whole system	Break date	Sup F statistic	Critical value	
	08/1986	347.182 **	257	
heterosk. cons.	06/1990	231.993	257	one coint. vec.

(C) Italy

Equation	Break date	P-Values Sup F	Exp	Ave
OP	07/1992	0.736	0.609	0.451
FFR	04/1988	0.223	0.166	0.135
Y	03/1991	0.132	0.084 *	0.049 **
P	09/1986	0.398	0.456	0.484
M	09/1992	0.093 *	0.049 **	0.016 **
SR	10/1992	0.099 *	0.095 *	0.041 **
EXC	07/1986	0.694	0.620	0.646

Whole system	Break date	Sup F statistic	Critical value
	08/1986	195.704	257
heterosk. cons.	09/1992	256.472 **	257

NOTE: System of seven variables: OP, FFR, Y, P, M, SR, EXC. Data from 1983:1 to 1998:12. P-values for heteroskedasticity consistent tests on each equation separately are from Hansen (1997). The whole system is tested by a Likelihood Ratio test, where the heteroskedasticity consistent test is based on Weighted Least Squares (all variables divided by FFR). Critical values are computed from Andrews (1993) as explained in the text. ** reject H0 (stability) at 5%, * reject H0 (stability) at 10%.

Table 2.13: Harvey-Collier (1977) stability tests; excluding the Volcker period.

Equation	P-Values		
	Germany	France	Italy
OP	0.453	0.232	0.283
FFR	0.783	0.230	0.111
Y	0.284	0.315	0.805
P	0.587	0.693	0.734
M	0.180	0.330	0.192
SR	0.495	0.091 *	0.306
EXC	0.719	0.108	0.038 **

NOTE: System of seven variables: OP, FFR, Y, P, M, SR, EXC. Data from 1983:1 to 1998:12. Tests for each equation individually following Green (1997), pp. 357. ** reject H0 (stability) at 5%, * reject H0 (stability) at 10%.

Table 2.14: Nyblom (1989) stability tests; including the German interest rate.

(A) France

Equation	Test statistic	Critical value 10% (5%)	Test statistic		Critical value 10% (5%)
	All parameters		Constant	Variance	
OP	2.154		0.034	0.097	
GESR	5.151 **		0.051	2.111 **	
Y	2.761		0.049	0.921 **	
P	5.015 **	3.64 (3.95)	0.033	0.150	0.353 (0.470)
M	4.651 **		0.311	0.913 **	
SR	5.246 **		0.043	0.914 **	
EXC	1.770		0.099	0.116	

(B) Italy

Equation	Test statistic	Critical value 10% (5%)	Test statistic		Critical value 10% (5%)
	All parameters		Constant	Variance	
OP	3.331		0.048	0.085	
GESR	4.445 **		0.093	2.100 **	
Y	3.023		0.049	0.960 **	
P	4.599 **	3.64 (3.95)	0.084	1.384 **	0.353 (0.470)
M	3.890 *		0.190	1.063 **	
SR	2.289		0.044	0.215	
EXC	2.224		0.092	0.088	

NOTE: System of seven variables: OP, GESR, Y, P, M, SR, EXC. Data from 1979:1 to 1998:12. Test of each equation in the system separately. See Hansen (1992) for details. ** reject H0 (stability) at 5%, * reject H0 (stability) at 10%.

Table 2.15: Andrews (1993) stability tests; including the German interest rate.

(A) France

Equation	Break date	P-Values Sup F	Exp	Ave
OP	06/1986	0.853	0.769	0.710
GESR	07/1982	0.732	0.723	0.690
FRY	02/1989	0.566	0.543	0.510
FRP	12/1986	0.021 **	0.017 **	0.007 **
FRM	09/1986	0.523	0.352	0.180
FRSR	03/1984	0.524	0.473	0.540
FREXC	01/1994	0.672	0.611	0.650

Whole system	Break date	Sup F statistic	Critical value
	03/1983	254.2	257
heterosk. cons.	08/1986	304.8 **	257

(B) Italy

Equation	Break date	P-Values Sup F	Exp	Ave
OP	09/1990	0.838	0.837	0.750
GESR	05/1993	0.669	0.547	0.300
ITY	02/1991	0.682	0.539	0.470
ITP	06/1984	0.010 **	0.006 **	0.020 **
ITM	11/1992	0.212	0.138	0.066 *
ITSR	01/1991	0.695	0.565	0.300
ITEXC	12/1992	0.631	0.565	0.390

Whole system	Break date	Sup F statistic	Critical value
	07/1982	207.9	257
heterosk. cons.	01/1988	244.7	257

NOTE: System of seven variables: OP, GESR, Y, P, M, SR, EXC. Data from 1979:1 to 1998:12. P-values for heteroskedasticity consistent tests on each equation separately are from Hansen (1997). The whole system is tested by a Likelihood Ratio test, where the heteroskedasticity consistent test is based on Weighted Least Squares (all variables divided by GESR). Critical values are computed from Andrews (1993) as explained in the text. ** reject H0 (stability) at 5%, * reject H0 (stability) at 10%.

Table 2.16: Harvey-Collier (1977) stability tests; including the German interest rate.

Equation	P-Values France	Italy
OP	0.644	0.595
GESR	0.945	0.045 **
Y	0.976	0.271
P	0.799	0.661
M	0.083 *	0.065 *
SR	0.526	0.344
EXC	0.912	0.454

NOTE: System of seven variables: OP, GESR, Y, P, M, SR, EXC. Data from 1979:1 to 1998:12. Tests for each equation individually following Green (1997), pp. 357. ** reject H0 (stability) at 5%, * reject H0 (stability) at 10%.

Chapter 3

The determinants of the overnight rate

3.1 Introduction

This chapter studies the determinants of the overnight interest rate and quantifies them. The overnight interest rate is at the short end of the yield curve and the equilibrium outcome of supply and demand for bank reserves. The here developed structural model for both supply and demand for reserves allows an in-depth analysis of the interaction between the central bank, as the sole net supplier of reserves, and commercial banks, on the demand side. The precise set-up of this market, i.e. institutional details of the reserve market, has important implications for the behavior of the overnight rate, both for conditional mean and variance. These implications are derived from a theoretical model and their magnitudes are estimated for the euro area overnight rate.

The behavior of the overnight interest rate is important for several reasons. Firstly, in most monetary models the central bank is assumed to have perfect control over the interest rate. The transmission mechanism of monetary policy in these models starts at the short-term interest rate.[1] A change in the short-term rate works through to long-term interest rates. These long-term rates are the relevant variables for firms' investment and households' savings decisions. Investment and saving then influence output and prices and, as a consequence, the final objectives of a central bank, e.g. price stability. However, the control of the short-term interest rate is far from perfect in practice. Interest rates are determined on markets, being influenced by both supply and demand side factors. The central bank has a strong influence on the supply side, but is not able to control it perfectly. This chapter studies the, widely overlooked, first

[1] See for example Walsh (1998) for a book-length treatment of monetary models.

step in the monetary transmission mechanism, the relation between reserves and the overnight rate. In particular, the assumption made in many models that the central bank has perfect control over the interest rate is analyzed. The ways in which the details of monetary policy implementation affect the behavior of the interest rate are documented.

Secondly, the short-term rate is an important explanatory variable for long-term interest rates. According to the expectation hypothesis the N-period yield is the average of expected future one-period yields, possibly adjusted for a risk premium.[2] Therefore, understanding better the behavior of the short end of the yield curve - the overnight rate - helps explaining other interest rates further out the term structure as well.[3]

Thirdly, in efficient markets there are no (long-lasting) arbitrage opportunities. Predictable patterns usually provide such arbitrage opportunities. Both mean and volatility of the overnight rate are tested for predictable patterns and implications for market efficiency are investigated.

Finally, central banks have a natural interest in studying the determinants of the overnight rate. This is particularly true nowadays as the operating target of many central banks is a short-term interest rate.[4] The behavior of the overnight rate depends on reserve supply, but equally important on the institutional framework for the reserve market.

With these issues in mind the overnight rate is analyzed and the reserve market is discussed with respect to market efficiency, the importance of institutional features and the ability of the central bank to control the interest rate.

In the literature so far the overnight interest rate has not been analyzed extensively, especially in the euro area. One of the earliest statistical descriptions of the daily behavior of the US overnight rate is given by Hamilton (1996 and 1997). More recently, also Bartolini et al. (2001 and 2002) develop models for the US overnight rate, which is known as the federal funds rate. Although the basic set-up in the US and euro area reserve markets are similar, there are important institutional differences making these models not very good descriptions of the euro area overnight rate. Pérez and Rodríguez (2003) provide an optimizing model for reserve demand in the euro area. Bindseil and Seitz (2001) model the supply of reserves in close relation to the institutional set-up

[2] Cochrane (2001) discusses extensively the expectation hypothesis and reviews models for the term structure of interest rates.

[3] See e.g. Fabozzi and Modigliani (1996) for a general analysis of money markets. More specifically, Cassola and Morana (2003 and 2004) and chapter 4 analyse the transmission of volatility along the euro area yield curve.

[4] Borio (1997) offers a detailed discussion of monetary policy operating procedures in industrial countries.

in the euro area, but the demand side is not derived explicitly. Välimäki (2002) is the first one to provide a model of optimizing behavior for both supply and demand side. However, he makes the simplifying assumption of daily supply of reserves. Under normal circumstances reserves are supplied only once a week in the euro area. Würtz (2003) proposes an econometric model of the overnight rate, focusing mainly on an empirical description. On the contrary, the present analysis derives the empirical formulation from a structural model of both supply and demand for reserves, which allows to pin down precisely the effects of implementation issues on the interest rate. Furthermore, the exact supply measure relevant for demand decisions is used and possible endogeneity of reserve supply is tackled.

The present analysis starts with a theoretical model for both supply and demand in the euro area reserve market. The central bank is the sole net supplier of reserves and commercial banks represent the demand side. The model is set up in an intertemporal optimization framework. Not only the current situation in the market is relevant for decisions, but also expected future events. The demand side follows closely Pérez and Rodríguez (2003), augmenting it in order to allow changes in the policy rate. The policy rate is the target rate for the overnight rate.[5] Since banks are forward looking expected changes in the policy rate are important for the behavior of the current overnight rate. Furthermore, a detailed description of the supply side, including all main institutional features of the central bank's operating procedure, is necessary to characterize adequately the determination of the overnight rate. Therefore, the supply of reserves is modeled with a weekly frequency. Special attention is paid to distinguish expected, unexpected, temporary and permanent supply changes and their effects on the overnight rate. The equilibrium in the reserve market is discussed extensively. The model also allows to analyze a special situation in the reserve market, the so-called underbidding. If the policy rate is expected to decrease in the near future total demand for bank reserves decreases immediately. In this case the central bank is not able to supply the desired amount of reserves. The total amount of reserves is then determined at the demand side, by commercial banks. Since reserves are supplied via auctions, this situation has been labelled underbidding. Underbidding is the consequence of some specific characteristics in the reserve market and will be discussed below.

The theoretical model is then taken to the data. Great care is applied in dealing with non-standard statistical properties of the overnight rate. Numerous specification tests are performed and sub-sample stability is analyzed.

One of the main issues in this chapter is to determine the effect of a change in reserve supply on the interest rate. A negative relation between reserves and the

[5] The minimum bid rate of variable rate tenders and the rate applied to fixed rate tenders for the euro area main refinancing operations can be interpreted as such a target rate.

interest rate is expected. This negative relation is usually called the liquidity effect. However, it is necessary to clarify what exactly is meant in the present analysis by the liquidity effect.

Empirical evidence for a liquidity effect comes from Christiano (1991), Gordon and Leeper (1992), Galí (1992), Strongin (1995), Bernanke and Mihov (1998b), Kim and Ghazali (1998) and Thornton (2001b), among others. Most of those works use monthly or quarterly data, and so the main difficulty is the identification of the relevant money supply and demand equations. Hamilton (1997) proposes an alternative by using daily data giving way for other identifying assumptions. However, as pointed out by Thornton (2001a) and Gilchrist (2001), not all papers identify the same effect. There are two different, although not unrelated, mechanisms at work. On the one hand, there is a daily demand for reserves in order to fulfill reserve requirements. If this demand is interest rate elastic, a reaction of the overnight rate to a change in liquidity is found. On the other hand, there is a longer-term interest rate elasticity of reserves. Banks have to hold a certain proportion of demand deposits as reserves. Those demand deposits are assumed to depend on an interest rate as opportunity cost. Therefore, if the interest rate changes, demand for deposits changes, and proportionally also reserve requirements. Whether this reaction happens contemporaneously depends on institutional features of reserve fulfillment. In the euro area required reserves are calculated from the previous month's deposits. This is to say that a change in today's interest rate affects next month's reserve requirement and next month's demand for reserves. Hence, the relationship between demand deposits and interest rate cannot be identified on a contemporaneous basis. Following this argumentation, the present work identifies the first effect, the liquidity effect on a daily basis. In other words, the responsiveness of the interbank rate to daily changes in the supply of reserves is analyzed. Although a possible relation between both effects is recognized, the further analysis of this issue is left for future research.

The next section provides a theoretical model for the reserve market. Both supply and demand for reserves are carefully modeled. The equilibrium overnight rate is derived. The effects of expected and unexpected supply changes on the interest rate are discussed. Underbidding is found to be an equilibrium outcome in the present set-up of the reserve market. Section 3.3 takes the model to the data. Numerous specification tests are performed and the determinants of the EONIA rate, a volume-weighted average of interbank overnight rates in the euro area, are analyzed extensively. Section 3.4 concludes and outlines further research. The appendix contains all graphs, figures and tables. In particular, it includes an illustration of the reserve market and a graphical summary of the theoretical model, as well as a detailed description of the data used and a review of predictable patterns in mean and volatility of the overnight rate.

3.2 A model of the reserve market

The reserve market is a money market where overnight, unsecured loans of reserves are exchanged.[6] In what follows a model for both, demand and supply side of this particular interbank market is set up. There are two types of agents in the market, the central bank on one hand and commercial banks on the other hand. The key ingredients of the model are the optimizing behavior of all agents and the inclusion of the main institutional features of the euro area interbank market. Both issues have important implications. Firstly, demand and supply equations are not simply postulated, rather they are derived from the first order conditions of the maximization problem, and so reflecting optimizing behavior of agents. Secondly, the institutional set-up of the interbank market influences the behavior of agents, therefore, the exact representation of institutional key features is necessary for an adequate model.

Commercial banks are obliged to hold deposits of a certain amount at the central bank, i.e. to hold a certain amount of reserves. However, this reserve requirement does not have to be fulfilled on a daily basis, rather it has to be fulfilled on average over a period of one month, which is called the reserve maintenance period (RMP).[7] The allowance of fulfilling reserves on average leads banks to face an intertemporal decision problem. Banks have to decide on an optimal path of daily reserve holdings. Given that banks have a certain amount of liquidity, it follows that the amount not desired to be held as reserves can be lend to other banks through the interbank market. In case a bank wants to hold more reserves than it has liquidity available, it can borrow at the interbank market. The price paid at the interbank market is the interbank rate. In addition, liquidity can be obtained from (or deposited at) the central bank, where the price for borrowing from the central bank is called the marginal lending rate, and the price for depositing at the central bank is called the deposit rate. To sum up, each bank decides every day on how much reserves to hold, how to act on the interbank market and what recourse to take to the standing facilities, i.e. how much to borrow from or deposit at the central bank. These decisions are made by maximizing profits from reserve management, taking the reserve requirement as a constraint. Profits are revenues minus costs, where costs of reserve management are given by borrowing from the central bank (at the lending rate) and at the interbank market (at the interbank rate), and revenues are interests earned by depositing at the deposit facility and lending to other banks.

[6] The very short-term money market in the US is called the federal funds market.

[7] The length of the reserve maintenance period in the US is two weeks.

The central bank in the model supplies liquidity in order that commercial banks can fulfill demand for reserves at an interest rate consistent with the policy rate i_t^*. Loosely speaking, the central bank can be seen as minimizing deviations of the interbank rate i_t from the policy rate i_t^*. Furthermore, the central bank also provides liquidity for the so-called autonomous factors. Examples of autonomous factors are banknotes in circulation and Treasury deposits. Figure 3.1 summarizes the above described interactions among central and commercial banks.

The timing of the model is represented in figure 3.2. When the market opens the central bank decides how much liquidity to supply, taking into account expected demand for reserves (at the policy rate) and the expected size of autonomous factors. Afterwards, commercial banks decide on how much reserves to hold and the interbank rate results. The market closes and the size of the autonomous factors for that day becomes known. Finally, the reserve position at the central bank and profits are determined. In general the central bank supplies liquidity only once a week, on Wednesday. On the following days up till the next Wednesday liquidity supply stays constant.[8] Although supply of total liquidity is constant throughout a week, reserve supply moves daily in response to shocks hitting the market.

The central bank's balance sheet can be summarized in a very stylized way as showing liquidity supply on the assets side and reserves holdings and autonomous factors on the liabilities side. From the balance sheet identity and given the supply of liquidity, it is easy to see that a change in the autonomous factors must be matched by an equal change of opposite sign in the reserve position. It follows that a forecast error in the autonomous factors affects directly the reserve position of commercial banks, hence, can be interpreted as a shock to supply of reserves. This shock changes banks' end of the day reserve positions. When making their decisions on reserve holdings banks take the existence of this supply shock into account.

3.2.1 Demand side

The demand side follows closely Pérez and Rodríguez (2003), being adapted to allow changes in the policy rate as well as in lending and deposit rates. The economy consists of a continuum of banks with measure one. Each bank maximizes expected profits from reserve management within each maintenance period, subject to the reserve requirement. The timing for any day within the reserve maintenance period is outlined in figure 3.2. The objective function for bank j is

[8] In practice most of the liquidity is indeed supplied weekly through open market operations (see the next section for details). However, the maturity of these open market operations is two weeks. Note that from March 2004 onwards the maturity of open market operations will be reduced to one week (see e.g. ECB, 2004).

$$\max_{\{B_t^j\}_{t=1}^T} E_1 \left[\sum_{t=1}^{T} \pi_t^j \right]. \tag{3.1}$$

Reserves lent to other banks in the interbank market are described by B_t^j and π_t^j is the profit from reserve management at day t. Reserves deposited at the central bank are denoted by M_t^j, i_t represents the interbank rate and u_t^j the supply shock. A_t^j is the amount of reserves a bank obtains from the central bank and it holds that $A_t^j = M_t^j + B_t^j$. The amount of reserves needed at t to fulfill the requirement for the whole maintenance period is denoted by R_t^j, with $R_1^j \equiv rr$ being the size of the reserve requirement:

$$R_{t+1}^j = \max \left\{ 0, R_t^j - \max \left[0, M_t^j + u_t^j \right] \right\}. \tag{3.2}$$

Note that no overdrafts are allowed, in other words banks cannot run a negative reserve balance (i.e. $M_t^j + u_t^j \geqslant 0$). In case of a potential overdraft an automatic recourse to the lending facility takes place in order to bring the bank's daily reserve position back to zero. Similarly, once the reserve requirements are fulfilled for the whole maintenance period (i.e. $R_t^j = 0$), all liquidity is put automatically at the deposit facility, which is to say banks do not hold more reserves than strictly necessary. The reserve requirement has to be fulfilled throughout the RMP. It is not important at which day contributions to the reserve requirement are made, but it has to be fulfilled at the end of the RMP, i.e. the reserve requirement can be written as $R_{T+1}^j = 0$.

The model is solved backwards from the last day of the maintenance period, T, since on that day reserve requirements have to be fulfilled at any cost and in consequence future expected variables are not relevant for banks' demand decisions. The resulting first order conditions describe the interbank rate i_t as a function of the bank's reserves, A_t^j. At the last day of the reserve maintenance period the demand equation is given by:

$$i_T = i_T^d + \left(i_T^l - i_T^d \right) * F \left(R_T^j + B_T^j - A_T^j \right), \tag{3.3}$$

where $F(\cdot)$ is the distribution function of the supply shock, $f(\cdot)$ its density function, i_t^l the marginal lending rate and i_t^d the deposit rate. Market clearing implies that aggregate borrowing and lending in the interbank market equals zero, i.e. $B_T = \int_0^1 B_T^j dj = 0$. Therefore, banks' aggregate reserves equal reserves deposited at the central bank, i.e. $A_T = M_T$. Aggregate reserve deficiencies at the last day in a RMP are described by $R_T = \int_0^1 R_T^j dj$. The demand curve for all other days, $t = 1, 2, ..., T-1$, is given by:

$$i_t = i_t^l * F\left(B_t^j - A_t^j\right) + i_t^d * \left[1 - F\left(R_t^j + B_t^j - A_t^j\right)\right] - \int_{B_t^j - A_t^j}^{R_t^j + B_t^j - A_t^j} \frac{\partial V_{t+1}\left(R_{t+1}^j, A_{t+1}^j; I_{t+1}\right)}{\partial R_{t+1}^j} f(u_t) du_t, \quad (3.4)$$

with the aggregate state variable defined as $I_t = \{i_t, i_{t+1}, ..., i_T\}$. The value function at the last day of the RMP is $V_T(R_T^j, A_T^j; I_T) = \max_{B_T^j} E_T\left[\pi_T^j\right]$ and for all other days $V_t(R_t^j, A_t^j; I_t) = \max_{B_t^j} E_t\left[\pi_t^j + V_{t+1}(R_{t+1}^j, A_{t+1}^j; I_{t+1})\right]$.

Given the central bank's supply of reserves, the above first order conditions determine the equilibrium interbank rate. These conditions are derived from optimizing behavior in the reserve management and describe the typical path for the interbank rate. Before discussing the behavior of the interbank rate further, the central bank's supply of reserves is analyzed.

3.2.2 Supply side

The institutional details of the interbank market are crucial for understanding the behavior of the interbank rate. So the supply side of the model closely matches the actual structure of the liquidity management in the euro area.

The central bank supplies liquidity in order to fulfill (expected) demand for reserves at an interest rate consistent with the policy rate i_t^*. Loosely speaking, the central bank can be seen as minimizing deviations of the interbank rate i_t from the policy rate i_t^*. Liquidity is supplied only once a week, with a maturity of two weeks. The main refinancing operations of the European Central Bank (ECB) have exactly these characteristics and almost all the liquidity provided in the euro area is supplied through main refinancing operations.[9]

The central bank's balance sheet identity requires at each day that

$$ca_t = omo_t + nsf_t - af_t = er_t + rr_t \quad (3.5)$$

or,

$$er_t = omo_t - af_t - rr_t + nsf_t, \quad (3.6)$$

[9]Besides main refinancing operations also fine tuning and long-term refininancing operations are used by the ECB to supply liquidity. However, fine tuning operations are executed only under special circumstances. Indeed, such fine tuning operations have been performed very few times, namely at 21/6/2000, 30/4/2001, 12 and 13/9/2001, 28/11/2001, 4 and 10/1/2002, 18/12/2002 and 23/05/2003. Long term refinancing operations are structural measures and usually constant throughout the maintenance period.

where ca_t stands for current account holdings, omo_t for outstanding open market operations, nsf_t for net recourse to standing facilities, af_t for autonomous factors, er_t for excess reserves and rr_t for required reserves.[10] Note that current account holdings are the reserves commercial banks hold at the central bank. Furthermore,

$$omo_t = mro_t + ltro_t + fto_t \tag{3.7}$$

where mro_t is the outstanding amount from main refinancing operation, $ltro_t$ from long-term refinancing operations and fto_t from fine tuning operations. It is assumed that $ltro_t$ and fto_t are constant throughout the maintenance period, that is $ltro_t = ltro$ and $fto_t = fto$ for all $t = 1, ..., T$.[11]

At an allotment day, normally Tuesday, the size of mro_t is decided such that the expected excess reserve holdings in seven days are equal to the target level er^*. An amount sufficiently large in order to provide for the expected autonomous factors and expected demand for reserves, taking into account the expected recourse to standing facilities, is allotted.

Days throughout the maintenance period are denoted by $t = 1, ..., T$. At $t = s$ a new main refinancing operation is settled, where $s \in S = \{s_1, s_2, ..., s_k\}$ with s_1 being the first Wednesday in the maintenance period, and s_k the last one.[12] The central bank targets average excess reserves, which means, making up for autonomous factor forecast errors of the previous week, $\{E_{s-8}[\sum_{j=s-7}^{s-1} af_j] - \sum_{j=s-7}^{s-1} af_j\}$. The target level for excess reserves is given by:

$$er_s^* = E_{s-1}[er_{s+n}] + \frac{1}{m}\left(\sum_{j=s-m}^{s-1} af_j - E_{s-8}\left[\sum_{j=s-m}^{s-1} af_j\right]\right) \tag{3.8}$$

with $m = \min\{7, s-1\}$ and $n = \min\{6, T-t\}$ and for all $s \in S$. At the first allotment in the maintenance period the average excess reserve measure, $er_{s_1-1}^*$, takes into account forecast errors only from $t = 1$ onwards, not including the days from the previous maintenance period. At the last allotment the liquidity situation at T is targeted, not the liquidity situation at the next allotment day.[13]

[10] Note that, strictly speaking, the division into required reserves and excess reserves is defined only at the last day of the maintenance period. However, excess reserves at the last day of the maintenance period are largely constant across maintenance periods $j = 1, ..., J$, that is $\frac{1}{J}\sum_{j=1}^{J} er_{T,j} \approx 0.7 * T$ billion euro (see the box on liquidity conditions in the ECB's Monthly Bulletin, various issues). Thus, it seems reasonable to assume excess reserves are build up linearly throughout the maintenance period, which leads to define the daily excess reserve, er_t, to be constant at 0.7 billion euro. It follows that $rr_t = ca_t - 0.7$.

[11] See footnote 9.

[12] All days $t = s$ are called settlement days, whereas $t = T$ is defined as the last day in the reserve maintenance period.

[13] In general, $E_{s-1}[er_{s+n}]$ is around $0.7 * (s + n)$ billion euro.

Finally, the possibility of changes in the policy rate and the so-called underbidding is included. The size of the open market operation is then:

$$\begin{aligned} mro_s &= er_s^* + (E_{s-1}[er_{s+m}(i_s^*)] - er_s^*) + rr \\ &+ E_{s-1}\frac{1}{n}\left[\sum_{j=s}^{s+n} af_j\right] - E_{s-1}\frac{1}{n}\left[\sum_{j=s}^{s+n} nsf_j\right] - ltro - fto. \end{aligned} \tag{3.9}$$

The central bank provides sufficient liquidity such that expected autonomous factors, $E_{s-1}\frac{1}{n}\left[\sum_{j=s}^{s+n} af_j\right]$, required reserves (rr) and targeted excess reserves (er_s^*) are covered. Long-term and fine tuning operations are subtracted as well as the expected net recourse to standing facilities, $E_{s-1}\frac{1}{n}\left[\sum_{j=s}^{s+n} nsf_j\right]$. Note that the central bank provides liquidity assuming a linear fulfillment of reserve requirements, that is, $rr = \frac{\sum_{t=1}^{T} rr_t}{T}$. The second term on the right hand side, $(E_{s-1}[er_{s+m}(i_s^*)] - er_s^*)$, corrects for the so-called underbidding. Although the central bank wants to provide a certain amount of liquidity, it cannot do so independently of demand. If demand for main refinancing operations is lower than the central bank's desired supply, one speaks of underbidding. Underbidding can be explained as the equilibrium outcome of an expected policy rate decrease together with the interest rate elasticity of reserves. If the policy rate is not expected to change, excess reserves next week are expected to equal this week's excess reserves, hence, the term in parenthesis cancels. If, however, banks expect the policy rate to change, supply of liquidity is determined by the expected demand curve, at the current policy rate. The demand curve shifts with the expected policy rate change, but the current interbank rate does not change, because it is bounded from below by the current policy rate.[14] Therefore, supply is determined by the new demand for excess reserves, er_{s+m}, at the current policy rate i_s^*.

Combining equations (3.6), (3.7) and (3.9) defines actual excess reserves on any given day:

$$\begin{aligned} er_t &= \{er_s^* + (E_{s-1}[er_{s+m}(i_s^*)] - er_s^*) + rr + E_{s-1}\frac{1}{n}\left[\sum_{j=s}^{s+n} af_j\right] \\ &- E_{s-1}\frac{1}{n}\left[\sum_{j=s}^{s+n} nsf_j\right] - ltro - fto\} + \{fto + ltro - af_t - rr_t + nsf_t\} \end{aligned} \tag{3.10}$$

which can be simplified to:

$$er_t = er_s^* + (E_{s-1}[er_{s+m}(i_s^*)] - er_s^*) + E_{s-1}\frac{1}{n}\left[\sum_{j=s}^{s+n} af_j\right] - af_t + nsf_t. \tag{3.11}$$

[14] Liquidity has been alloted up to June 2000 through fixed rate tenders and variable rate tenders afterwards. However, a minimum bid rate is applied, which, in the underbidding case, defines a lower bound for the interbank rate. The minimum bid rate and the rate applied in fixed rate tenders correspond to the mid-point of lending and deposit rate, denoted here as policy rate.

Note that the relevant settlement day is the most recent one, s_l. However, for the ease of exposition, the subscript is omitted whenever it is not misleading. Daily total supply of reserves, TR_t, is then:

$$\begin{aligned} TR_t &= rr + er_t \\ &= rr + er_s^* + (E_{s-1}[er_{s+m}(i_s^*)] - er_s^*) \\ &\quad + \left\{ E_{s-1}\frac{1}{n}\left[\sum_{j=s}^{s+n} af_j\right] - af_t \right\} + nsf_t. \end{aligned} \tag{3.12}$$

As discussed in the section on demand, in the present model it is assumed that recourse to standing facilities takes place automatically, at the end of the day after the market has closed. In this case $nsf_t = 0$ throughout the market session, and the relevant supply of reserves, $\bar{M}_t$, is given by $\bar{M}_t = TR_t - nsf_t$.[15] Splitting up the autonomous factor term leads to:

$$\begin{aligned} \bar{M}_t &= rr + er_s^* + (E_{s-1}[er_{s+m}(i_s^*)] - er_s^*) \\ &\quad + \left\{ \frac{1}{n}\left(\sum_{j=s}^{s+n} E_{s-1}\left[af_j\right]\right) - E_{s-1}\left[af_t\right] \right\} + \{E_{s-1}\left[af_t\right] - af_t\}. \end{aligned} \tag{3.13}$$

Three factors shift the daily supply of reserves, namely underbidding, deviations of the actual autonomous factors from its average forecasts and the daily forecast errors itself. The first term in parenthesis on the right hand side represents underbidding, which is demand driven and related to expectations on a changing policy rate. The second term, in braces, denotes divergence of expected autonomous factors from its average forecast, which comes from the fact that liquidity is supplied only once a week. The last term in braces represents daily forecast errors, which are pure supply shocks. The supply shock which occurs at the end of day t is denoted as $u_t = \{E_{s-1}\left[af_t\right] - af_t\}$. The relevant supply variable for banks when making their decision is $M_t = \bar{M}_t - u_t$, because the size of the supply shock becomes known only after the market closes.

Note that if net recourse to standing facilities is interest rate elastic, total supply of reserves, as given in equation (3.12), depends on the interest rate. This might be rationalized by the fact that at a very high interest rate banks simply finance themselves by the marginal lending facility, not making use of the interbank market any more. Similarly, if the interest rate is very low, it might be preferable to make use of the deposit facility instead of lending to the interbank market.[16]

The deviation of actual excess reserves from its target is defined as $b_t \equiv er_t - er_s^*$. The variable b_t depicts deviations from the neutral allotment, i.e. from a situation

[15] In the US $\bar{M}_t$ is typically called non-borrowed reserves.

[16] See e.g. Thornton (2001a) for a similar formulation.

where liquidity differs from the amount necessary to keep the interest rate at the policy rate. On all days before the last settlement, $t = 1, ..., s_k - 1$, expected excess liquidity at the end of the maintenance period is:

$$E_t[b_T] = (E_{s-1}[er_{s+m}(i_s^*)] - er_s^*). \tag{3.14}$$

If there is underbidding, the liquidity shortage created in the underbidding is expected to prevail till the end of the maintenance period. However, forecast errors of autonomous factors are expected to be offset in the next main refinancing operation. After the last allotment, additionally accumulated daily forecast errors of autonomous factors and accumulated recourse to standing facilities affect the expected liquidity situation at the last day of the maintenance period, i.e. for $t = s_k, ..., T$:

$$E_t[b_T] = (E_{s-1}[er_{s+m}(i_s^*)] - er_s^*) + \sum_{j=s_k-1}^{t-1} \{(E_{s_k-1}[af_j] - af_j) + nsf_j\}. \tag{3.15}$$

3.2.3 Equilibrium

The interbank rate as equilibrium outcome of supply and demand for reserves is illustrated in figures 3.3 and 3.4. The exact functional form of the demand curve depends on the distribution function of the supply shocks. For illustrative purposes supply shocks are assumed to be drawn from a normal distribution. Figure 3.3 depicts the demand curve for the last day of the maintenance period. Note that the interbank rate equals the policy rate, $i_T = i_T^* \equiv (i_T^l + i_T^d)/2$, whenever reserve deficiencies equal supply of liquidity, $R_T = M_T$, in other words, when there is no liquidity shortage throughout the market session. If $R_T \neq M_T$, the interbank rate differs from the policy rate. By how much the change in liquidity moves the interest rate depends on the distribution function of the supply shock. During the market session of day T, banks know that before the end of the maintenance period there is still one supply shock, u_T, to come. This shock can make up for reserve deficiencies or force a bank to take recourse to marginal lending facility in case of overdraft. The probability of each of these events is determined by the distribution of the supply shock and, hence, the interbank rate reflecting these considerations also depends on the distribution of the shock. Reasons why M_T might deviate from R_T are discussed in the following section.

The demand function for all other days is more complicated, since the expected value of a change in the reserve deficiencies, $\frac{\partial V_{t+1}}{\partial R_{t+1}^j}$, which in general also depends on supply shocks, is involved. However, from equation (3.4) it can be seen that for very large M_t the interbank rate moves towards the deposit rate, i_t^d, and for very small M_t the lending rate, i_t^l, is approached. Besides that, the general model, as presented above, does not lead to a straightforward conclusion on the exact shape of the demand curve. Nevertheless, the probabilities for M_t to be so large (small) that the interest rate reaches the deposit (lending) rate are close to zero, especially at the beginning of the RMP. Therefore, the only important term in the demand equation is

$$\begin{aligned} i_t &\approx -\int_{B_t^j - A_t^j}^{R_t^j + B_t^j - A_t^j} \frac{\partial V_{t+1}(R_{t+1}^j, A_{t+1}^j; I_{t+1})}{\partial R_{t+1}^j} f(u_t) du_t \\ &\approx -\int_{B_t^j - A_t^j}^{R_t^j + B_t^j - A_t^j} - i_{t+1} f(u_t) du_t. \end{aligned} \tag{3.16}$$

Making use of a simplifying assumption on the supply side allows to approximate the middle part of the demand curve. Suppose that the central bank performs open market operations daily, opposed to weekly as assumed above. In this case expected interest rates do not depend on supply shocks, because the central bank corrects daily for these supply shocks, and consequently the expected interest rate simply depends on the expected policy rate and the expected liquidity situation. The policy rate is by definition independent of daily supply shocks and, in the simplified model, the expected liquidity situation is independent of supply shocks, too. The demand curve then has a flat part around the expected interest rate. Demand and supply curves for this approximation are plotted in figure 3.4.

The supply function in this model is rather simple. During the market session, i.e. before the realization of the shock, supply equals the sum of required reserves, targeted excess reserves, and the difference between the average forecast of autonomous factors and the present day forecast. This follows from equation (3.13) and defines the vertical part of the supply curve. Furthermore, via the two standing facilities the central bank provides (and absorbs) an unrestricted amount of liquidity at the lending (deposit) rate. Hence, there are two horizontal parts, being equal to the deposit rate for small values of M_t and equal to the lending rate for large values.

3.2.4 Expected and unexpected changes in supply

The main purpose of this section is to illustrate the effects supply changes have on the interbank rate. There are fundamental differences whether these changes happen at the last day(s) of the maintenance period, or at some earlier days, as well as whether these changes are expected or unexpected. For the ease of exposition and to concentrate on the effects of supply changes it is assumed that no underbidding occurs.

Recalling equation (3.13) and noting that the size of the autonomous factors, af_t, becomes known at the end of each day, the supply of reserves relevant for commercial banks, i.e. the expected amount of reserves available during the market session, M_t, is then given by:

$$\begin{aligned} M_t &= M + v_t \text{ with} \\ v_t &= \left\{ \frac{1}{n} \left(\sum_{j=s}^{s+n} E_{s-1}\left[af_j\right] \right) - E_{s-1}\left[af_t\right] \right\}, \\ M &= rr + er_s^* \text{ and } n = \min\{6, T-t\}. \end{aligned} \tag{3.17}$$

The variable v_t denotes the daily deviation of the expected autonomous factors from its expected average value. In other words, the weekly provision of liquidity implies an expected daily fluctuation for the supply of reserves, which is represented by v_t.

At the last day of the reserve maintenance period even a non-zero v_T has usually no impact on the overnight rate, i_T. Recall that the central bank allots liquidity such that liquidity provision is neutral at T, i.e. $\sum_{t=s_K}^{T-1} v_t + v_T = 0$. The overnight rate at the last day of the maintenance period, i_T, is determined by $(R_T - M_T) = -\left(\sum_{t=s_K}^{T-1} v_t + v_T\right) + \vartheta_T$. The last term, ϑ_T, summarizes other variables potentially influencing the overnight rate apart from the sum of expected supply changes. This term ϑ_T includes supply shocks, u_t, and the effects of underbidding. Since the sum of expected supply changes, $\sum_{t=s_K}^{T-1} v_t + v_T$, is zero the exact size of v_T does not matter for the determination of the overnight rate at T. Under certain assumptions the term ϑ_T equals zero and the overnight rate equals then the policy rate, $i_T = i_T^*$. These assumptions are that 1) all supply shocks having occurred since the last allotment day sum up to zero, i.e. $\sum_{t=s_K-1}^{T-1} u_t = 0$, 2) the boundary conditions given in equation (3.2) have not been hit and 3) supply shocks are distributed symmetrically.

In fact, whenever the central bank makes its allotment decision such that liquidity provision is neutral at T, the interbank rate at T is not affected by expected moves in the autonomous factors.[17] Nevertheless, if the central bank differs expectedly from the neutral allotment, the interbank rate at T is likely to react.

Unexpected changes in reserves - supply shocks - enter the demand function at T via the variable R_T. Shocks that occurred before the last allotment of the maintenance period are neutralized by the central bank latest at the last allotment, hence, do not enter R_T. However, all shocks which occur after the last allotment do enter the variable R_T in the following non-linear way:

$$R_T = \max\{0, R_{T-1} - \max\{0, M_{T-1} + u_{T-1}\}\}. \tag{3.18}$$

[17] In pratice, however, if the last settlement day happens to fall at day T, it is not so clear whether the liquidity provision at T is made caring only about the liquidity situation at T. Put differently, liquidity provision at T might not be totally independent of the expected liquidity situation in the following maintenance period, and, therefore, creating a non-neutral liquidity situation at T.

Suppose for simplicity that the last allotment takes place at $T-1$, which implies M_{T-1} is such that the sum of supply shocks contained in R_{T-1} are neutralized. As long as u_{T-1} is small enough (in absolute values) not to hit the restrictions imposed by equation (3.18), its effect on R_T is linear. However, a shock larger than $(R_{T-1}-M_{T-1})$ affects R_T only up to the point that it makes $R_T = 0$. Similarly, a very large negative shock, $u_{T-1} \leqslant -M_{T-1}$, leads to an automatic recourse to the marginal lending facility, since overdrafts are not allowed. The only effect that shock has is to neutralize the impact the liquidity supply M_{T-1} has on the fulfillment of the reserve requirement, that is, to make $R_T = R_{T-1}$.

The discussion of supply changes for other days than the last day of the maintenance period is based on a simplified version of the model. The simplified version includes daily, not weekly, supply of reserves.[18] The demand curve for other than the last day shows a horizontal part, besides those ones at the lending and deposit rate. Reserves changing within a certain range do not affect the interest rate. However, for small or large values of M_t, the interest rate i_t moves away from the expected future interest rate $E_t[i_{t+1}]$. Supply shocks have no impact on the interest rate at all. Recall that a supply shock at t enters the demand equation at $t+1$. In the simplified version of the model liquidity is provided every day, neutralizing all past shocks, hence, the supply shock u_t does not have any effect neither on i_t nor on i_{t+1}. The only exception is a very large positive supply shock, big enough to fulfill the reserve requirements for the entire banking sector for the whole maintenance period. In this case the interest rate jumps to the deposit rate, i.e. $i_t = i_t^d$.

The demand curves, as presented in figures 3.3 and 3.4, serve as benchmark for the empirical investigation, described in the next section. The exact size of the slopes is estimated and the assumed functional form is tested for. Furthermore, it is checked whether expected and unexpected supply changes have the same impact on the interbank rate. It is important to distinguish between both types of supply changes. As seen above, expected supply changes are the result of weekly supply of liquidity, hence, an institutional features, whereas unexpected supply changes are pure forecast errors.

[18] The graphical representation of the demand curve at t assumes that the central bank provides liquidity daily, making up for past shocks every day. Therefore the expected interest rate, $E_t[i_{t+1}]$, does not depend on shocks and can be taken out of the integral. As described above, liquidity in the euro area is provided only once a week, and consequently the assumption does not hold in general. However, this simplification might be close to true on a day which happens to be an allotment day and the penultimate day in the maintenance period at the same time, i.e. for $t = s_k - 1 = T - 1$. Nevertheless, the simplified version of the model should be useful for highlighting the basic differences between the last day of the maintenance period (or, more generally, the days after the last allotment of a maintenance period) and the days before the last day.

3.2.5 Underbidding

Underbidding refers to a situation in which the central bank cannot allot its desired amount of reserves due to insufficient demand.[19] If reserves are supplied through fixed rate tender procedures, or variable rate tenders with a minimum bid rate, an expected interest rate cut makes current supply relatively expensive, hence, shifting demand into the future. In the euro area several episodes of underbidding have occurred so far. In general, underbidding is the equilibrium outcome of rational agents.

In case liquidity not demanded in one week is supplied the following week, underbidding is definitely an optimal choice for commercial banks: If expectations are correct and the interest rate will be cut, reserves will be bought at a lower rate. If interest rates are not cut, the price in the following week is simply this week's price. However, if the central bank does not make up in the following week for liquidity deficiencies due to underbidding, the outcome depends on the demand elasticity. Suppose the supply curve is vertical between the two rates of the standing facilities, and the demand curve is also vertical at the last day of the maintenance period. Any supply shortage due to underbidding is not offset in the following main refinancing operation, hence, it moves the supply curve at the last day of the RMP. This implies that the interbank rate jumps to the marginal lending rate. Since the interest rate on a given day is a function of the expected rate at the last day of the RMP, the current interest rate jumps as well, making underbidding not an optimal choice.[20]

In the previous section it has been shown that the demand curve at the last day of the maintenance period is downward sloping. Consequently, a small amount of underbidding does not push the expected interbank rate to the marginal lending rate. It does increase the expected rate and therefore also the current interbank rate, but the amount of the increase depends on both the size of underbidding and the slope of the demand curve. There is then an equilibrium amount of underbidding, equalizing the current minimum bid rate with the expected interest rate at the last day of the RMP. Note that the only way to avoid underbidding in this model is to fine those banks which underbid. If all banks are penalized in the same way by simply allotting less liquidity than necessary, it is always profitable for one bank to underbid, given the others do not underbid. Then, in equilibrium all banks will underbid. However, if a bank has to pay a fine being larger than its potential gains from underbidding,

[19] Ewerhart (2002) develops a game theoretic model of liquidity provision to study underbidding and he discusses ways of eliminating it.

[20] This holds for any sensible interest rate cut expectation. However, it does not hold, if the interest rate cut is expected to be more than $(i_t^l - i_t^d)/2$, i.e. more than 100 basis points. In other words, if the expected marginal lending rate is lower than the current minimum bid rate. In this case obtaining liquidity in the future from the marginal lending facility is expected to be cheaper than obtaining it now from the current main refinancing operations.

i.e. the underbidding amount times the expected interest rate cut, this bank will not underbid. Nevertheless, the implementation of such a scheme is very complicated. An easier way to avoid underbidding is to change the policy rate, as a rule, only at the beginning of each RMP. This is part of a reform in the operating procedure proposed recently by the ECB.[21]

3.3 Empirical analysis

3.3.1 Model specification

The empirical model is heavily based on the demand equations derived from the theoretical model. In other words, the functional form and the variables included in the estimated equations are not assumed, rather they come from the first order conditions of the theoretical model, representing optimizing behavior of agents. Recall that at the last day of the maintenance period the aggregate demand equation is given by:

$$i_T = i_T^d + (i_T^l - i_T^d) * F(R_T - M_T). \tag{3.19}$$

In order to estimate this equation a functional form for the distribution function of the supply shocks, $F(\cdot)$, has to be chosen. The distribution function $F(\cdot)$ is proxied by a linear function, which is justified since the interest rate throughout the whole sample reached the upper bound, the lending rate, only at three very special occasions, the so-called underbidding episodes. These underbidding episodes are modeled separately, because the behavior of the interest rate at these days was very different from other days. At all other days the relation between the interest rate, i_T, and $(R_T - M_T)$ is well described by the linear part of the distribution function.

Reserve deficiencies, R_T, are easy to compute, and the end of the day supply of reserves, $\bar{M}_T = M_T + u_T$, are published on a daily basis by the ECB. Nevertheless, the relevant decision variable for a commercial bank are the supply of reserves during the market session M_T, that is, expected reserves, which do not include the supply shock u_T. Making use of autonomous factor forecast errors allows the computation of the relevant supply variable, M_T. Note that $R_T - M_T$ equals the sum of autonomous factor forecast errors and net recourse to standing facilities from the last allotment on up to $T-1$, $R_T - M_T = \sum_{t=s_k-1}^{T-1}(u_t + nsf_t)$.[22] In the following estimations a series $\widetilde{b_t}$ containing accumulated forecast errors and accumulated recourse to standing facilities

[21] See the public consultation "Measures to improve the efficiency of the operational framework for monetary poliy" at www.ecb.int or ECB (2004).

[22] This holds strictly only in case of neutral allotment. Note, however that this assumption is indeed fulfilled for almost all days, except allotments around the underbidding episodes.

is used, where $\widetilde{b_t} \approx \sum_{j=s_l-1}^{t-1}(u_j + nsf_j)$ with s_l being the most recent settlement day.[23] Figure 3.7 shows a plot of this series.[24]

On all other days, the demand equation does not depend only on reserve deficiencies and reserve supply, but also the expected interest rate is important for the determination of the interbank rate. The expected interest rate depends basically on two factors, the expected policy rate and the expected liquidity situation. The expected policy rate is proxied by a forward rate fw_t, with

$$fw_t = 2 * r_t^{(2)} - r_t^{(1)}, \tag{3.20}$$

where $r_t^{(2)}$ and $r_t^{(1)}$ are the two and one-week EONIA swap rates, respectively.[25] This forward rate reflects the expected one-week rate in one week's time, which, in general, provides a good assessment of the expected policy rate.[26] The benchmark case, as illustrated in figure 3.4, assumes daily liquidity provision and the demand curve is characterized by a horizontal part. However, banks might not consider reserve holdings of different days as perfect substitutes, which implies a downward sloping demand curve. Furthermore, the weekly provision of liquidity may introduce non-linearities into the demand curve. From the general model above, these non-linearities are not precisely defined. The following, testable, specification for the demand curve is proposed. Its main features are: 1) For very large (small) M_t, the interbank rate equals the deposit (lending) rate; 2) In the absence of a) supply shocks, b) expected temporary deviations of M_t from its average values, c) expected net recourse to standing facilities and d) expected policy rate changes, i.e. $u_t = v_t = nsf_t = (i_{t+1}^* - i_t^*) = 0$ for all t, the interbank rate equals the policy rate, $i_t = i_t^*$. Note that this is exactly the scenario described in the benchmark case. The interbank rate is then formulated as a function

[23] This information is not publicly available. I am very grateful to Clara Martin Moss and Steen Ejerskov from the Monetary Policy Stance Divsion of the European Central Bank who compiled this series and made it available to me. Their series shows the deviation of the liquidity situation from neutral, expected to prevail at the next settlement day or the last day of the RMP, whatever comes first. In general, this deviation equals the sum of accumulated forecast errors and accumulated net recourse to standing facilities since the last allotment day.

[24] Commercial banks can proxy this variable fairly well.

[25] Approximating the expected policy rate by other forward rates does not seem to change the results. In the previous version of the paper forward rates constructed from both Euribor and EONIA swap rates with maturities of one and two months have been used, but parameter estimates are very similar.

[26] Short-term money market rates follow the policy rate quite closely, in particular this holds for the one month rate. Hence, the expected one month rate should follow closely the expected policy rate. For the predictive power of forward and future rates see e.g. Poole and Rasche (2000) or Gaspar et al (2001). The variable needed for the estimation of i_t is the expected policy rate at $t+1$, or more generally, the expected policy rate within this maintenance period. If the interest rate is expected to change in e.g. five weeks, the forward rate changes, but the expected policy rate for this period does not change. In this case, the forward rate does not provide a good proxy for the expected policy rate. Nevertheless, it is assumed that changes in the forward rate reflect expected changes in this maintenance period's policy rate, mainly, because agents are likely to make forecasts at short horizons due to the low precision of long horizon forecasts.

of deviations from the benchmark.

The liquidity situation at each day, given by R_t and M_t, differs from the benchmark due to supply shocks and anticipated supply changes. Deviations of reserve supply, M_t, and reserve deficiencies, R_t, from the benchmark, M_t^{bench} and R_t^{bench}, change the liquidity situation at t, and potentially move the interest rate away from the policy rate. Liquidity variables expressed as deviations from the benchmark case are given by:

$$\begin{aligned} & (R_t - M_t) - (R_t^{bench} - M_t^{bench}) \\ = & -\sum_{j=s_l-1}^{t-1} \{\max(-M_j, u_j) + nsf_j\} - \sum_{j=s_l}^{t-1} v_j - v_t \text{ and} \end{aligned} \tag{3.21}$$

$$M_t - M_t^{bench} = v_t. \tag{3.22}$$

It follows that supply shocks and anticipated deviations from the average supply of reserves have the potential to drive a wedge between the interbank and the policy rate, either directly, via $R_t - M_t$ and M_t, or indirectly via

$$E_t[i_{t+1}] = E_t[\Psi(R_t, R_{t+1}, ..., R_T, M_t, M_{t+1}, ..., M_T, i_t^*, i_{t+1}^*, ..., i_T^*)]. \tag{3.23}$$

$\Psi(\cdot)$ is a general function which needs not be further specified for the moment. Note that at all allotment days and at the last day of the maintenance period the sum of expected supply changes is zero, i.e. $\sum_{j=s_l}^{t-1} v_j = 0$ for $t \in \{s_1 - 1, s_2 - 1, ..., s_k - 1, T\}$. Furthermore, liquidity supply is such that reserve deficiencies at any settlement day, R_t for $t \in \{s_1, .., s_k\}$, do not depend on past supply shocks other than u_{t-1}. Therefore, supply shocks occurring before the last allotment day, $t = s_k - 1$, are expected to affect the liquidity situation only temporarily, but are not relevant for the total liquidity situation of the entire reserve maintenance period. Equally, expected supply changes, v_t for all t, affect the liquidity situation temporarily only. In contrast, supply shocks occurring after the last allotment day have an effect on the liquidity situation at T, the last day of the RMP.

One of the central questions in this chapter is if temporary changes in supply have an effect on the interest rate, in other words, if a daily liquidity effect exists. The two sources of temporary changes are different in style and can have different implications. If expected supply changes have an effect on the interest rate on a daily basis, then there exists a daily liquidity effect. However, if supply shocks have an effect, it might be due to a daily liquidity effect, but also that commercial banks do not expect supply shocks to be fully offset in the next allotment decision. A daily liquidity effect results whenever banks do not see daily reserves as perfect substitutes. Whereas, even if there is no daily liquidity effect, supply shocks affect the interest rate if the allotment strategy of neutralizing supply shocks is not fully credible.

Recall that deviations of the liquidity situation from its benchmark are measured by the sum of forecast errors and net recourse to standing facilities, $\widetilde{b_t} \approx \sum_{j=s_l-1}^{t-1}(u_j + nsf_j)$ with s_l being the most recent settlement day. However, net recourse to standing facilities is very close to zero on most days, except for some days near the end of the maintenance period, as can be seen in figure 3.5. Therefore, supply shocks are the main driving forces of the liquidity situation.

In figure 3.6 the interbank rate together with the lending and deposit rate are plotted and some basic statistics are given in table 3.1. Normally the interbank rate follows the policy rate, which is the mid-point of lending and deposit rate, quite closely, but occasionally there are large spikes. As discussed above, the deviation of the interbank rate from the policy rate can be caused by changes in liquidity or changes in the expected policy rate. A series for changes in liquidity and the forward rate, a proxy for the expected policy rate, are plotted in figures 3.8 and 3.9, respectively.

Standard unit root tests confirm that the interest rate, within the sample, is integrated of order one. Furthermore, it is co-integrated with the policy rate, i_t^*. Therefore, the interest rates, i_t, is modelled in first differences, $\Delta i_t \equiv (i_t - i_{t-1})$, and a unit co-integrating vector, $(i_{t-1} - i_{t-1}^*)$, is imposed.[27] The model then is:

$$\begin{aligned}
\Delta i_t &= c + \phi(i_{t-1} - i_{t-1}^*) + x_t\beta + h_t\eta_t \qquad (3.24)\\
x_t &= \{\ b_t - b_{t-1}, b_{t-1} - b_{t-2}, ..., b_{s_l}, fw_t - fw_{t-1}, d_t\}\\
\ln(h_t^2) &= z_t\lambda + \sum_{j=1}^{q}\delta_j\left(\ln(h_{t-j}^2) - z_{t-j}\lambda\right) + \alpha\left\{|\eta_{t-1}| - E|\eta_{t-1}| + \gamma\eta_{t-1}\right\}\\
\eta_t &\sim iid(0, p + (1-p) * \sigma^2).
\end{aligned}$$

The parameter ϕ captures how fast the interest rate, i_t, returns to its long-run value, the target rate i_t^*. The mean equation includes a constant, c, and other explanatory variables, x_t. Deviations of liquidity from the neutral allotment are given by the variable b_t.[28] The most recent settlement day is indexed by $t = s_l$. The autocorrelation function in figure 3.10 shows clear evidence for conditional heteroskedasticity, which is modeled with an EGARCH specification.[29] The conditional standard deviation of the

[27] Results on tests for the order of integration and co-integration are not reported. All test results are available from the author.

[28] Both, the actual liquidity situation at each day, that is, $b_t = \widetilde{b_t} \approx \sum_{j=s_l-1}^{t-1}(u_j + nsf_j)$ and $b_t \approx \sum_{j=s_l-1}^{t-1} u_j$, the sum of autonomous factor forecast errors alone, are used. Estimation results are practically identical.

[29] An EGARCH model has some advantages over more standard GARCH models, notably restrictions on some parameters are not necessary in order to ensure nonnegativity of conditional variances. See for example Bollerslev et al (1992).

interest rate is given by h_t. The vector z_t contains explanatory variables for the conditional volatility equation. Of particular interest are variables related to the operating procedure and calendar days. Standardized residuals are denoted by η_t. Frequent small changes and occasionally large spikes characterize the interbank rate, suggesting the underlying distribution to be a mixture of two normal distributions.[30] The probability to come from the first distribution with variance one is p, and the probability to come from the second distribution with variance σ^2 is $(1-p)$. The exponential GARCH model applied here allows to estimate the different impact positive and negative surprise changes of the interest rate have on the volatility, which is given by the parameter γ.

The vector d_t (z_t) may include further explanatory variables for the conditional mean (variance). This specification allows to test for a wide range of possible effects related to the central bank's operating procedure and calendar days.

One of the main issues of this chapter is the analysis of the liquidity effect. Hence, the parameters of main interest are those related to the liquidity variables b_t. These parameters can be interpreted as determining the slopes of the demand curves. Note that also lagged liquidity variables are included in x_t, which permits to analyze how fast banks react to changes in supply. If there is an immediate reaction only $b_t - b_{t-1} \approx u_{t-1}$ should be significant. On the contrary, if other liquidity variables are also significant one can conclude that banks react sluggishly to new information. This sluggish reaction might be banks' choice, or simply reflect the slow diffusion of information.

The liquidity variables used here are those which reflect precisely the liquidity situation banks are faced with when taking their demand decisions.[31] For example, Würtz (2003) uses the accumulated recourse to standing facilities at the last day of the maintenance period, and average reserve surplus on other days. Those variables do not measure the prevailing liquidity situation exactly. The accumulated recourse to standing facilities includes the supply shock which occurs at the end of the last day of the maintenance period, but banks do not know the size of this shock when making their decisions. Furthermore, as seen above, it is not only recourse to standing facilities which defines the liquidity situation, but also the sum of forecast errors. In addition, by using average reserve surplus it is not taken into account that the central bank makes up for past forecast errors and, again, that the end of the day shock is not known to banks. What is more, the recourse to standing facilities might depend on the interest rate (see e.g. Thornton, 2001a). In other words, banks might decide actively on the use of the standing facilities, not only take recourse by force, e.g. in case of

[30] The student t-distribution has also been used, but the mixture of normals allows fatter tails together with a larger mass around zero, which is supported by the data.

[31] The same liquidity data is used in Ejerskov et al (2003). However, they estimate a weekly model for demand and supply of liquidity.

overdraft. Then, recourse to standing facilities becomes an endogenous variable and cannot be used directly in the estimation of the demand curve. The current model does not suffer from this caveat, since forecast errors are by definition exogenous and, therefore, can be used to estimate the liquidity effect.[32]

3.3.2 Estimation results and discussion

The estimated model is presented in table 3.2.[33] Residuals, standardized residuals and conditional log volatility are plotted in figures 3.11, 3.12 and 3.13, respectively. Standard tests indicate that the model is well specified. There is no serial correlation left, neither in the standardized residuals nor in the squared standardized residuals (see figures 3.15 and 3.16) and the empirical distribution of the residuals is very close to its assumed distribution (see figure 3.17). Lagrange multiplier tests for omitted variables, given in tables 3.3 to 3.5, do not show any apparent misspecification. Furthermore, estimated parameters are very stable across sub-samples.[34]

From the theoretical discussion above it has been seen that institutional details have the potential of influencing the interbank rate. Indeed, all key features of the theoretical model are confirmed by the data. In addition the interbank rate is characterized by some other effects not showing up directly in the theoretical model, but clearly being related to the operating procedure. The main results are summarized in table 3.6, where all predictable patterns of mean and volatility of the overnight rate are stated. Most of these patterns are related to the implementation of monetary policy, but also some calendar day effects are present. In what follows, each of these patterns will be discussed in detail.

It cannot be rejected that the demand curves look like in the benchmark model, as presented in figures 3.3 and 3.4. In other words, the demand curve is downward sloping only at the last day of the maintenance period. All four parameters on liquidity at the last day of the maintenance period are negative and significant (panel A in table 3.2). On all other days the parameter on liquidity is not significant (see panel F in table 3.5) . Hence, on all days other than the last day of the RMP, the demand curve is flat. Recall that this statement holds for not too big deviations from a neutral liquidity situation. Furthermore, note that banks react sluggishly to new information.

[32] The estimation results given below are obtained by using the actual liquidity situation at each day, that is, $b_t = \widetilde{b_t} \approx \sum_{j=s_l-1}^{t-1}(u_j + nsf_j)$. Results for $b_t \approx \sum_{j=s_l-1}^{t-1} u_j$, the sum of autonomous factor forecast errors alone, are practically identical.

[33] Numerical optimization has to be applied to estimate this model. Several starting values are used to check whether a global maximum has been reached. Standard errors are based on the second derivatives of the log likelihood function. The outer-product estimates are almost identical.

[34] Parameter estimates presented here are very similar to the estimates contained in the previous version of this chapter, which uses data up to July 2002.

The interest rate at T differs from its previous day value also if a change in supply has occurred on the preceding days. It is not only the current supply change, which matters. A positive supply change at T of one billion euro decreases the interest rate, i.e. $(i_T - i_{T-1})$, by 7.7 basis points. Note that the supply shock at day t occurs after the market closes, therefore, affecting supply at $t + 1$. Accordingly, u_{T-1} denotes the unexpected supply change at day T. If the change in supply occurred before $t = T$ the interest rate does not react until the last day of the RMP. The effect is smaller than for contemporaneous changes in supply, but still considerable. Lagged supply changes of one billion euro move the interest rate by around 5 basis points into the opposite direction. This sluggish reaction might explain why a permanent change in supply, that is a supply shock after the last allotment day, does not affect the interest rate until the last day. What is more, allowing the interest rate to react also to lagged supply changes permits to pin down the liquidity effect more precisely.

Estimating a model with weekly frequency Ejerskov et al. (2003) find an asymmetric liquidity effect. Positive supply changes imply a larger reaction of the interest rate than negative changes. This asymmetric effect cannot be confirmed in the present analysis, as indicated by panel G in table 3.5.

An expected change in the future interest rate should move the current interest rate by (almost) the same size. One way to measure this relationship is the use of a forward rate. However, the forward rate at t is not a perfect signal of the expected interest rate at $t + 1$, thus the estimated parameter is likely to be different from one. Indeed, a change in the forward rate moves today's interest rate, but by less than one. Estimated at the first day of a RMP, a change in the forward rate by 10 basis points increases the interbank rate by 6 basis points. The forward rate is best used at this day, since it mostly reflects expected policy rate changes within the current maintenance period. For other days, especially for those close to the end of the maintenance period, expected policy rate changes in the next maintenance period become more important for the determination of the forward rate. However, expected changes in the policy rate in the next maintenance period should not affect the current interest rate.

Summarizing, it can be said that transitory changes in supply do not affect the interbank rate. In other words, there is no daily liquidity effect for temporary supply changes. After the last allotment day all changes in supply as analyzed here are permanent in the sense that they affect the liquidity situation at the last day of the RMP and, accordingly, the reserve position of the whole maintenance period. These permanent changes do not impact on the interest rate till the last day of the maintenance period. The slow diffusion of new information on supply changes, or the low benefits of closely watching total reserve supply in the market are possible reasons for this finding. There is some evidence that the relation between current and future expected interest rate is close to one. All in all, a permanent and fully known change in supply should move the interest rate up to the level expected to prevail at the last day of the maintenance period. The level of the interest rate at the last day depends on the slope of the demand curve and the deviation of liquidity from neutral. Assuming that the liquidity change takes place before the last allotment, the relevant slope is -0.08. Therefore, a liquidity shortage of 13 billion or more moves the interest rate towards the marginal lending rate.

In the underbidding episodes such permanent liquidity shortages were created. Underbidding the weekly allotment by e.g. four billion lower than the neutral amount creates a total liquidity shortage over the whole week of 4*7=28 billion and, in consequence, leads the interbank rate to touch the upper bound. This is exactly what can be observed in the data, which provides corroboration that the effect of permanent and fully expected supply changes on the interest rate are largely determined by the slope of the demand curve at the last day of the maintenance period.[35] It is important to have in mind that liquidity supply is assumed to be neutral. However, if the central bank expectedly differs from this policy, the above described relationships may change as well.

First differences of the interest rate exhibit slight autocorrelation. This behavior does not come out directly from the theoretical model and contradicts market efficiency. However, in practice it might be costly to obtain information on supply changes directly, so some banks might use past interest rates as a proxy for supply changes.

There is no systematic pattern for the mean of the interest rate throughout the reserve maintenance period, as can be seen in table 3.3. Various measures are used to test for a possible increase of the interest rate towards the end of the reserve maintenance period, but there is no evidence for such an interest rate hike in the present model. Neither the announcement nor allotment or settlement of the last open market operation in each RMP influences systematically the mean of the interest rate (see panel H in table 3.3). Furthermore, the mean of the interest rate does not behave differently at days of the ECB's Governing Council meeting or press conference than at other days (see panel L in table 3.3).

Volatility is higher for days after the last allotment day till the last day of the maintenance period, as can be seen very clearly in figure 3.14. Additionally, there is an increase in volatility at the first day, last day and next to last day in each RMP, as well as at the allotment day of the last open market operation. Volatility increases also at the day of a policy rate change and the day after. As predicted by the theoretical model there is no increase neither in the mean nor in the volatility of the interbank

[35] See for example Bindseil (2002) or Välimäki (2002).

rate for other days before the last allotment day (see table 3.3).

Positive surprise changes in the interest rate increase volatility more than negative surprise changes. The relevant parameter γ is estimated to be around 9 percent, as can be seen in panel H of table 3.2. Positive changes in the interest rate indicate an increased probability of ending up the reserve maintenance period with too few reserves, or an expected increase in the policy rate. Banks may be worried more about not fulfilling the reserve requirement than about holding too many reserves, which then can increase volatility. Alternatively, banks are likely to view an increase in the policy rate as less favorable than a decrease, which then also can push up volatility.

One striking difference of monetary policy implementation in the euro area to other countries is the low frequency of open market operations. An important question is then to study the effects of frequency of open market operations. It has been shown that volatility increases after the last allotment day. Hence, for infrequent open market operations, the period after the last allotment day becomes longer and therefore the number of days with high volatility increases. Throughout the sample period the number of days which pass after the last allotment until the last day of the reserve maintenance period varies every month. In general, the last allotment is performed on Tuesday and the last day in a reserve maintenance period is the 23rd of each month. However, there have been some recent changes in the operational framework of the ECB, becoming effective from March 2004 onwards (see e.g. ECB, 2004). Now, there are always five (business) days after the last allotment until the last day of the RMP. It is therefore interesting to test if the volatility increase at the end of the RMP depends on the number of days after the last allotment day. Lagrange multiplier tests, as outlined in panels D to G in table 3.3, indicate that the number of days after the last allotment day does not matter for volatility. It has to be said that this is only a descriptive analysis, which depends on the current structure of the money market and especially on the current details of open market operations. No general conclusions are drawn on the effects of changing the frequency of open market operations.

All the above characteristics of the interbank rate are related in some way or another to the operating procedure of the central bank. There are some other interesting patterns, which are pure calendar day effects. At the last day of the month the interbank rate increases by 5 basis points. At the end of the second quarter the increase is 18 basis points and 31 basis points at the end of the year. However, this increase is reversed on the following day, the first day of the month, as panel B in table 3.4 indicates. Volatility of the interbank rate is higher around the end of the month, too. These effects are likely to be the result of window dressing, i.e. banks adjusting their balance sheets at the end of the month. However, currently the ECB does not counteract this interest rate changes. One possibility to avoid this end-of-month effects could be to provide more liquidity at the end of the month, subtracting it at the beginning of a month. Nevertheless, supply changes around the end of a month are not found to affect the interest rate (see panel D of table 3.5). The non-existing liquidity effect around the end of the month may be due to a measurement problem. Supply changes are measured by the unexpected component, namely, with supply shocks. As discussed above, banks react sluggishly to these (unexpected) changes in supply, thus, possibly making it difficult to estimate a downward sloping demand curve around the end of a month. Nevertheless, expected changes in supply might very well influence the interest rate. For example, a credible commitment by the central bank to provide liquidity at the last day of each month should reduce the interest rate. The day of the week does not explain the behavior of the overnight rate. Neither mean nor volatility of the interbank rate depend on the weekday, as can be seen in panel A of table 3.4.

By comparing the reaction of commercial banks to supply shocks one can test the efficiency of banks' reserve management.[36] The theoretical model motivates changes in the interbank rate as a function of liquidity. The size of the reaction depends on the distribution of supply shocks. The observed standard deviation of supply shocks is around 7 billion euro for days after the last allotment day and around 24 billion euro throughout the whole RMP. Relevant supply shocks are those occurring after the last allotment, because all other shocks are neutralized in subsequent open market operations. It has been shown that the interest rate at the last day of the RMP is given by $i_T = i_T^d + (i_T^l - i_T^d) * F(R_T - M_T)$, which can be approximated by $i_T = (i_T^d + 1) + \tilde{\beta} * (R_T - M_T)$. Recalling that $(R_T - M_T) \approx \sum_{t=s_k-1}^{T-1} u_t$ and using the standard deviation of the supply shocks, it follows that $\tilde{\beta} \approx -0.08$, which is very close to the estimated parameter on u_{T-1}.[37] In other words, the reaction of banks to supply shocks is fully rational, at least as far as magnitudes are concerned. However, it has been found that banks react sluggishly to new information, a pattern which is not easily explained for rational agents. One possible explanation is that banks do not have timely information on the exact size of the supply shocks. However, banks should be able to proxy the size of the supply shock fairly well. Alternatively, gains from reacting quickly to supply changes might be small. Although the exact size of potential profits is still an open question, a preliminary assessment shows that there may exist some arbitrage opportunities.

From the theoretical model one expects the parameter on u_T to be zero, that is, a supply shock occurring at the end of day T should not have any influence on the interest rate at that day. Nevertheless, the estimated parameter is significantly

[36] I thank Christian Ewerhart for pointing this out.

[37] The last settlement day can fall at any weekday. Therefore, on average $(R_T - M_T)$ contains supply shocks from three business days. It follows that $Var(R_T - M_T) \approx 3 * Var(u_t^{last}) = 3 * (7.02)^2$, with u_t^{last} being a supply shock occuring at or after the last allotment day.

different from zero. One reason can be that during the market session commercial banks have already some clue about the size of the supply shock, thus, they can react to it. This seems to make good sense since this parameter is only different from zero at the last day of the RMP, when banks are supposedly watching their reserve accounts closely.[38]

3.4 Conclusions and further research

This chapter studies the determinants of the overnight interest rate and quantifies them. The overnight interest rate is the equilibrium outcome of supply and demand for bank reserves. The here developed structural model for both supply and demand for reserves allows a detailed analysis of the interactions between the central bank, as the sole net supplier of reserves, and commercial banks, on the demand side. The precise set-up of this market, i.e. institutional details of the reserve market, has important implications for the behavior of the overnight rate, both for conditional mean and variance. These implications are derived from a theoretical model and their magnitudes are estimated for the euro area overnight rate.

The overnight rate reacts to expected future changes in the policy rate and to permanent changes in supply of reserves. In fact, a substantial liquidity effect is estimated: a change in reserve supply of one billion euro, expected to prevail till the end of the maintenance period, moves the interbank rate eight basis points into the opposite direction. The theoretical model relates the magnitude of the liquidity effect to the distribution of supply shocks, which is confirmed by the data. Interestingly, banks do not react immediately to supply changes. This sluggish reaction to supply changes is not easily explained for rational agents. Temporary supply changes have no effect on the overnight rate.

Predictable patterns are found for the overnight rate. The mean is high at the last day of a month, even higher on the end of a semester or a year. The end of the month, semester and year increases are completely reversed at the first day of the following month. End of month effects are most likely due to window dressing operations. The mean of the overnight rate does not vary systematically throughout the reserve maintenance period. Therefore, the short-term money market does not contain clear arbitrage opportunities, with the possible exception of the sluggish reaction to supply shocks.

[38] The alternative interpretation is measurement error. Since the size of the supply shock for T is not available, it was constructed as: $u_T = -nsf_T - \sum_{j=s_l-1}^{T-1}(u_j + nsf_j)$. Although it is in principle possible that u_T is measured with some error, there is no obvious reason why the above equation should not hold exactly.

The conditional volatility of the overnight rate is closely related to monetary policy implementation. Conditional volatility is especially high at the allotment day of the last open market operation and even higher at days afterwards. Volatility increases at the day of a change in the policy rate and around the end of a month.

In this chapter the relation between operating procedures and the overnight interest rate has been analyzed in great detail. However, equally important is how the here identified effects work through the yield curve and affect other interest rates. As long as these effects are limited to the very short end of the yield curve, implications for the economy as a whole are probably insignificant. On the contrary, if long-term interest rates react strongly as well, implications are far more important. Nevertheless, not much is known about this transmission along the yield curve. Cassola and Morana (2003 and 2004) and the next chapter provide a first analyses of volatility transmission along some money market rates.

While the present analysis focuses on policy implementation of one particular central bank, an interesting area of research is the comparison of alternative operating procedures and their effects on the behavior of interest rates. However, little work has been done so far in this field.

3.5 Appendix

3.5.1 Basic statistics and estimation results

Table 3.1: Basic statistics for selected series.

Variable	Mean	Std. Dev.	Skewness	Kurtosis
EONIA rate, in levels	3.343	0.931	0.283	2.043
EONIA rate, in first differences	0.000	0.143	0.884	16.745
Forward rate, in levels	3.342	0.900	0.272	1.895
Supply shock, u_t	0.543	24.524	1.363	50.897
Supply shock, after last allotment day	0.489	7.017	1.800	11.612

NOTE: The EONIA rate is a volume-weighted average of interbank rates in the euro area. See table 3.7 for a detailed description of the other variables. Sample: All business days from 24/03/1999 to 19/02/2004, both included.

Table 3.2: Parameter estimates for the Overnight Interest Rate (EONIA).

Model: $\Delta i_t = c + \phi(i_{t-1} - i^*_{t-1}) + x_t\beta + h_t\eta_t$

$\ln(h_t^2) = z_t\lambda + \Sigma_j \delta_j \{ \ln(h_{t-j}^2) - z_{t-j}\lambda \} + \alpha\{|\eta_{t-1}| - E|\eta_{t-1}| + \gamma\eta_{t-1}\}$

$\eta_t \sim iid(0, p + (1-p)*\sigma^2)$.

Sample: All business days from 24/03/1999 to 19/02/2004, both included.

Variable	Parameter	Std. Error	p-value
Mean equation			
(A) Liquidity effects at the last day in a RMP, t = T			
u_{T-1}	-0.077	0.014	0.000
u_{T-2}	-0.055	0.009	0.000
$u_{T-3} + u_{T-4} + u_{T-5}$	-0.052	0.009	0.000
u_T	-0.046	0.009	0.000
(B) Expected future policy rate			
$E_t[i^*_{t+k}]$ at the first day in a RMP, t = 1	0.628	0.060	0.000
$E_t[i^*_{t+k}]$ at other days, t = 2,…,T	0.000	0.007	0.946
(C) Calendar day effects			
End of month, reversed begin of month; except end of semester	0.051	0.002	0.000
End of 2nd quarter, reversed begin of 3rd quarter	0.178	0.020	0.000
End of 4th quarter, reversed begin of first quarter	0.310	0.033	0.000
(D) Other variables			
First day in a RMP, t = 1	0.030	0.005	0.000
dunderbidding	-0.303	0.014	0.000
$(i_{t-1} - i_{t-2})$*(1 - first day - begin of month)	0.067	0.011	0.000
Constant	0.001	<0.001	0.173
Error correction term $(i_{t-1} - i^*_{t-1})$ at the first day in a RMP, t = 1	-1.000	-	-
Error correction term $(i_{t-1} - i^*_{t-1})$ at all other days, t = 2,…T	-0.040	0.008	0.000

Table 3.2 (continued)

Variable	Parameter	Std. Error	p-value
Volatility equation			
(E) Days of reserve maintenance period			
First day, t = 1	1.516	0.194	0.000
Last allotment day	0.841	0.250	0.001
All days after last allotment	3.045	0.381	0.000
Next to last day, t = T-1	1.850	0.393	0.000
Last day, t = T	2.315	0.510	0.000
(F) Calendar days			
End of month and the day before	0.471	0.171	0.006
Begin and end of a quarter, additionally	1.500	0.665	0.024
Begin and end of a semester, additionally	2.170	0.455	0.000
Policy rate change and the day after	1.087	0.287	0.000
(G) Other dummy variables			
dunderbidding	1.754	0.195	0.000
GC meeting after last allotment (Sep and Oct 1999)	4.028	0.291	0.000
Underbidding at end of RMP (Dec 2003)	1.047	0.356	0.003
January 2002 (Cash changeover)	3.175	0.725	0.000
(H) EGARCH parameters			
Constant	-6.394	0.151	0.000
α	2.403	0.211	0.000
δ	0.678	0.037	0.000
γ	0.089	0.033	0.007
σ	0.203	0.011	0.000
p	0.324	0.003	0.000
Standardised residuals:			
Mean	0.019		
Variance	0.368		
Skewness	0.599		
Kurtosis	12.657		
Q(20), p-value	0.023		
Q(20) for squared residuals, p-value	0.970		

NOTE: i_t = volume-weighted average of interbank rates in the euro area, the EONIA rate. i^*_t = policy rate, or target rate, which is defined as the fixed rate (until June 27, 2000) and the minimum bid rate (after June 27, 2000) at which the European Central Bank conducts its weekly open market operations. Any change in the policy rate is assumed to become effective at the day of announcement, not at the day when the next open market operation is settled. All rates are quoted as annual rates, e.g. $i_t = 5$ means a five percent annual interest rate. Liquidity effects in panel A are estimated using the relevant supply changes, i.e. those occurring at or after the last allotment day in each RMP. See table 3.7 and the main text for a detailed description of the variables used in the estimation. The parameters in the variance equation represent the effect on the log of the conditional volatility. A zero liquidity effect is tested for and then imposed at two underbidding episodes and after Easter 2003. The respective days are 23/10/2001, 23/12/2002 and 23/04/2003. Q(j) denotes the Ljung-Box test for serial correlation at lag length j.

Table 3.3: Lagrange multiplier tests for omitted variables; days of the reserve maintenance period.

Omitted variable	**p-value**	
	Mean	**Variance**
(A) D_t = 1 at days after last allotment and when t equals:		
T	0.088	-
T-1	0.016	-
T-2	0.972	0.033
T-3	0.007*	0.102
T-4	0.078	0.465
(B) D_t = 1 at days before last settlement and when t equals:		
T-1	0.333	0.400
T-2	0.034	0.000*
T-3	0.144	0.332
T-4	0.608	0.528
(C) D_t = 1 at all days after last allotment, if last allotment is at:		
T-5	0.589	0.096
T-4	0.033	0.340
T-3	0.666	0.171
T-2	0.185	0.429
(D) D_t = number of days after last allotment minus one and t equals:		
T	0.896	0.448
T-1	0.061	0.187
T-2	0.025	0.250
T-3	0.872	0.076
(E) D_t = five minus number of days after last allotment and t equals:		
T	0.010	0.121
T-1	0.275	0.190
T-2	0.062	0.253
T-3	0.835	0.041
(F) D_t = 1 when t equals T and:		
T is a settlement day	0.077	0.088
T is NOT a settlement day	0.276	0.106
T-1 is a settlement day	0.166	0.102
T-1 is NOT a settlement day	0.486	0.325
T-2 is a settlement day	0.137	0.317
T-2 is NOT a settlement day	0.419	0.398
(G) D_t = 1 when t equals T-1 and:		
T-1 is a settlement day	0.043	0.387
T-1 is NOT a settlement day	0.874	0.102
T-2 is a settlement day	0.005*	0.097
T-2 is NOT a settlement day	0.017	0.985
	0.573	0.972
(H) D_t = 1 when t falls on:		
The last settlement day in each RMP	0.147	0.237
The last allotment day in each RMP	0.866	-
The last announcement day in each RMP	0.066	0.007*

Table 3.3 (continued)

Omitted variable	p-value Mean	p-value Variance
(I) $D_t = 1$ for $t = T - k$, with k:		
1	0.872	0.399
2	0.047	0.013
3	0.074	0.957
4	0.717	0.414
5	0.589	0.096
6	0.300	0.482
7	0.273	0.485
8	0.577	0.832
9	0.160	0.000*
10	0.802	0.439
11	0.051	0.014
12	0.396	0.221
13	0.123	0.007*
14	0.407	0.568
15	0.135	0.503
16	0.105	0.276
17	0.950	0.760
18	0.081	0.749
19	0.546	0.052
20	0.192	0.020
21	0.515	0.605
(J) $D_t = 1$ when t is the first day in a RMP and falls on:		
Monday	0.346	0.712
Tuesday	0.798	0.751
Wednesday	0.877	0.239
Thursday	0.650	0.878
Friday	0.628	0.669
(K) $D_t = 1$ when t is the last day of a RMP and falls on:		
Monday	0.666	0.332
Tuesday	0.103	0.903
Wednesday	0.273	0.195
Thursday	0.980	0.488
Friday	0.408	0.890
(L) $D_t = 1$ when t falls on:		
The day of a Governing Council meeting	0.316	0.360
The day of a press conference	0.665	0.218
The day of a press conference, before December 2001	0.154	0.195
All days before November 9, 2001 (bi-weekly policy decisions)	0.019	0.000*
The day of a policy rate change	0.610	0.665
The day after a policy rate change	0.237	0.660

NOTE: See table 3.7 for a detailed description of the abbreviations used. The variable D_t takes value zero unless otherwise specified. H0: D_t is correctly omitted from the original model specification. * denotes significance at 1%.

Table 3.4: Lagrange mutliplier tests for omitted variables; calendar days.

Omitted variable	p-value	
	Mean	**Variance**
(A) D_t = 1 when t falls on:		
Friday	0.891	0.567
Thursday	0.622	0.746
Wednesday	0.956	0.526
Tuesday	0.892	0.484
Monday	0.529	0.602
(B) D_t = 1 when t is:		
End of month, except end of semester	0.367	0.004*
End of 1st quarter	0.255	0.219
End of 2nd quarter	0.848	0.132
End of 3rd quarter	0.649	0.749
End of 4th quarter	0.944	0.462
End of any quarter	0.244	0.609
End of 2nd and 4th quarter	0.849	0.170
End of 1st and 3rd quarter	0.214	0.198
Begin of 1st quarter	0.944	0.040
Begin of 2nd quarter	0.074	0.125
Begin of 3rd quarter	0.848	0.416
Begin of 4th quarter	0.847	0.405
Begin of any quarter	0.128	0.597
(C) D_t = 1 for t being the day after:		
Begin of month	0.408	0.166
Begin of month, except begin of quarter	0.887	0.053
Begin of 1st quarter	0.044	0.365
Begin of 2nd quarter	0.460	0.177
Begin of 3rd quarter	0.041	0.627
Begin of 4th quarter	0.704	0.085
Begin of any quarter	0.115	0.855

NOTE: See table 3.7 for a detailed description of the abbreviations used. The variable D_t takes value zero unless otherwise specified. H0: D_t is correctly omitted from the original model specification. * denotes significance at 1%.

Table 3.5: Lagrange multiplier tests for omitted variables; liquidity effects and lagged dependent and explanatory variables.

Omitted variable	p-value Mean	
(A) Lagged dependent variable:		
$D_t = \Delta i_{t-2}$, for all days, t = 1,..,T	0.052	
$D_t = \Delta i_{t-22}$, when t = T	0.014	
(B) When t is the first day in a RMP and:		
$D_t = \Delta i_{t-1}$	0.088	
$D_t = \Delta i_{t-2}$	0.950	
$D_t = \Delta i_{t-3}$	0.959	
$D_t = i_{t-1} - i^*_{t-1}$	0.133	
$D_t = i_{t-2} - i^*_{t-2}$	0.709	
$D_t = i_{t-3} - i^*_{t-3}$	0.805	
(C) Lagged policy rate changes:		
$D_t = \Delta i^*_{t-1}$	0.598	
$D_t = \Delta i^*_{t-2}$	0.022	
(D) Liquidity effects around end of the month; $D_t = u_{t-1}$ when t falls on:		
Begin of month	0.779	
End of month	0.524	
Begin of quarter	0.739	
End of quarter	0.616	
(E) Liquidity effects at the end of a reserve maintenance period:		
$D_t = u_{t-1}$, when last allotment was before t and		
t equals T-1	0.976	
t equals T-2	0.903	
t equals T-3	0.280	
$D_t = u_{t-2}$, when last allotment was before t-1 and		
t equals T-1	0.162	
t equals T-2	0.571	
t equals T-3	0.572	
(F) Liquidity effects before the last settlement day of a RMP:		
$D_t = u_{t-1}$, when t is before the last settlement day	0.503	
(G) Asymmetric liquidity effects for days after the last allotment:	for $D_t < 0$	for $D_t > 0$
$D_t = u_{t-1}$ and t equals T	0.085	0.136
$D_t = u_{t-2}$ and t equals T	0.655	0.583
$D_t = u_{t-1}$ and t equals T-1	0.093	0.136
$D_t = u_{t-2}$ and t equals T-1	0.397	0.047
$D_t = u_{t-1}$ and t equals T-2	0.258	0.832
$D_t = u_{t-2}$ and t equals T-2	0.105	0.729

NOTE: See table 3.7 for a detailed description of the abbreviations used. The variable D_t takes value zero unless otherwise specified. H0: D_t is correctly omitted from the original model specification. * denotes significance at 1%.

Table 3.6: Predictability of the interbank rate.

Potential effects	**Empirically significant effects** Mean	Variance
Related to operating procedure		
Days of the reserve maintenance period (RMP):		
First day in a RMP, i.e. t = 1	X	
Last allotment day		X
Any day after the last allotment day		X
Next to last day in a RMP, i.e. t = T-1		X
Last day in a RMP, i.e. t = T		X
Any day before the last allotment day, except t = 1		
Day of policy rate change and the day after		X
Liquidity effect at:		
Last day in a RMP, i.e. t = T	X	
Any day after the last allotment day, except t = T		
Any day, except t = 1 and t = T		
Sluggish reaction to supply changes	X	
Expected supply change, temporary		
Expected supply change, permanent	X	
Expected policy rate	X	
Related to calendar days		
End of month	X	X
Begin of month	X	
End of semester, additional effect	X	X
Begin of semester, additional effect	X	X
End of year, additional effect	X	X
Begin of year, additional effect	X	X
Weekdays		

NOTE: Empirically significant effects are denoted by X. Results are based on the estimated empirical model and Lagrange multiplier tests. See the relevant tables for details.

3.5.2 Data description

Table 3.7: Description of variables.

Dummy variable	Takes value one at:
T	The last day of each reserve maintenance period (RMP)
T-1	The next to last day of each RMP
First day, t = 1	The first day in a RMP
Last allotment day	The last day in a RMP at which a regular main refinancing operation is allotted (usually a Tuesday)
Last settlement day	The last day in a RMP at which a regular main refinancing operation is settled (usually a Wednesday)
Underbidding allotment day	All allotment days when underbidding occurred. These days are 14/02/01, 11/04/01, 10/10/01, 07/11/01, 04/12/02, 18/12/02, 04/03/03, 04/06/03, 26/11/03
dunderbidding (Volatility equation)	All allotment days when underbidding occurred. Additionally, some underbidding settlement days are also included. Namely, all underbidding settlement days for February, April and October 2001, and both for December 2002 (4th and 18th). Furthermore, this dummy takes value one at days 19/12/02 till 24/12/02, to take into account volatility increase from underbidding close to the end of the RMP
dunderbidding (Mean equation)	This variable takes into account the underbidding effects for the mean, in 2002 and 2003. It takes value one at Wednesdays for underbidding at December 4, 2002, June 4, 2003 (settlement days), the day after settlement March 5, 2003 and the settlement following the underbidding week, March 12, 2003
January 2002	The last four days in the first RMP of 2002. Euro cash changeover
GC meeting after last allotment	Governing Council meeting after the last allotment and policy rate change expectations. Takes value one the days before the last allotment, 20/9/1999 and 18/10/1999 and the days before and after it, i.e. 17/9/99 and 19/10/1999
Underbidding at end of RMP	Allotment and settlement days of the last regular main refinancing operation in the December 2003 RMP, 16 and 17/12/2003
Policy decisions bi-weekly	All days until 7th of November 2001. From this time onwards policy decisions are made only once a month (in general)
Press conference	The day of the press conference held after the ECB's Governing Council meeting
Governing Council meeting	The day of the European Central Bank's Governing Council meeting
Policy rate change	The day at which a change in the policy rate is announced

Other variables	
i_t	Volume-weighted average of interbank rates in the euro area, the EONIA rate.
i^*_t	Policy rate, or target rate, which is defined as the fixed rate (until June 27, 2000) and the minimum bid rate (after June 27, 2000) at which the European Central Bank conducts its weekly open market operations. Any change in the policy rate is assumed to become effective at the day of announcement, not at the day when the next open market operation is settled
$E_t[i^*_{t+k}]$	Expected future policy rate. Proxied by a forward rate constructed with one and two-week EONIA swap rates
u_t	Supply shock, which is approximately the forecast error on autonomous factors (see main text for details)

3.5.3 Figures

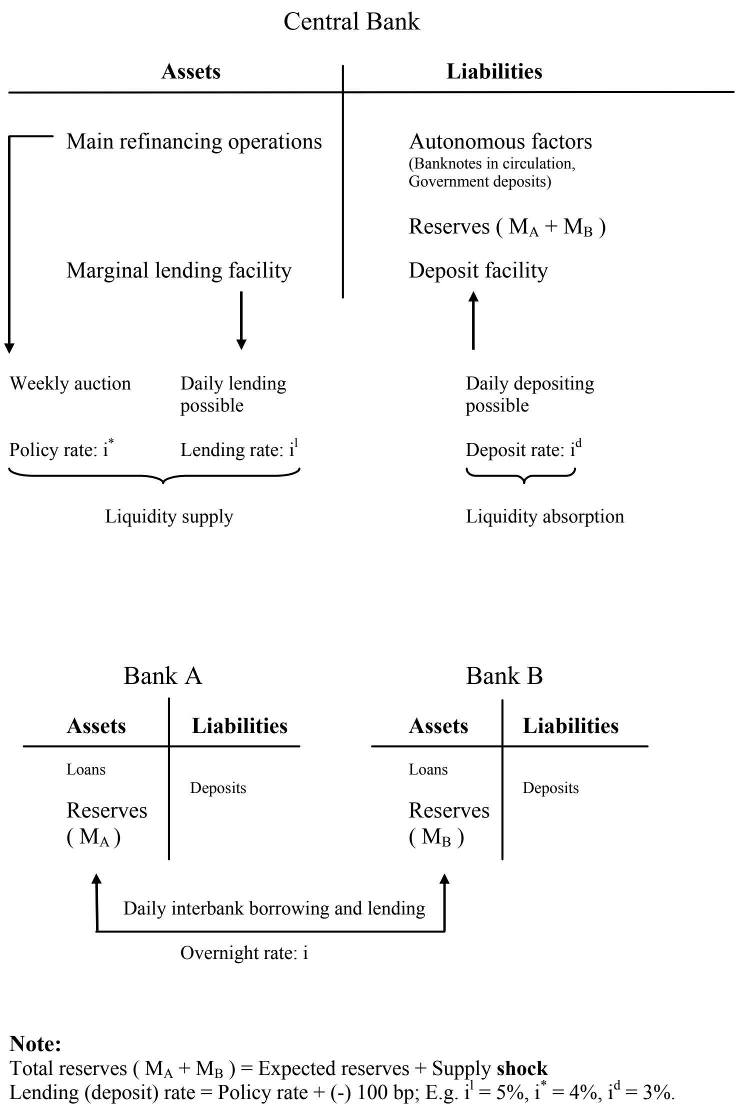

Figure 3.1: Illustrative summary of demand and supply of reserves. See main text for details and further discussion.

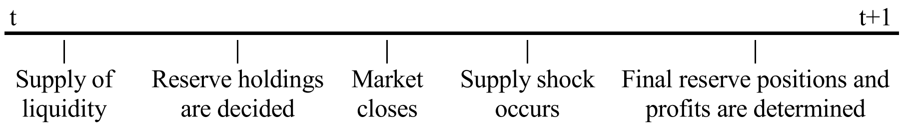

Figure 3.2: Timing in the interbank market. In general, supply of liquidity is constant throughout a week, changing only on Wednesday.

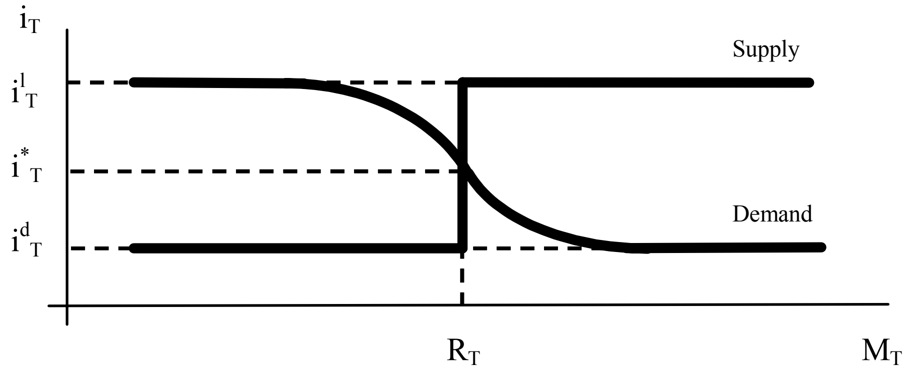

Figure 3.3: Demand and supply of bank reserves at the last day of a reserve maintenance period. M_T denotes current reserve holding and R_T the amount of reserves necessary to fulfill the reserve requirement for the entire reserve maintenance period. The overnight rate is denoted by i_T, marginal lending and deposit rates by i_T^l and i_T^d, respectively, and the policy rate by i_T^*.

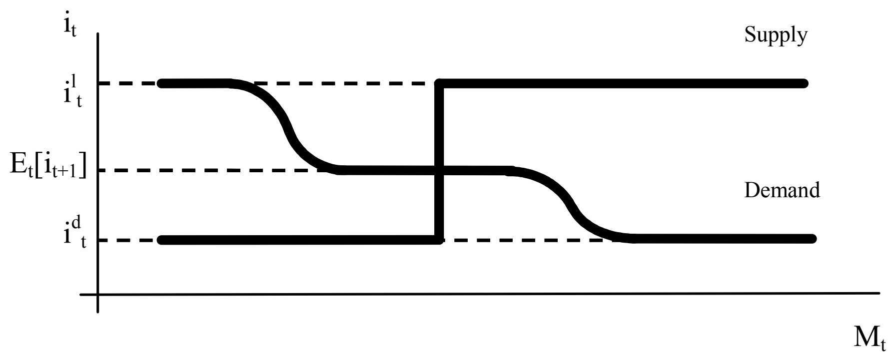

Figure 3.4: Demand and supply of bank reserves at days other than the last day of the reserve maintenance period. Simplified model. M_t denotes current reserve holding. The overnight rate is denoted by i_t and marginal lending and deposit rates by i_t^l and i_t^d, respectively.

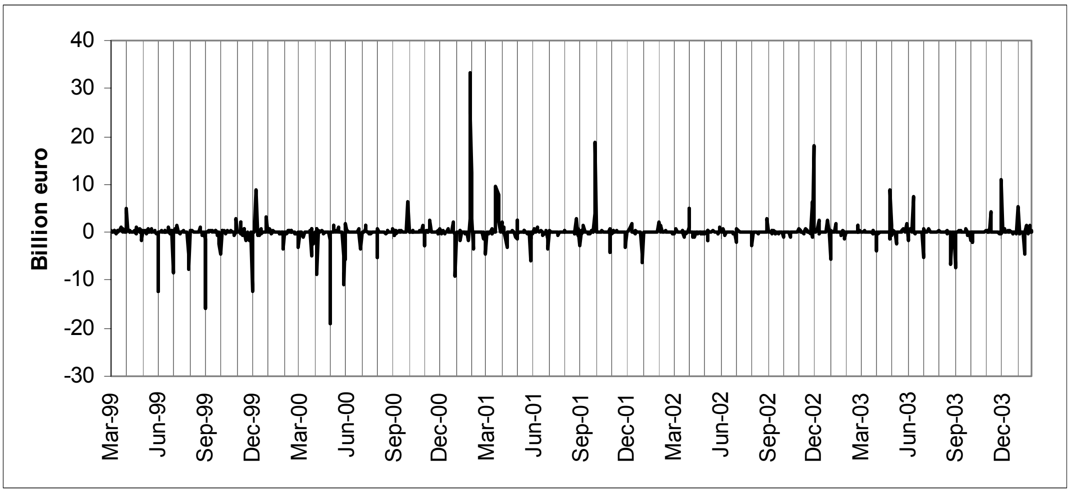

Figure 3.5: Net recourse to standing facilities. Vertical lines indicate the last day in each reserve maintenance period.

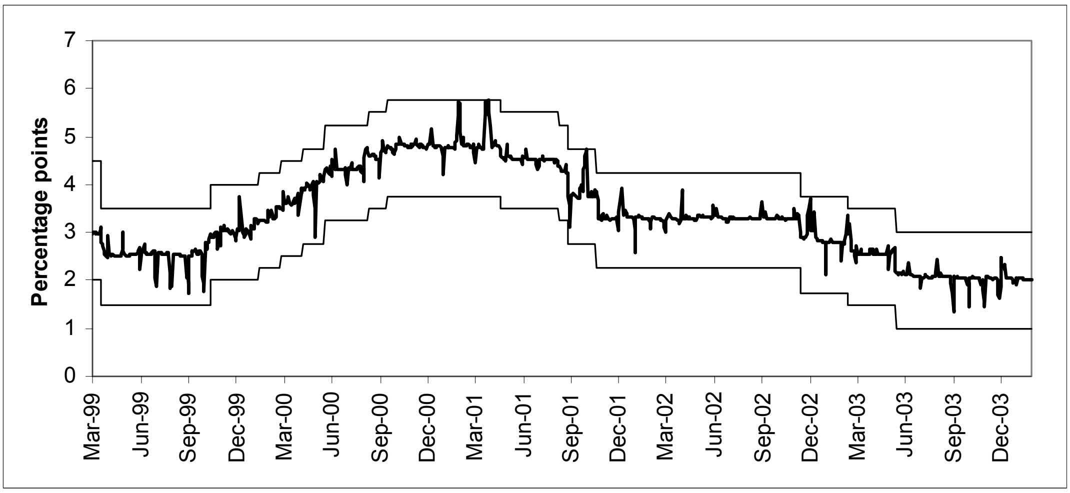

Figure 3.6: Euro Area Overnight Interbank Rate (EONIA) together with deposit and marginal lending rates, which define lower and upper bounds, respectively.

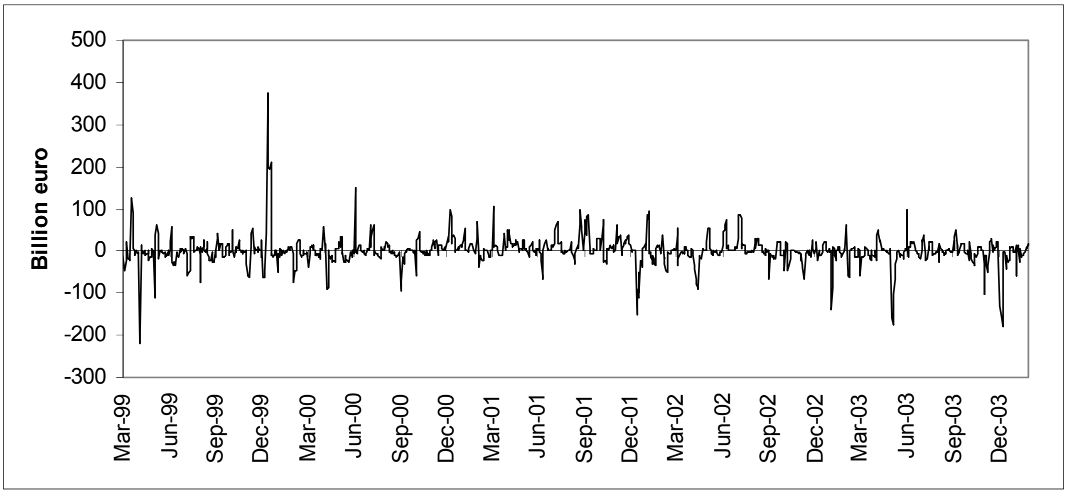

Figure 3.7: Deviation from neutral liquidity.

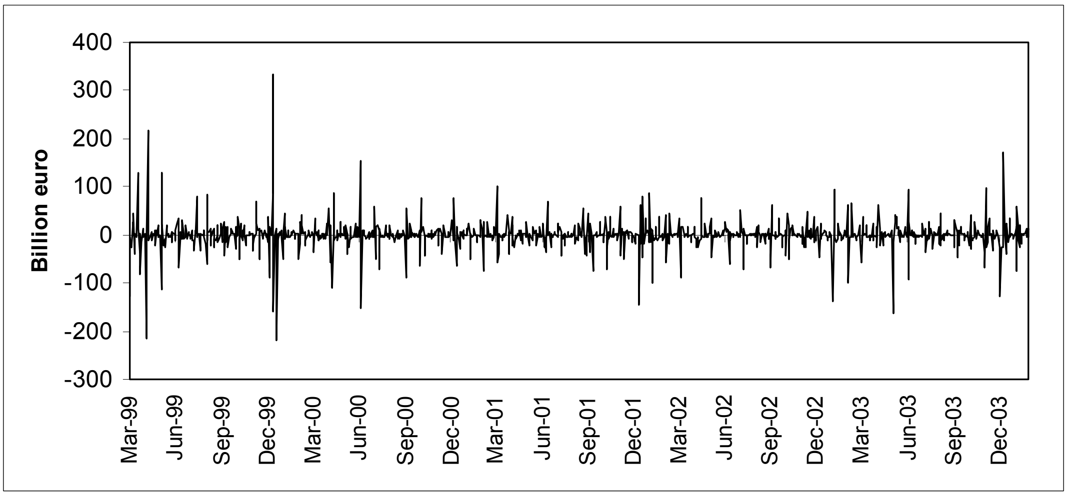

Figure 3.8: Change in deviation from neutral liquidity.

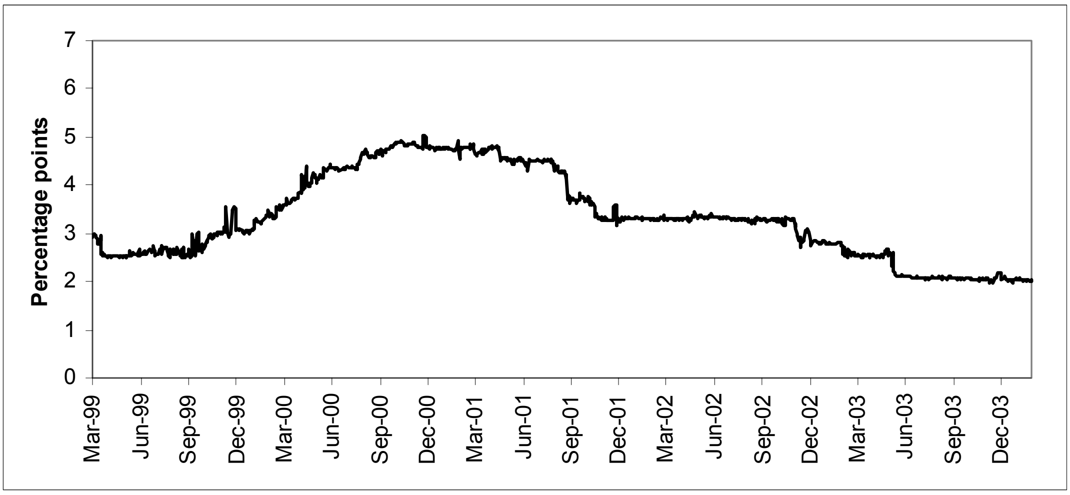

Figure 3.9: Proxy for expected policy rate. Constructed from two and one-week EONIA swap rates.

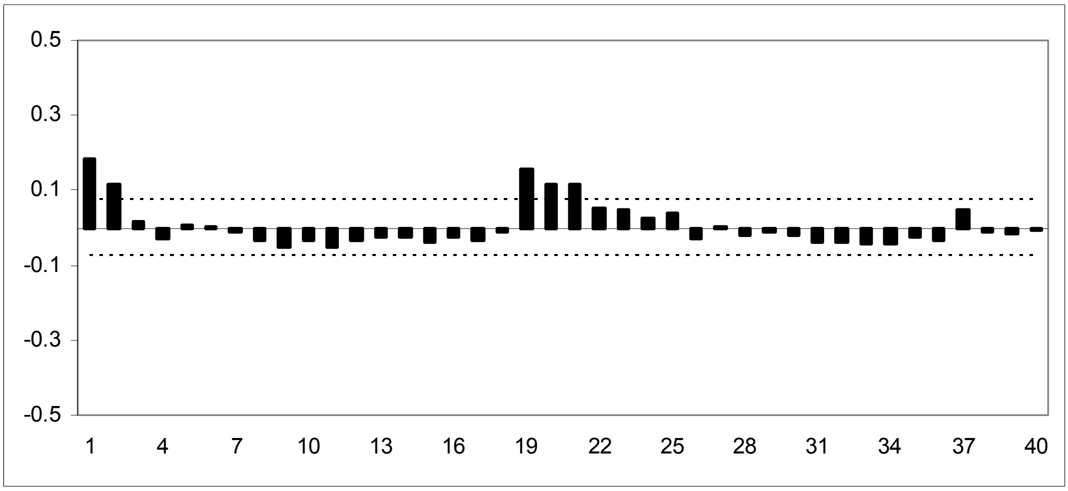

Figure 3.10: Autocorrelation function for squared residuals from Least Square estimation. Dotted lines represent significance at 1%.

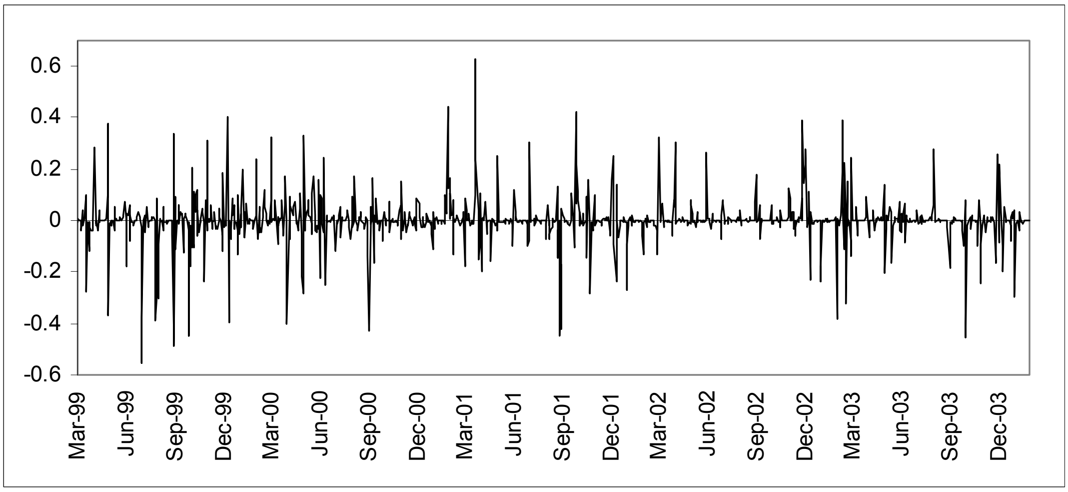

Figure 3.11: Residuals from EGARCH model.

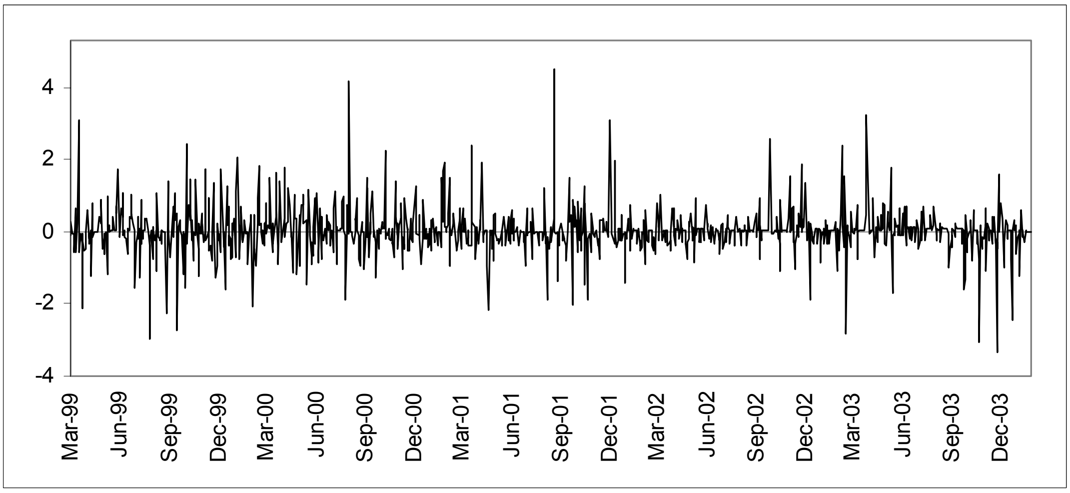

Figure 3.12: Standardized residuals from EGARCH model.

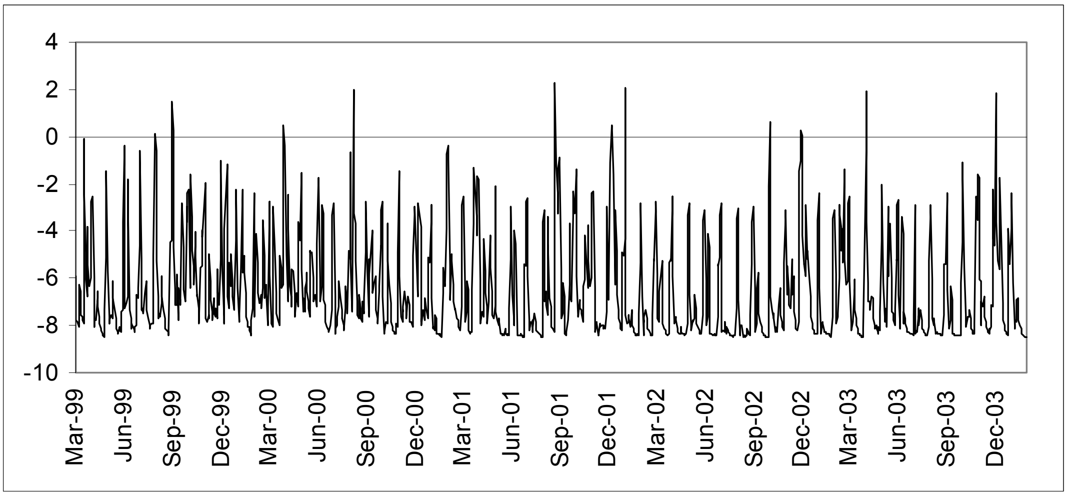

Figure 3.13: Logarithm of Conditional Volatility from EGARCH model.

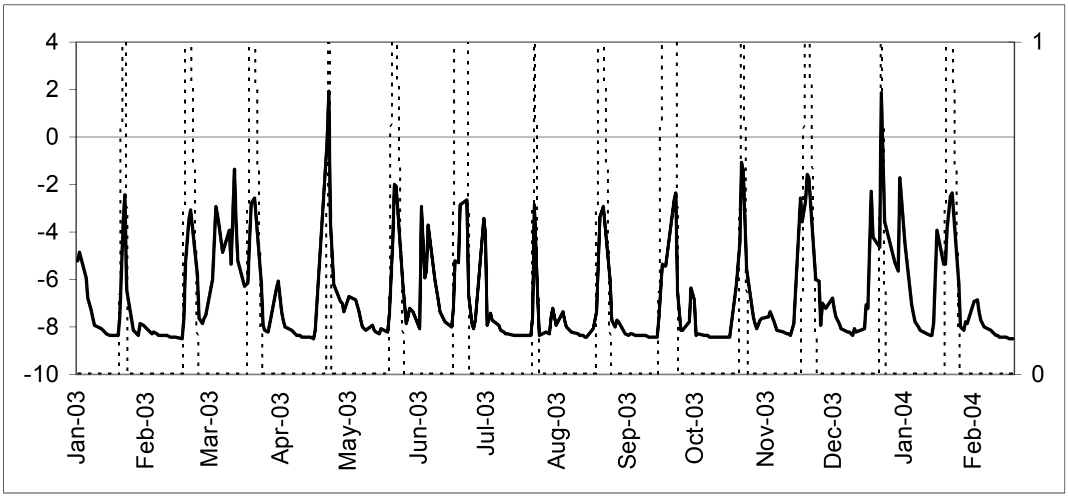

Figure 3.14: Logarithm of Conditional Volatility from EGARCH model (left scale). Dotted lines represent a dummy variable taking value one on all days after the last allotment day until the last day of a RMP and value zero otherwise (right scale).

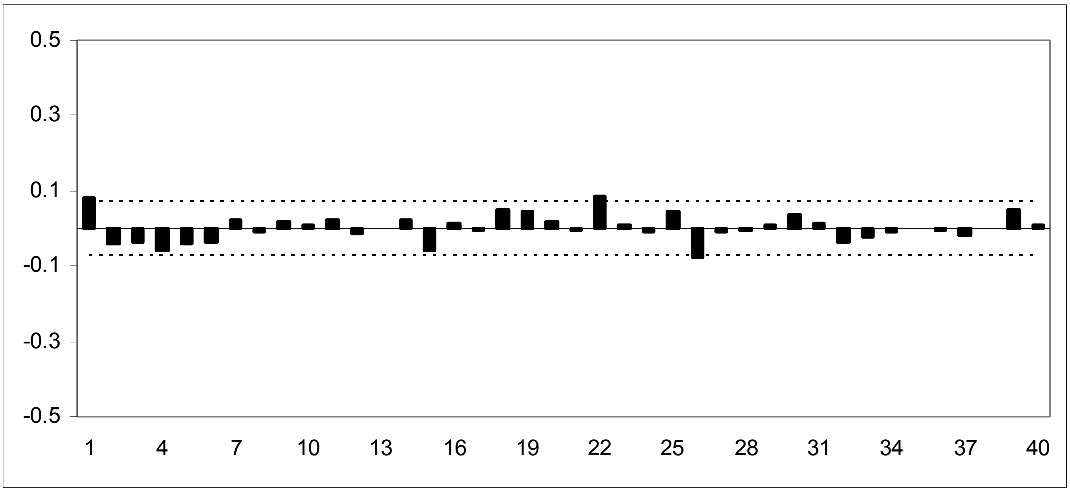

Figure 3.15: Autocorrelation function for residuals from EGARCH model. Dotted lines represent significance at 1%.

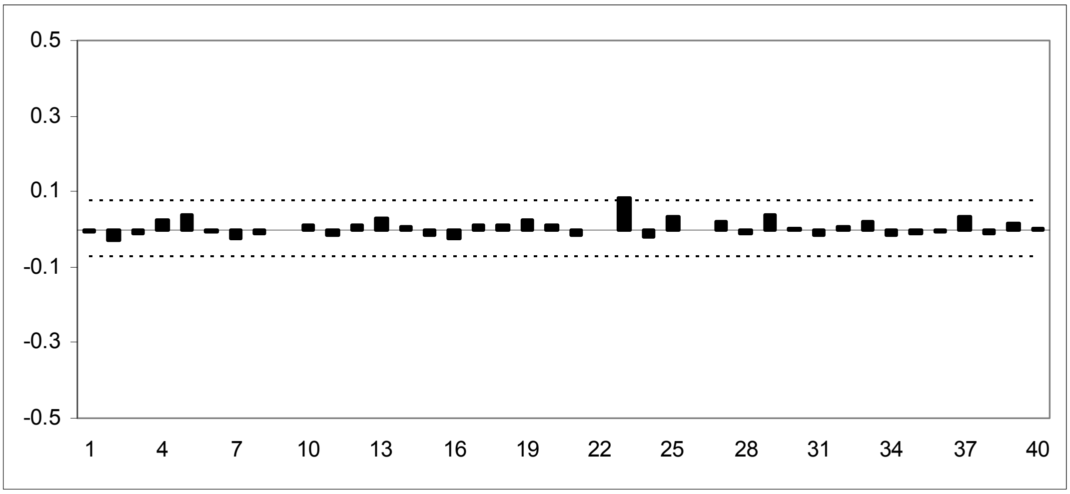

Figure 3.16: Autocorrelation function for squared residuals from EGARCH model. Dotted lines represent significance at 1%.

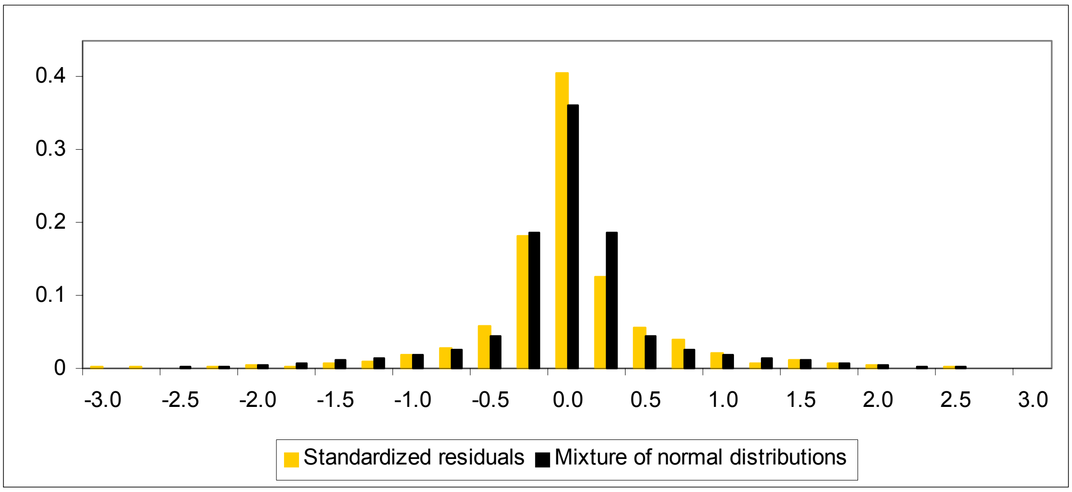

Figure 3.17: Estimated and assumed distribution of residuals from EGARCH model.

Chapter 4

Monetary policy implementation and volatility

4.1 Introduction

Nowadays most central banks target a short-term interest rate in order to achieve their primary objectives, like price stability. By signalling its target rate and managing the liquidity situation in the money market a central bank steers short-term money market rates. This chapter describes how the European Central Bank manages the liquidity situation in the money market and its implications for interest rates of various maturities. In particular, volatility of interest rates and its transmission along the yield curve is discussed extensively.

Central banks differ substantially in how they manage the liquidity situation in the money market. These differences in the operational framework may have implications for the behavior of interest rates, in particular for their volatility. Central banks are eager to avoid high volatility, especially for interest rates with long maturities. Firstly, high volatility of money market rates may give market participants confusing signals on the monetary policy stance. However, the central bank wants to communicate its monetary policy stance clearly, without unnecessary noise, and, therefore, avoid high volatility. Secondly, and maybe even more important, long-term interest rates are relevant for firms' investment and households' consumption decisions. High volatility of an asset's price requires, in general, higher returns on this asset and, therefore, increases the costs of an investment. Again, there are benefits of avoiding high volatility.

High volatility of interest rates at the short end of the yield curve is less of a concern. Volatility at the short end - as long as it is not transmitted along the yield curve - is mainly interpreted as money market noise, without affecting the real side of the economy. This chapter analyses volatility in money market rates and its transmission from the short to the long end of the yield curve. It provides insights into the operational framework of the European Central Bank and the effects of this framework on money market rates.

This chapter is not only important for the conduct of monetary policy, but also to understand better the term structure of interest rates. It is widely accepted that short-term rates explain a large part of the movements in longer term rates. In what follows money market rates of various maturities are modeled carefully and the linkages between them are explored. The empirical model specifications for both, conditional mean and volatility are tested extensively for misspecification, especially for omitted variables. The models presented here also allow a detailed discussion of the expectation hypothesis, comovements of interest rates of different maturities and the adjustment of interest rates to their long-run equilibria.

There exists very little empirical evidence for euro area money markets rates and transmission of volatility along the yield curve. Related work has been done for the UK (e.g. Wetherilt, 2003 and Panigirtzoglou et al., 2000) and for some other countries. The sample period in most of these other studies ends in or before 1998, the year preceding the creation of the European Monetary Union (e.g. Cohen, 1999 and Ayuso et al., 1997). The only publications dealing with the euro area money market are Cassola and Morana (2003 and 2004). The first paper applies a multivariate unobserved component model to decompose interest rate volatility into a cyclical and a persistent component. The cyclical components are related mainly to the characteristics of the operating procedure and accounting conventions. It is found that the institutional features of the operating procedure affect volatility exclusively at the short end of the yield curve. The later paper explores volatility transmission further, using a different measure of volatility and estimation method. It is shown that volatility processes of the different money market rates experienced structural breaks. Although these breaks differ across maturities volatility from the two-week up to the three-month maturity move together. Furthermore, two factors driving the long-run evolution of the volatility processes are identified. The first factor explains volatility at the short end of the yield curve, whereas the second factor drives volatility further out the term structure. Both papers use high-frequency data, which allows to analyze the intra-daily behavior of money market volatility. Both, the evolution of volatility during a typical day and the reaction of volatility to specific events are described. The intra-daily pattern of volatility is particularly interesting around the ECB's Governing Council (GC) meetings. Before November 2001 monetary policy decisions were taken at every GC meeting and at the first GC meeting in each month afterwards. Comparing the typical intra-daily pattern of volatility with the realized volatility at these days provides insights on the effects of monetary policy decisions on market uncertainty.

This chapter looks at the effects of monetary policy implementation from a different angle. First of all, it bases the analysis on a careful theoretical model of the overnight interest rate. The overnight interest rate is the starting point of the yield curve and plays a crucial role in explaining interest rates further out the term structure. The daily behavior of the overnight interest rate has been analyzed extensively in the previous chapter. The model developed in that chapter is the starting point for the present analysis. Dealing with daily data allows the use of liquidity, which has been shown to be an important explanatory variable for the interest rate behavior. Furthermore, expectations on the future policy rate are modeled and included into the empirical specification, as well. Second, both mean and volatility of all money market rates are tested explicitly for a wide range of possible omitted variables, especially for those related to the operating procedure and calendar days. Thirdly, the estimation method is different. Both, mean and volatility of money market rates are estimated jointly. The mean of the interest rates is modeled in first differences, testing for and then imposing long-run convergence towards the policy rate, the interest rate targeted by the central bank. The models applied here allow investigating the expectation hypothesis of the term structure, as well. Conditional volatility is specified as a fairly standard exponential GARCH process. Finally, the use of daily data permits to extend the sample considerably, namely starting at the beginning of 1999.

The next section discusses the data used and the general methodology. Section 4.3 provides a model of the euro area overnight rate, the so-called EONIA rate. The EONIA rate is a very important rate in the conduct of euro area monetary policy. The EONIA rate represents the short end of the money market yield curve and it is heavily influenced by the European Central Bank's policy decisions. Section 4.4 models interest rates of longer maturities. The expectation hypothesis is discussed extensively. The conditional volatility of the EONIA rate is included as an explanatory variable for the volatility of all other interest rates. This is a straightforward way to test for transmission of volatility along the yield curve. In addition, the estimated volatility curve is analyzed and its U-shape is rationalized. Section 4.5 concludes. The appendix contains all tables and figures.

4.2 Data and Methodology

The interest rates used in this study are an overnight rate (EONIA rate), and EONIA swap rates with maturities of two weeks, and one, three, six and twelve months. Ideally repo rates should have been chosen, because repo transactions are based on collateral and, therefore, do not involve any credit risk. After all, there is still no unified repo market for the euro area. Instead EONIA swap rates have emerged as a benchmark for the euro area money market. The EONIA swap market is very liquid and the risk involved is very small. In an EONIA swap two parties agree to exchange the difference between the agreed fixed interest rate and the EONIA rate, accrued over a given period and for an agreed notional amount. Since the principal amount is not exchanged, the credit risk involved in swap transactions is very low.

The sample starts at 24/03/1999 and ends at 19/02/2004. Daily averages of bid and ask quotes from Reuters (for all money market rates, except the six and twelve-month swap rates) and Bloomberg (for the six and twelve-month swap rates) are used.

Descriptive statistics for all money market rates are provided in table 4.1, in the appendix. The standard deviation of interest rate changes is highest for the overnight maturity, decreasing up to the six-month rate, and then increasing again. Interest rate changes are not normally distributed. Normal distributions are symmetric around the mean, so that their skewness is zero. Their kurtosis is three, anything beyond that is called excess kurtosis. Rate changes for all maturities are negatively skewed, except the overnight and the twelve-month rate, which are positively skewed. Excess kurtosis is present for all maturities, which means that its tails are heavier compared to the normal distribution.

The model applied for all interest rates follows closely the model outlined in chapter 3.[1] Both, conditional mean and volatility of the respective interest rate are estimated jointly. The specification takes into account the operational framework of the euro area, models it carefully and tests extensively for omitted variables.[2] Standard unit root tests confirm that all interest rates, within the sample, are integrated of order one, as shown in table 4.2.[3] Furthermore, they are co-integrated with the target rate, i_t^*. The target rate is assumed to be the fixed rate (until June 27, 2000) and the minimum bid rate (after June 27, 2000) at which the European Central Bank conducts its weekly open market operations.[4] Results from co-integration tests and the estimated co-integrating vectors are reported in tables 4.3 and 4.4. Interest rates of all maturities show a unit co-integrating relationship with the policy rate. Note that these findings are consistent with the expectation hypothesis (e.g. Campbell and

[1] See the references therein. Hamilton (e.g. 1997) was one of the first authors to study the behavior of short-term interest rates by using advanced time-series techniques.

[2] Selected results for tests on omitted variables are discussed in the relevant sections below. The full set of results is available from the author.

[3] Economic and finance theory usually assumes that interest rates are stationary, whereas the empirical literature usually finds interest rates to be integrated. In a strict sense interest rates cannot be integrated, because they are bounded below by zero. Nevertheless, the statistical characteristics of interest rate data are better described by integrated than stationary processes.

[4] The target or policy rate, as defined here, coincides with the mid-point of the deposit and marginal lending rate. Only for the first few weeks in 1999 the corridor formed by deposit and lending rate was not symmetric around the policy rate.

Shiller, 1991), which will be discussed in more detail below. Taking these results into account, all interest rates, i_t, are modeled in first differences, $\Delta i_t \equiv (i_t - i_{t-1})$, and a unit co-integrating vector, $(i_{t-1} - i^*_{t-1})$, is imposed. The model then is:

$$\begin{aligned}
\Delta i_t &= c + \phi(i_{t-1} - i^*_{t-1}) + x_t\beta + h_t\eta_t \\
\ln(h_t^2) &= z_t\lambda + \sum_{j=1}^{q} \delta_j \left(\ln(h^2_{t-j}) - z_{t-j}\lambda\right) + \alpha \left\{|\eta_{t-1}| - E|\eta_{t-1}| + \gamma\eta_{t-1}\right\} \\
\eta_t &\sim iid(0, p + (1-p) * \sigma^2).
\end{aligned}$$

The parameter ϕ captures how fast the interest rate, i_t, returns to its long-run value, the target rate i^*_t. The mean equation includes a constant, c, and other explanatory variables, x_t. The vector x_t contains lags of the dependent variable and the target rate, as well as variables related to the operating procedure and to calendar days. The conditional standard deviation of the interest rate is given by h_t. The vector z_t contains explanatory variables for the conditional volatility equation. Of particular interest are variables related to the operating procedure and calendar days. Standardized residuals are denoted by η_t. Some of the interest rates are characterized by frequent small changes and occasional large moves. This behavior is modeled with a mixture of two normal distributions. The probability to come from the first distribution with variance one is p, and the probability to come from the second distribution with variance σ^2 is $(1-p)$. The exponential GARCH model applied here allows to estimate the different impact good and bad news have on the volatility, which is given by the parameter γ.[5] Further details of the models are explained in the respective sections below.

4.3 Overnight interest rate (EONIA)

The EONIA rate is a volume-weighted average of interbank rates in the euro area and is a particularly important interest rate. It is important for the conduct of monetary policy, but also to understand the term structure of interest rates. It defines the short end of the yield curve and potentially influences all other interest rates further out the maturity spectrum.

The EONIA rate is closely related to reserves held at the central bank. On the interbank market commercial banks actively trade these reserve holdings. The main reasons for holding reserves are transaction purposes and to meet the reserve requirement imposed by the central bank. The reserve requirement has not to be met on a daily basis, but on average over one month, the reserve maintenance period (RMP).[6] Profit maximizing banks, therefore, hold reserves when they are relatively cheap, and

[5] See e.g. Bollerslev et al (1992) for an overview of models for conditionial volatility.

[6] Throughout the sample period, the reserve maintenance period starts at the 24th of each month

lend reserves to other banks when they are relatively expensive. Hence, the expected future interest rate is an important explanatory variable for today's reserve holdings, and, thus, today's interest rate. The expected future interest rate depends mainly on two factors, the expected supply of reserves and the expected target interest rate.

The central bank is the sole net supplier of reserves, in consequence, it has a strong influence on this market. Nevertheless, the central bank cannot control the reserve supply perfectly. Supply shocks hit the reserve market, moving the reserve supply unexpectedly. After all, the institutional details of how and when the central bank supplies reserves have an important - and expected - impact on the EONIA rate, both on its mean and volatility. Supply of reserves is executed through open market operations, in general, via a weekly auction. Usually, on every Tuesday the respective amount is allotted and settled on Wednesday. In what follows these days are labelled allotment and settlement days.

The empirical model for the EONIA rate follows closely the model outlined in the previous chapter. This specification is based on a theoretical model for both supply and demand for reserves, which recognizes that the EONIA rate is the equilibrium interest rate in the market for reserves.

Parameter estimates for this model are given in table 4.5, in the appendix. The mean of the EONIA rate moves in reaction to permanent changes in supply (see the previous chapter for further details). The supply of reserves may be endogenous, therefore, supply shocks are used as instruments to measure correctly the slope of the demand curve. Any supply shock occurring after the last open market operation of the reserve maintenance period is a permanent change in supply since it affects the reserve situation for the entire maintenance period. This is so, because the central bank, in the current set-up, makes up for past supply shocks only at the weekly open market operation. Therefore, after the last open market operation in a reserve maintenance period, the central bank does not, in general, intervene in the market and supply shocks accumulate towards the end of the RMP. However, supply shocks occurring at days before the last open market operation are neutralized by the central bank at the open market operation conducted in the following week. The slope of the demand curve is estimated to be roughly eight basis points per one billion of euro. The relevant change in supply is measured by the supply shock occurring at the end of day $T-1$, u_{T-1}. Since this shock occurs after the market closes, it affects the interest rate at the following day, at T. A permanent change of reserves by one billion euro moves the EONIA rate by eight basis points into the opposite direction. Interestingly, supply shocks occurring after the last open market operation, but before the last day

and ends at the 23rd of the following month. From March 2004 onwards begin and end of the reserve maintenance periods will be related to the European Central Bank's Governing Council meetings.

of the RMP do not have any immediate effect. These supply shocks, denoted by $u_{T-2}, u_{T-3}, u_{T-4}$ and u_{T-5}, impact on the EONIA rate only at the last day of the RMP, as can be seen in panel A of table 4.5. Lagrange multiplier tests show that supply changes occurring at any other day do not affect the EONIA rate. A test for the significance of the respective parameter has a p-values of 0.5. This is consistent with the theoretical prediction. Supply changes at any other day are temporary, and, therefore, should not have an effect on the interest rate.

Besides changes in reserves also the expected future target or policy rate influences the EONIA rate. The future expected policy rate is measured by a forward rate.[7] Only changes in the policy rate which occur in the current RMP are relevant for the current EONIA rate. Therefore, the expected future policy rate is easiest to approximate at the first day of each RMP. As the end of the RMP is approached expectations of policy rate changes in the following RMP become more important for the forward rate. Indeed, the parameter for the expected future policy rate is only significantly different from zero at the first day of the RMP (see panel B of table 4.5).

Strong mean-reversion towards the policy rate is found. As can be seen in panel D of table 4.5 the estimated parameter is -0.04 for all days of the reserve maintenance period, except the first day. At the first day the overnight rate reverses to the policy rate completely. The implied parameter restriction on mean-reversion at the first day is accepted with a p-value of 0.13 and, therefore, imposed on the model presented here.

The only calendar day effects found in the present study are related to the end and begin of a month, as can be seen in panel C of table 4.5. The EONIA rate increases at the last day of each month by 5 basis points. At the end of the second quarter the increase is 18 basis points and at the end of the year 30 basis points. These increases are completely reversed at the first day of the following month. These calendar day effects are not easily explained in a theoretical model (e.g. the model explained in the previous chapter). These effects are likely to be the result of window dressing, i.e. banks adjusting their balance sheets at the end of the month. However, currently the ECB does not counteract this interest rate changes. One possibility to avoid this end-of-month effects could be to provide more liquidity at the end of the month, subtracting it at the beginning of a month. Nevertheless, supply changes around the end of a month are not found to affect the interest rate (see panel D of table 4.12). The non-existing liquidity effect around the end of the month may be due to a measurement problem. Supply changes are measured by the unexpected component, namely, with supply shocks. As discussed above, banks react sluggishly to these (unexpected) changes in supply, thus, possibly making it difficult to estimate

[7] The two and one-week EONIA swap rates are used to construct the one-week rate in one week. In the previous chapter rates with other maturities have been used, but results are almost identical.

a downward sloping demand curve around the end of a month. Nevertheless, expected changes in supply might very well influence the interest rate. For example, a credible commitment by the central bank to provide liquidity at the last day of each month should reduce the interest rate at that day.

Figure 4.1 plots the conditional log volatility for the EONIA rate. To get a better intuition for the driving forces of volatility, figure 4.2 zooms in the previous graph and shows the estimated volatility starting in 2003. Volatility increases around the end of the reserve maintenance period, as well as around the end of the month and around policy rate changes (March and June 2003) are clearly visible.

Until June 2000 the ECB performed its weekly auction at a fixed rate, and with a minimum bid rate afterwards. Whenever there are expectations of an imminent cut in this tender rate, the policy rate, commercial banks may want to postpone reserve holdings till the next week. Therefore, demand for reserves can fall short of the amount the central bank plans to allot. This so-called underbidding has led to higher volatility, as can be seen in panel G of table 4.5.

The model has been tested extensively for omitted variables. Tables 4.12 to 4.15 give the potentially omitted variables for which both, mean and volatility equations have been tested for. A few results are worth mentioning in more detail. Throughout the sample period the number of days which pass after the last allotment until the last day of the reserve maintenance period varies every month. In general, the last allotment is performed on Tuesday and the last day in a reserve maintenance period is the 23rd of each month. However, there have been some recent changes in the operational framework of the ECB, becoming effective from March 2004 onwards (see e.g. ECB, 2004). Now, there are always five (business) days after the last allotment until the last day of the RMP. It is therefore interesting to test if the volatility increase at the end of the RMP depends on the number of days after the last allotment day. Lagrange multiplier tests, as outlined in panels D to G of table 4.13, indicate that the number of days after the last allotment day does not matter for volatility.

4.4 Money market interest rates

One of the main motivations for this chapter is to test for the transmission of volatility from the short end of the yield curve to the long end. As has been seen in the previous section the operating procedures, i.e. the institutional details of how monetary policy is implemented, explain a considerable part of both mean and volatility of the EONIA rate. In this section it is investigated how much of the EONIA volatility is transmitted to interest rates with longer maturity. This is an important question to answer. Central banks are concerned of keeping volatility low, especially at the long end of the yield curve. Therefore, it is crucial to know if certain operating procedures imply high volatility across the term spectrum of interest rates, or if high volatility is limited to the short end. Furthermore, financial agents are equally interested in learning more about the behavior of money market rates and linkages among them.

In what follows money market rates with maturities from two weeks up to one year are analyzed. The basic model is closely related to the one applied for the EONIA rate. However, the conditional volatility of the EONIA rate, as estimated in the previous section, is included as an explanatory variable for the conditional volatility of all other rates. This is a straightforward way of testing for volatility transmission along the yield curve.

The mean equation is very similar for all rates. All potential variables, as outlined in tables 4.13 to 4.15, have been tested for significance. The only significant variables are a constant, the error-corretion term, lagged changes in the policy rate and one lag of the dependent variable.[8] The volatility equations for each rate are explained in detail below. Standard specification tests for each money market rate are shown in the respective tables. All models seem to be well specified. There is no evidence of serial correlation neither in residuals nor in squared residuals.

4.4.1 Expectation hypothesis

Before discussing in detail the effects of monetary policy implementation it is worth noting that the models presented here also provide insights into the expectation hypothesis.[9] The expectation hypothesis states that the N-period interest rate is a constant plus an average of the current and expected future short-term interest rates (see e.g. Campbell and Shiller, 1991). Several ways have been proposed to test the implications of the expectation hypothesis. Some of the most popular approaches can be summarized as 1) the spread of the long-term rate over the short-term rate predicts future changes in the long-term rate, 2) the spread of the long-term rate over the short-term rate predicts cumulative future changes in the short-term rate and 3) the long-run behavior of short and long-term rates are described by the co-integrating vector [-1,1]. Hall et al. (1992) discuss extensively the relation between the expectation hypothesis and co-integration. If interest rates are integrated of order one, and the term premia is stationary, the spread of the long-term rate over the one-period rate is also stationary and both rates are characterized by a unit co-integration relationship. Table 4.2 provides strong evidence that all interest rates are integrated of order one. Furthermore, the spreads of all interest rates over the policy rate are stationary, as

[8] All mean equations contain the error correction term and a constant. Lagged changes in the policy rate and lags of the dependent variables are excluded if not significant at the 10% level.

[9] I am grateful to Nuno Cassola for pointing this out and for his comments and suggestions.

well. The only exception might be the spread of the twelve-month rate, which is not stationary at conventional significance levels. Co-integration tests, reported in table 4.3, suggest that the policy rate and all six money market rates are best described by a system of six co-integrating vectors. In other words, there is one common factor driving the term structure of the whole money market. Table 4.4 shows the co-integrating vectors for all maturities. Strong support for the expectation hypothesis is found. Interest rates of all maturities have a unit co-integrating relationship with the policy rate.

One way of dealing with co-integrated interest rates is an error-correction model. The parameters on the error-correction term contain information on the adjustment of interest rates towards their long-run equilibria. Alternatively, and in line with the first implication of the expectation hypothesis, as outlined above, the error-correction term measures the predictive power of the spread for long-term rates. The error-correction term is defined as the money market rate with the respective maturity over the policy rate.[10] The parameters on the error-correction term, reported in tables 4.6 to 4.10, are highly significant for all maturities, except the one-month rate. The expectation hypothesis predicts a positive parameter, which is indeed found for all maturities longer than two weeks. The two-week rate reacts negatively to the spread. Money market rates, above the two-week maturity, increase whenever the spread is positive, and decrease whenever the spread is negative. Nevertheless, the two-week rate reacts in the opposite way. This behavior of money market rates can be explained by looking at the institutional features of monetary policy in the euro area. A policy meeting, and, therefore, a possible policy rate change, took place every two weeks before November 2001 and once a month afterwards. This policy rate served as the fixed rate, before June 2000, and as the minimum bid rate, after June 2000, for the ECB's open market operations. These open market operations are allotted every Tuesday and have a maturity of two weeks.[11] Two-week swap rates are therefore closely related to the open market operations and its interest rate, the policy rate. As has been discussed above the policy rate is the long-run value of the two-week rate. Whenever the two-week rate diverges from the policy rate, strong mean-reversion towards the policy rate is observed. Since the policy rate normally is not changed for at least two weeks, before November 2001, and for at least one month from November 2001 onwards, the adjustment towards the policy rate comes entirely from the two-week rate. This is, however, different for money market rates with maturities longer than two weeks. The adjustment to the long-run value, the policy rate, can come either from the money

[10] Similar parameter values are estimated for models including the spread over the overnight rate (EONIA).

[11] From March 2004 onwards the maturity of open market operations is one week (see e.g. ECB, 2004).

market rate, or from the policy rate. The expectation hypothesis predicts that both, short and long-term rates increase, whenever the spread is positive, and decrease whenever the spread is negative. However, the short-term rates should move faster in order to bring the interest rates back to their long-run values. Indeed, the adjustment pattern for money market rates seems to be as described by the expectation hypothesis. To sum up, strong evidence for several implications of the expectation hypothesis has been found. All interest rates show a unit co-integrating relationship with the policy rate, the spreads of money market rates over the policy rate are stationary, and these spreads predict future movements of long-term rates.

4.4.2 Volatility and volatility transmission

In what follows the conditional volatility equations and the effects of monetary policy implementation on volatility are discussed. The estimated model for the two-week rate is given in table 4.6 . Indeed, there is considerable transmission of volatility. More than 30 percent of the EONIA rate volatility is transmitted to the two-week rate. Before November 2001 monetary policy decisions were, in general, made at any of the Governing Council meetings. However, after this date policy decisions were, as a rule, only made at the first meeting in each month. This change goes along with a significant reduction in volatility of the two-week rate.

Weekdays have been tested for volatility effects. On Thursdays the log volatility of the two-week rate increases by about 0.8. It has been seen in the previous section that underbidding had a considerable effect on the EONIA rate, both on mean and volatility. The allotment day, on which underbidding occurred, increases substantially the volatility of the two-week rate as well. However, there is no effect of underbidding on the mean of the two-week rate.

Some negative parameters show up in panel B and C of table 4.6, in particular around the end of the maintenance period and around the end of a month. The volatility of the EONIA rate is very high at these days. As has been seen a substantial part of the volatility of the EONIA rate is transmitted to the two-week rate, but on these special days, the volatility of the two-week rate does not increase as much as the volatility of the EONIA rate. The negative parameter values capture this effect. Lagrange multiplier tests do not provide any evidence that volatility transmission is different at other days, than at the days just mentioned (see table 4.15 for details).

Furthermore, besides the days already discussed no other calendar days or days of the reserve maintenance period affect the volatility of the two-week rate (see tables 4.13 and 4.14).

Table 4.7 provides the estimated model for the one-month rate. There is still significant volatility transmission, however, it is lower than for the two-week rate. About 14 percent of the EONIA volatility is transmitted to the one-month rate. In addition, volatility is higher at the days of a press conference and at days of a change in the policy rate. Underbidding in the open market operations also led to an increase in volatility. Again, volatility decreased after November 2001, when policy decisions were taken, in general, only once a month. Figure 4.3 plots the conditional log volatility for the full sample. It shows very nicely the decrease of volatility after November 2001, as discussed above. Figure 4.4 zooms in the previous graph, starting in 2003. Increases in volatility around policy rate changes (March and June 2003) and towards the end of the RMP are clearly visible.

Transmission of volatility is not different across days of the RMP or on specific calendar days (see table 4.15). There are no other effects on the conditional volatility, neither (see tables 4.13 and 4.14).

Table 4.8 contains the parameter estimates for the three-month rate. Volatility transmission is highly significant and amounts to 13 percent. However, this transmission is partly reversed on the last settlement day in a RMP and at the last day of a semester, which can be seen by the negative parameters in panels B and C of table 4.8. Furthermore, the day of the press conference and the policy rate change increase volatility. The change in the frequency of policy decisions has had no effect on the three-month rate.

Besides the above mentioned effects, no other explanatory variables have been found to explain a significant portion of the volatility of the three-month rate (see tables 4.13 and 4.14).

Results for the six-month rate are given in table 4.9. Volatility transmission stands at 14 percent. However, it is not the contemporaneous EONIA volatility, rather the one day lagged volatility, which is transmitted. Again, the day of the press conference increases volatility. Interestingly, the change in the frequency at which policy rate decisions are generally made seems to have had an effect. Recall that this effect is not present for the three-month rate, although it is significant for the two-week and one-month rates. Volatility of the six-month rate decreased after the frequency of policy decisions were reduced to monthly.

No other variables have been found to explain significantly the volatility of the six-month rate (see tables 4.13 and 4.14).

It has been documented that there is substantial transmission of volatility along the yield curve, up to a maturity of six months. The twelve-month rate is different, as can be observed in table 4.10. The EONIA volatility has no effect on the twelve-month rate. The only significant parameters for the volatility equation are those on the day of the press conference and the day of a policy rate change. Figure 4.5 shows the conditional log volatility for the twelve-month rate, starting in 2003. No clear pattern can be observed, except for the policy rate changes in March and June 2003. In other words, volatility is transmitted along the yield curve, but not too far out. The twelve-month rate seems to be the inflection point. None of the numerous other explanatory variables which are tested are found to be significant (see tables 4.13 and 4.14).

4.4.3 Volatility curve

One way of summarizing the results of this chapter is to plot the volatility curve of the euro area money market rates. The volatility curve shows a measure of volatility for interest rates with different maturities, plotted against their maturities. The here estimated volatility curve has a U-shape, as can be observed in figure 4.6. This pattern has been documented also for the US e.g. by Piazzesi (2003). What is more, she provides a theoretical model of bond yields, which rationalizes this particular shape of the volatility curve. Volatility is high at the short end of the yield curve, decreases up to the six-month maturity and then increases again. The increase in volatility beyond the six-month rate may be related to interest rate smoothing of the central bank, in short, inertia in monetary policy. Central banks usually adjust the target interest rate in several small steps. Financial markets, therefore, expect a change in the interest rate to be followed by another change. However, there is uncertainty when this change actually will occur. This uncertainty is then reflected in the volatility of interest rates with maturity larger than six months. High volatility at the short end of the yield curve is related mainly to money market noise. Money market noise summarizes the effects of short-term changes in liquidity in the money market and uncertainty about imminent policy rate changes.

At days when monetary policy decisions are made, monetary policy shocks are likely to dominate policy inertia and money market noise as the driving forces for volatility. Indeed, the entire volatility curve shifts up at days of the central bank's policy meetings. Monetary policy shocks in this context are shocks to the target rate, which happen mostly at policy meeting days. At these days volatility for all money market rates is higher than at "normal" days. Figure 4.6 plots the volatility curve for policy meeting days and the remaining, "normal", days. From the beginning of 1999 up to November 2001 policy decisions were made (in general) at each of the bi-weekly ECB's Governing Council meetings. From November 2001 onwards the frequency of policy decisions changed to monthly. Only the first Governing Council meeting in each month, which coincides also with the Press Conference, is a policy meeting. Note that this change in the frequency of policy meetings seems to have reduced volatility in the money market, especially at the short end, as documented both in figure 4.6 and in tables 4.5 to 4.10

4.5 Conclusions

This chapter studies the effects of monetary policy implementation on the euro area money market. In particular, volatility of interest rates with various maturities and volatility transmission along the yield curve is analyzed. It has been shown that the operating procedure explains a substantial part of the behavior of interest rates. Money market rates up to six months maturity are significantly affected by the way how the central bank implements its monetary policy decisions. The one year rate is the inflection point. Only events related to monetary policy decisions, like press conferences and changes in the target rate, and not events related to the implementation of those decisions, affect the volatility of the twelve-month rate.

Notwithstanding, firms' investment and households' consumption decisions depend mostly on longer term rates, which indicates that the operating procedures in place implement monetary policy decisions very efficiently, without inducing real costs on the economy. Nevertheless, the short end of the yield curve is substantially affected by the institutional features of monetary policy implementation. Especially the begin and end of a reserve maintenance period as well as allotment and settlement days of open market operations affect volatility. These effects are strongest at the very short end of the maturity spectrum, at the overnight rate. The volatility of the overnight rate is transmitted to interest rates further out the term structure, up to the six-month rate. More than 30 percent of the overnight rate volatility is transmitted to the two-week rate. The transmission to other money market rates is around 14 percent. However, no volatility transmission is found for the twelve-month rate.

Independent corroboration of the effects of the operating procedure on money market rates is provided by Cassola and Morana (2003 and 2004). Although these authors differ in the estimation method and sample period, their findings are in line with the results presented here.

Strong evidence for several implications of the expectation hypothesis has been found. All money market interest rates show a unit co-integrating relationship with the policy rate. Furthermore, the spreads of money market rates over the policy rate are stationary and these spreads predict future movements of long-term rates.

Natural extensions of this work are to look at rates further out the maturity spectrum or to include other money market rates, like repo or Euribor rates. Most likely the results presented here will be confirmed. The one year rate is disconnected from the operating procedure, therefore, it seems likely that rates with longer maturities are largely independent from operating procedures as well. Macroeconomic news are the probable candidates to explain volatility of long-term rates, not the operating procedure. In the present analysis swap rates have been used, because they have emerged as a euro area benchmark for the money market. It would be interesting to use repo rates, since they do not involve credit risk. However, for the time being there does not exist a unified repo market. The use of Euribor rates is more complex, because the credit risk is substantially higher than for swap rates. This credit risk then would have to be modeled somehow. Nevertheless, there are no obvious reasons why operating procedures should affect other money market rates, like repo or Euribor rates, but not affecting swap rates, and vice versa. Therefore, it is likely that the results presented here will be confirmed.

An interesting extension would be to model all money market rates jointly, within a system of equations. Nevertheless, it is rather complex to estimate a volatility model for a system of equations with as much as seven variables. Furthermore, including all of the numerous explanatory variables, which are necessary for a well-specified model, is likely to increase considerably the difficulties in estimating such a system.

4.6 Appendix

4.6.1 Basic statistics and estimation results

Table 4.1: Basic statistics for money market rates.

	Maturity					
	Overnight	Two weeks	One month	Three months	Six months	Twelve months
	Level					
Mean	3.343	3.342	3.345	3.352	3.378	3.480
Std. dev.	0.931	0.901	0.905	0.916	0.933	0.951
Skewness	0.283	0.277	0.280	0.268	0.231	0.137
Kurtosis	2.043	1.896	1.894	1.901	1.937	1.949
Maximum	5.750	4.945	4.935	5.065	5.145	5.275
Minimum	1.340	1.981	2.012	2.005	1.943	1.825
	First differences					
Mean	0.000	-0.001	-0.001	-0.001	-0.001	-0.001
Std. dev.	0.143	0.043	0.040	0.038	0.037	0.040
Skewness	0.884	-0.581	-0.549	-0.717	-1.073	0.248
Kurtosis	16.745	22.882	26.257	42.201	88.475	5.042
Maximum	1.160	0.268	0.285	0.370	0.525	0.180
Minimum	-0.980	-0.420	-0.368	-0.415	-0.580	-0.188

NOTE: All statistics are computed for EONIA swap rates, except for the overnight maturity, which is the EONIA rate itself. The EONIA rate is a volume-weighted average of interbank rates in the euro area. Sample: All business days from 24/03/1999 to 19/02/2004, both included.

Table 4.2: ADF unit root tests.

Interest rate	Test statistic
(A) Levels	
Policy Rate	-0.26
Overnight	-1.21
Two-week	-0.13
One-month	0.09
Three-month	0.21
Six-month	0.14
Twelve-month	-0.14
(B) First differences	
Policy Rate	-14.41*
Overnight	-19.86*
Two-week	-14.43*
One-month	-14.48*
Three-month	-14.41*
Six-month	-13.42*
Twelve-month	-13.84*
(C) Spreads over policy rate	
Overnight	-12.08*
Two-week	-8.44*
One-month	-6.19*
Three-month	-3.67*
Six-month	-2.60*
Twelve-month	-2.07

NOTE: All statistics are computed for EONIA swap rates, except for the overnight maturity, which is the EONIA rate itself, and the policy rate. The EONIA rate is a volume-weighted average of interbank rates in the euro area. The policy rate is defined as the fixed rate (until June 27, 2000) and the minimum bid rate (after June 27, 2000) at which the European Central Bank conducts its weekly open market operations. Any change in the policy rate is assumed to become effective at the day of announcement, not at the day when the next open market operation is settled. All rates are quoted as annual rates. Sample: All business days from 24/03/1999 to 19/02/2004, both included. Augmented Dickey-Fuller test statistics are carried out with five lags and an intercept. 10% (5%) critical values are -2.57 (-2.86), e.g. Hamilton (1994). * denotes rejection of the H0 (unit root) at the 10% significance level.

Table 4.3: Co-integration tests.

H0: number of co-integrating vectors r	Likelihood ratio	Critical Value (5%)
r = 0	593.55	124.24*
r ≤ 1	410.76	94.15*
r ≤ 2	268.27	68.52*
r ≤ 3	153.46	47.21*
r ≤ 4	74.76	29.68*
r ≤ 5	29.34	15.41*
r ≤ 6	3.10	3.76

NOTE: Tests for co-integration are based on a VAR with 5 lags comprised of the EONIA rate; EONIA swap rates with maturities two weeks, one, three, six and twelve months; and the policy rate. The EONIA rate is a volume-weighted average of interbank rates in the euro area. The policy rate is defined as the fixed rate (until June 27, 2000) and the minimum bid rate (after June 27, 2000) at which the European Central Bank conducts its weekly open market operations. Any change in the policy rate is assumed to become effective at the day of announcement, not at the day when the next open market operation is settled. All rates are quoted as annual rates. Sample: All business days from 24/03/1999 to 19/02/2004. The likelihood ratio test is based on the trace statistic (e.g. Johansen, 1991) and critical values are from Osterwald-Lenum (1992). * denotes rejection of the H0 (respective number of co-integrating vectors) at the 5% significance level.

Table 4.4: Co-integrating vectors.

	Policy Rate	Overnight	Two-week	One-month	Three-month	Six-month	Twelve-month
Coefficient	-1.000	0.979	1.001	1.000	1.003	1.014	1.052
Std. Error	-	0.011	0.008	0.011	0.025	0.041	0.068
t-statistic (H0: unity)	-	-1.934	0.136	-0.042	0.129	0.335	0.764

NOTE: Parameter estimates for each of the six normalized co-integrating vectors are shown. The coefficient on the policy rate is normalized to minus unity. All other parameters are zero, except the parameter for the rate with the relevant maturity. For example, the third column shows the coefficient estimate for the first co-integrating vector, the spread of the overnight rate over the policy rate. This co-integrating vector is [-1, 0.979, 0, 0, 0, 0, 0]. The fourth column shows the coefficient estimate for the second co-integrating vector, the spread of the two-week rate over the policy rate. This co-integrating vector is [-1, 0, 1.001, 0, 0, 0, 0], and so on. The last row presents t-statistics for the null hypothesis that the estimated parameters equal unity, as predicted by the expectation hypothesis (e.g. Hall et al, 1992 or Sarno and Thornton, 2003). The estimation of the co-integration vectors follows Johansen's (1991) maximum likelihood procedure and is based on a VAR with 5 lags comprised of the EONIA rate; EONIA swap rates with maturities two weeks, one, three, six and twelve months; and the policy rate. The EONIA rate is a volume-weighted average of interbank rates in the euro area. The policy rate is defined as the fixed rate (until June 27, 2000) and the minimum bid rate (after June 27, 2000) at which the European Central Bank conducts its weekly open market operations. Any change in the policy rate is assumed to become effective at the day of announcement, not at the day when the next open market operation is settled. All rates are quoted as annual rates. Sample: All business days from 24/03/1999 to 19/02/2004.

Table 4.5: Parameter estimates for the Overnight Interest Rate (EONIA).

Model: $\Delta i_t = c + \phi(i_{t-1} - i^*_{t-1}) + x_t\beta + h_t\eta_t$
$\ln(h_t^2) = z_t\lambda + \Sigma_j \delta_j \{ \ln(h_{t-j}^2) - z_{t-j}\lambda \} + \alpha\{|\eta_{t-1}| - E|\eta_{t-1}| + \gamma\eta_{t-1}\}$
$\eta_t \sim iid(0, p + (1-p)*\sigma^2)$.
Sample: All business days from 24/03/1999 to 19/02/2004, both included.

Variable	Parameter	Std. Error	p-value
Mean equation			
(A) Liquidity effects at the last day in a RMP, t = T			
u_{T-1}	-0.077	0.014	0.000
u_{T-2}	-0.055	0.009	0.000
$u_{T-3} + u_{T-4} + u_{T-5}$	-0.052	0.009	0.000
u_T	-0.046	0.009	0.000
(B) Expected future policy rate			
$E_t[i^*_{t+k}]$ at the first day in a RMP, t = 1	0.628	0.060	0.000
$E_t[i^*_{t+k}]$ at other days, t = 2,…,T	0.000	0.007	0.946
(C) Calendar day effects			
End of month, reversed begin of month; except end of semester	0.051	0.002	0.000
End of 2nd quarter, reversed begin of 3rd quarter	0.178	0.020	0.000
End of 4th quarter, reversed begin of 1st quarter	0.310	0.033	0.000
(D) Other variables			
First day in a RMP, t = 1	0.030	0.005	0.000
dunderbidding	-0.303	0.014	0.000
$(i_{t-1} - i_{t-2})$*(1 - first day - begin of month)	0.067	0.011	0.000
Constant	0.001	<0.001	0.173
Error correction term $(i_{t-1} - i^*_{t-1})$ at the first day in a RMP, t = 1	-1.000	-	-
Error correction term $(i_{t-1} - i^*_{t-1})$ at all other days, t = 2,…T	-0.040	0.008	0.000

Table 4.5 (continued)

Variable	Parameter	Std. Error	p-value
Volatility equation			
(E) Days of reserve maintenance period			
First day, t = 1	1.516	0.194	0.000
Last allotment day	0.841	0.250	0.001
All days after last allotment	3.045	0.381	0.000
Next to last day, t = T-1	1.850	0.393	0.000
Last day, t = T	2.315	0.510	0.000
(F) Calendar days			
End of month and the day before	0.471	0.171	0.006
Begin and end of a quarter, additionally	1.500	0.665	0.024
Begin and end of a semester, additionally	2.170	0.455	0.000
Policy rate change and the day after	1.087	0.287	0.000
(G) Other dummy variables			
dunderbidding	1.754	0.195	0.000
GC meeting after last allotment (Sep and Oct 1999)	4.028	0.291	0.000
Underbidding at end of RMP (Dec 2003)	1.047	0.356	0.003
January 2002 (Cash changeover)	3.175	0.725	0.000
(H) EGARCH parameters			
Constant	-6.394	0.151	0.000
α	2.403	0.211	0.000
δ	0.678	0.037	0.000
γ	0.089	0.033	0.007
σ	0.203	0.011	0.000
p	0.324	0.003	0.000
Standardised residuals:			
Mean	0.019		
Variance	0.368		
Skewness	0.599		
Kurtosis	12.657		
Q(20), p-value	0.023		
Q(20) for squared residuals, p-value	0.970		

NOTE: i_t = volume-weighted average of interbank rates in the euro area, the EONIA rate. i^*_t = policy rate, or target rate, which is defined as the fixed rate (until June 27, 2000) and the minimum bid rate (after June 27, 2000) at which the European Central Bank conducts its weekly open market operations. Any change in the policy rate is assumed to become effective at the day of announcement, not at the day when the next open market operation is settled. All rates are quoted as annual rates, e.g. i_t = 5 means a five percent annual interest rate. Liquidity effects in panel A are estimated using the relevant supply changes, i.e. those occurring at or after the last allotment day in each RMP. See table 4.11 and the main text for a detailed description of the variables used in the estimation. The parameters in the variance equation represent the effect on the log of the conditional volatility. A zero liquidity effect is tested for and then imposed at two underbidding episodes and after Easter 2003. The respective days are 23/10/2001, 23/12/2002 and 23/04/2003. Q(j) denotes the Ljung-Box test for serial correlation at lag length j.

Table 4.6: Parameter estimates for the Two-week EONIA Swap Rate.

Model: $\Delta i_t = c + \phi(i_{t-1} - i^*_{t-1}) + x_t\beta + h_t\eta_t$
$\ln(h_t^2) = z_t\lambda + \Sigma_j \delta_j \{ \ln(h_{t-j}^2) - z_{t-j}\lambda \} + \alpha\{|\eta_{t-1}| - E|\eta_{t-1}| + \gamma\eta_{t-1}\}$
$\eta_t \sim iid(0, p + (1-p)*\sigma^2)$.
Sample: All business days from 24/03/1999 to 19/02/2004, both included.

Variable	Parameter	Std. Error	p-value
Mean equation			
Constant	0.001	0.001	0.173
Error correction term ($i_{t-1} - i^*_{t-1}$)	-0.029	0.011	0.010
Lagged change of the policy rate	0.256	0.045	0.000
Lagged dependent variable	-0.085	0.025	0.001
Volatility equation			
(A) Transmission of volatility			
Conditional EONIA volatility	0.311	0.039	0.000
(B) Days of maintenance period			
Policy decisions bi-weekly	1.491	0.224	0.000
Last day, t = T	-1.936	0.294	0.000
Next to last day, t = T-1	-1.416	0.311	0.000
First day, t = 1	-0.781	0.235	0.001
(C) Calendar days			
End of month	-0.959	0.217	0.000
Thursday	0.801	0.128	0.000
(C) Other variables			
Underbidding allotment day	2.516	0.837	0.003
Constant	-4.651	0.372	0.000
α	1.026	0.165	0.000
δ	0.907	0.021	0.000
γ	0.047	0.051	0.356
σ	0.339	0.022	0.000
p	0.174	0.003	0.000
Standardised residuals:			
Mean	0.000		
Variance	0.282		
Skewness	0.096		
Kurtosis	10.793		
Q(10), p-value	0.395		
Q(20), p-value	0.010		
Q(20) for squared residuals, p-value	0.557		

NOTE: i_t = two-week EONIA swap rate. i^*_t = policy rate, or target rate, which is defined as the fixed rate (until June 27, 2000) and the minimum bid rate (after June 27, 2000) at which the European Central Bank conducts its weekly open market operations. Any change in the policy rate is assumed to become effective at the day of announcement, not at the day when the next open market operation is settled. All rates are quoted as annual rates, e.g. $i_t = 5$ means a five percent annual interest rate. See table 4.11 for a detailed description of the variables used in the estimation. The parameters in the variance equation represent the effect on the log of the conditional volatility. Q(j) denotes the Ljung-Box test for serial correlation at lag length j. Conditional EONIA volatility stands for the logarithm of the conditional EONIA volatility as estimated with the model described in table 4.5.

Table 4.7: Parameter estimates for the One-month EONIA Swap Rate.

Model: $\Delta i_t = c + \phi(i_{t-1} - i^*_{t-1}) + x_t\beta + h_t\eta_t$
$\ln(h_t^2) = z_t\lambda + \Sigma_j \delta_j \{ \ln(h_{t-j}^2) - z_{t-j}\lambda \} + \alpha\{|\eta_{t-1}| - E|\eta_{t-1}| + \gamma\eta_{t-1}\}$
$\eta_t \sim \text{iid}(0, p + (1-p)*\sigma^2)$.
Sample: All business days from 24/03/1999 to 19/02/2004, both included.

Variable	Parameter	Std. Error	p-value
Mean equation			
Constant	-0.001	0.001	0.013
Error correction term $(i_{t-1} - i^*_{t-1})$	0.008	0.007	0.232
Lagged change of the policy rate	0.176	0.084	0.037
Lagged dependent variable	-0.065	0.023	0.005
Volatility equation			
(A) Transmission of volatility			
Conditional EONIA volatility	0.134	0.033	0.000
(B) Days of maintenance period			
Press conference	0.938	0.265	0.000
Policy rate change	2.879	0.542	0.000
Policy decisions bi-weekly	1.611	0.168	0.000
First day, t = 1	0.726	0.237	0.002
(C) Other variables			
Underbidding allotment day	3.010	0.550	0.000
Constant	-6.227	0.335	0.000
α	1.434	0.199	0.000
δ	0.800	0.052	0.000
γ	-0.103	0.052	0.047
σ	0.277	0.017	0.000
p	0.185	0.002	0.000
Standardised residuals:			
Mean	0.008		
Variance	0.254		
Skewness	0.702		
Kurtosis	13.221		
Q(20), p-value	0.050		
Q(20) for squared residuals, p-value	0.991		

NOTE: i_t = one-month EONIA swap rate. i^*_t = policy rate, or target rate, which is defined as the fixed rate (until June 27, 2000) and the minimum bid rate (after June 27, 2000) at which the European Central Bank conducts its weekly open market operations. Any change in the policy rate is assumed to become effective at the day of announcement, not at the day when the next open market operation is settled. All rates are quoted as annual rates, e.g. $i_t = 5$ means a five percent annual interest rate. See table 4.11 for a detailed description of the variables used in the estimation. The parameters in the variance equation represent the effect on the log of the conditional volatility. Q(j) denotes the Ljung-Box test for serial correlation at lag length j. Conditional EONIA volatility stands for the logarithm of the conditional EONIA volatility as estimated with the model described in table 4.5.

Table 4.8: Parameter estimates for the Three-month EONIA Swap Rate.

Model: $\Delta i_t = c + \phi(i_{t-1} - i^*_{t-1}) + x_t\beta + h_t\eta_t$
$\ln(h_t^2) = z_t\lambda + \Sigma_j \delta_j \{ \ln(h_{t-j}^2) - z_{t-j}\lambda \} + \alpha\{|\eta_{t-1}| - E|\eta_{t-1}| + \gamma\eta_{t-1}\}$
$\eta_t \sim iid(0, p + (1-p)*\sigma^2)$.
Sample: All business days from 24/03/1999 to 19/02/2004, both included.

Variable	Parameter	Std. Error	p-value
Mean equation			
Constant	-0.002	0.000	0.000
Error correction term ($i_{t-1} - i^*_{t-1}$)	0.020	0.003	0.000
Lagged change of the policy rate	0.091	0.048	0.056
Lagged dependent variable	-0.036	0.019	0.059
Volatility equation			
(A) Transmission of volatility			
Conditional EONIA volatility	0.132	0.025	0.000
(B) Days of maintenance period			
Press conference	1.001	0.243	0.000
Policy rate change	1.534	0.444	0.001
Last settlement day	-1.262	0.186	0.000
(C) Calendar days			
End of semester	-1.257	0.347	0.000
(D) Other variables			
Constant	-4.462	0.328	0.000
α	2.126	0.289	0.000
δ_1	-0.128	0.091	0.157
δ_2	0.290	0.079	0.000
δ_3	0.451	0.089	0.000
δ_4	0.324	0.076	0.000
γ	-0.058	0.040	0.147
σ	0.217	0.016	0.000
p	0.081	0.001	0.000
Standardised residuals:			
Mean	0.006		
Variance	0.134		
Skewness	1.634		
Kurtosis	35.309		
Q(20), p-value	0.118		
Q(20) for squared residuals, p-value	0.994		

NOTE: i_t = three-month EONIA swap rate. i^*_t = policy rate, or target rate, which is defined as the fixed rate (until June 27, 2000) and the minimum bid rate (after June 27, 2000) at which the European Central Bank conducts its weekly open market operations. Any change in the policy rate is assumed to become effective at the day of announcement, not at the day when the next open market operation is settled. All rates are quoted as annual rates, e.g. $i_t = 5$ means a five percent annual interest rate. See table 4.11 for a detailed description of the variables used in the estimation. The parameters in the variance equation represent the effect on the log of the conditional volatility. Q(j) denotes the Ljung-Box test for serial correlation at lag length j. Conditional EONIA volatility stands for the logarithm of the conditional EONIA volatility as estimated with the model described in table 4.5.

Table 4.9: Parameter estimates for the Six-month EONIA Swap Rate.

Model: $\Delta i_t = c + \phi(i_{t-1} - i^*_{t-1}) + x_t\beta + h_t\eta_t$
$\ln(h_t^2) = z_t\lambda + \Sigma_j \delta_j \{ \ln(h_{t-j}^2) - z_{t-j}\lambda \} + \alpha\{|\eta_{t-1}| - E|\eta_{t-1}| + \gamma\eta_{t-1}\}$
$\eta_t \sim iid(0, p + (1-p)*\sigma^2)$.
Sample: All business days from 24/03/1999 to 19/02/2004, both included.

Variable	Parameter	Std. Error	p-value
Mean equation			
Constant	-0.002	0.001	0.000
Error correction term ($i_{t-1} - i^*_{t-1}$)	0.013	0.002	0.000
Lagged change of the policy rate	0.063	0.025	0.011
Lagged dependent variable	-0.059	0.029	0.042
Volatility equation			
(A) Transmission of volatility			
Conditional EONIA volatility, lagged one day	0.142	0.023	0.000
(B) Days of maintenance period			
Press conference	0.781	0.287	0.007
Policy decisions bi-weekly	0.763	0.219	0.001
(C) Other variables			
Constant	-5.825	0.280	0.000
α	0.995	0.164	0.000
δ_1	0.207	0.071	0.004
δ_2	0.658	0.077	0.000
γ	0.101	0.078	0.192
σ	0.417	0.025	0.000
p	0.250	0.011	0.000
Standardised residuals:			
Mean	0.008		
Variance	0.389		
Skewness	0.514		
Kurtosis	8.478		
Q(20), p-value	0.509		
Q(20) for squared residuals, p-value	0.336		

NOTE: i_t = six-month EONIA swap rate. i^*_t = policy rate, or target rate, which is defined as the fixed rate (until June 27, 2000) and the minimum bid rate (after June 27, 2000) at which the European Central Bank conducts its weekly open market operations. Any change in the policy rate is assumed to become effective at the day of announcement, not at the day when the next open market operation is settled. All rates are quoted as annual rates, e.g. $i_t = 5$ means a five percent annual interest rate. See table 4.11 for a detailed description of the variables used in the estimation. The parameters in the variance equation represent the effect on the log of the conditional volatility. Q(j) denotes the Ljung-Box test for serial correlation at lag length j. Conditional EONIA volatility stands for the logarithm of the conditional EONIA volatility as estimated with the model described in table 4.5.

Table 4.10: Parameter estimates for the Twelve-month EONIA Swap Rate.

Model: $\Delta i_t = c + \phi(i_{t-1} - i^*_{t-1}) + x_t\beta + h_t\eta_t$
$\ln(h_t^2) = z_t\lambda + \Sigma_j \delta_j \{ \ln(h_{t-j}^2) - z_{t-j}\lambda \} + \alpha\{|\eta_{t-1}| - E|\eta_{t-1}| + \gamma\eta_{t-1}\}$
$\eta_t \sim iid(0, p + (1-p)*\sigma^2)$.
Sample: All business days from 24/03/1999 to 19/02/2004, both included.

Variable	Parameter	Std. Error	p-value
Mean equation			
Constant	-0.004	0.001	0.000
Error correction term ($i_{t-1} - i^*_{t-1}$)	0.009	0.002	0.000
Volatility equation			
(A) Transmission of volatility			
Conditional EONIA volatility	-0.012	0.026	0.641
(B) Days of maintenance period			
Press conference	0.509	0.219	0.020
Policy change and the day after	1.016	0.332	0.002
(C) Other variables			
Constant	-7.109	0.227	0.000
α	0.242	0.046	0.000
δ_1	0.380	0.215	0.077
δ_2	0.566	0.211	0.007
γ	-0.062	0.093	0.502
σ	2.033	0.188	0.000
p	0.832	0.247	0.000
Standardised residuals:			
Mean	0.037		
Variance	1.546		
Skewness	0.334		
Kurtosis	4.626		
Q(20), p-value	0.075		
Q(20) for squared residuals, p-value	0.494		

NOTE: i_t = twelve-month EONIA swap rate. i^*_t = policy rate, or target rate, which is defined as the fixed rate (until June 27, 2000) and the minimum bid rate (after June 27, 2000) at which the European Central Bank conducts its weekly open market operations. Any change in the policy rate is assumed to become effective at the day of announcement, not at the day when the next open market operation is settled. All rates are quoted as annual rates, e.g. $i_t = 5$ means a five percent annual interest rate. See table 4.11 for a detailed description of the variables used in the estimation. The parameters in the variance equation represent the effect on the log of the conditional volatility. Q(j) denotes the Ljung-Box test for serial correlation at lag length j. Conditional EONIA volatility stands for the logarithm of the conditional EONIA volatility as estimated with the model described in table 4.5.

4.6.2 Data description

Table 4.11: Description of variables used in the empirical models.

Dummy variable	**Takes value one at:**
T	The last day of each reserve maintenance period (RMP)
T-1	The next to last day of each RMP
First day, t = 1	The first day in a RMP
Last allotment day	The last day in a RMP at which a regular main refinancing operation is allotted (usually a Tuesday)
Last settlement day	The last day in a RMP at which a regular main refinancing operation is settled (usually a Wednesday)
Underbidding allotment day	All allotment days when underbidding occurred. These days are 14/02/01, 11/04/01, 10/10/01, 07/11/01, 04/12/02, 18/12/02, 04/03/03, 04/06/03, 26/11/03
dunderbidding (Volatility equation)	All allotment days when underbidding occurred. Additionally, some underbidding settlement days are also included. Namely, all underbidding settlement days for February, April and October 2001, and both for December 2002 (4th and 18th). Furthermore, this dummy takes value one at days 19/12/02 till 24/12/02, to take into account volatility increase from underbidding close to the end of the RMP
dunderbidding (Mean equation)	This variable takes into account the underbidding effects for the mean, in 2002 and 2003. It takes value one at Wednesdays for underbidding at December 4, 2002, June 4, 2003 (settlement days), the day after settlement March 5, 2003 and the settlement following the underbidding week, March 12, 2003
January 2002	The last four days in the first RMP of 2002. Euro cash changeover
GC meeting after last allotment	Governing Council meeting after the last allotment and policy rate change expectations. Takes value one the days before the last allotment, 20/9/1999 and 18/10/1999 and the days before and after it, i.e. 17/9/99 and 19/10/1999
Policy decisions bi-weekly	All days until November 7, 2001. From this time onwards policy decisions are made only once a month (in general)
Press conference	The day of the press conference held after the ECB's Governing Council meeting
Governing Council meeting	The day of the European Central Bank's Governing Council meeting
Underbidding at end of RMP	Allotment and settlement days of the last regular main refinancing operation in the December 2003 RMP, 16 and 17/12/2003
Policy rate change	The day at which a change in the policy rate is announced
Other variables	
i_t	Money market interest rate of the respective maturity
i^*_t	Policy rate, or target rate, which is defined as the fixed rate (until June 27, 2000) and the minimum bid rate (after June 27, 2000) at which the European Central Bank conducts its weekly open market operations. Any change in the policy rate is assumed to become effective at the day of announcement, not at the day when the next open market operation is settled
$E_t[i^*_{t+k}]$	Expected future policy rate. Proxied by a forward rate constructed with one and two-week EONIA swap rates
u_t	Supply shock, which is approximately the forecast error on autonomous factors

4.6.3 Specification tests

Lagrange multiplier tests for all variables listed in the following tables have been performed for all money market rates, both on mean and volatility equations. Test results indicate that at the 1% significance level almost all of these variables are correctly omitted from the models as outlined in the tables above. There are no obvious ways of including the few remaining significant variables.

Table 4.12: Lagrange multiplier tests for omitted variables; only EONIA rate. Liquidity effects and lagged dependent explanatory variables.

Omitted variable
(A) Lagged dependent variable:
$D_t = \Delta i_{t-2}$, for all days, t = 1,..,T
$D_t = \Delta i_{t-22}$, when t = T
(B) When t is the first day in a RMP and
$D_t = \Delta i_{t-1}$
$D_t = \Delta i_{t-2}$
$D_t = \Delta i_{t-3}$
$D_t = i_{t-1} - i^*_{t-1}$
$D_t = i_{t-2} - i^*_{t-2}$
$D_t = i_{t-3} - i^*_{t-3}$
(C) Lagged policy rate changes:
$D_t = \Delta i^*_{t-1}$
$D_t = \Delta i^*_{t-2}$
(D) Liquidity effects around end of month; $D_t = u_{t-1}$ when t falls on:
Begin of month
End of month
Begin of quarter
End of quarter
(E) Liquidity effects at the end of a reserve maintenance period:
$D_t = u_{t-1}$, when last allotment was before t and
t equals T-1
t equals T-2
t equals T-3
$D_t = u_{t-2}$, when last allotment was before t-1 and
t equals T-1
t equals T-2
t equals T-3
(F) Liquidity effects before the last settlement day of a RMP:
$D_t = u_{t-1}$, when t is before the last settlement day

NOTE: See table 4.11 for a detailed description of the abbreviations used. The variable D_t takes value zero unless otherwise specified. H0: D_t is correctly omitted from the original model specification.

Table 4.13: Lagrange multiplier tests for omitted variables; days of the reserve maintenance period.

Omitted variable
(A) D_t = 1 at days after last allotment and when t equals:
T
T-1
T-2
T-3
T-4
(B) D_t = 1 at days before last settlement and when t equals:
T-1
T-2
T-3
T-4
(C) D_t = 1 at all days after last allotment, if last allotment is at:
T-5
T-4
T-3
T-2
(D) D_t = number of days after last allotment minus one and t equals:
T
T-1
T-2
T-3
(E) D_t = five minus number of days after last allotment and t equals:
T
T-1
T-2
T-3
(F) D_t = 1 when t equals T and:
T is a settlement day
T is NOT a settlement day
T-1 is a settlement day
T-1 is NOT a settlement day
T-2 is a settlement day
T-2 is NOT a settlement day
(G) D_t = 1 when t equals T-1 and:
T-1 is a settlement day
T-1 is NOT a settlement day
T-2 is a settlement day
T-2 is NOT a settlement day
(H) D_t = 1 when t falls on:
The last settlement day in each RMP
The last announcement day in each RMP
The last announcement day in each RMP

Table 4.13 (continued)

Omitted variable
(I) $D_t = 1$ for $t = T - k$, with k:
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
(J) $D_t = 1$ when t is the first day in a RMP and falls on:
Monday
Tuesday
Wednesday
Thursday
Friday
(K) $D_t = 1$ when t is the last day of a RMP and falls on:
Monday
Tuesday
Wednesday
Thursday
Friday
(L) $D_t = 1$ when t falls on:
The day of a Governing Council meeting
The day of a press conference
The day of a press conference, before December 2001
All days before November 9, 2001 (bi-weekly policy decisions)
The day of a policy rate change
The day after a policy rate change

NOTE: See table 4.11 for a detailed description of the abbreviations used. The variable D_t takes value zero unless otherwise specified. H0: D_t is correctly omitted from the original model specification.

Table 4.14: Lagrange multiplier tests for omitted variables; calendar days.

	Omitted variable
(A) $D_t = 1$ when t falls on:	
	Friday
	Thursday
	Wednesday
	Tuesday
	Monday
(B) $D_t = 1$ when t is:	
	End of month, except end of semester
	End of 1st quarter
	End of 2nd quarter
	End of 3rd quarter
	End of 4th quarter
	End of any quarter
	End of 2nd and 4th quarter
	End of 1st and 3rd quarter
	Begin of 1st quarter
	Begin of 2nd quarter
	Begin of 3rd quarter
	Begin of 4th quarter
	Begin of any quarter
(C) $D_t = 1$ for t being the day after:	
	Begin of month
	Begin of month, except begin of quarter
	Begin of 1st quarter
	Begin of 2nd quarter
	Begin of 3rd quarter
	Begin of 4th quarter
	Begin of any quarter

NOTE: See table 4.11 for a detailed description of the abbreviations used. The variable D_t takes value zero unless otherwise specified. H0: D_t is correctly omitted from the original model specification.

Table 4.15: Lagrange multiplier tests for omitted variables; transmission of conditional EONIA volatility.

Omitted variable
(A) D_t = conditional EONIA volatility when t equals:
T
T-1
T-2, T-3 or T-4
(B) D_t = conditional EONIA volatility when t falls on:
End of 2nd quarter
End of 4th quarter
Begin of 1st quarter
Begin 3rd quarter
End of month
Begin of month
Day after begin of month
First day in a RMP
The day of a policy rate change
The day after a policy rate change
The last allotment day in a RMP
The allotment day at which underbidding occurred
The day after an underbidding allotment
Two days after an underbidding allotment
Three days after an underbidding allotment
(C) D_t = 1 when t falls on:
The day of an underbidding allotment
The day after an underbidding allotment
Two days after an underbidding allotment
Three days after an underbidding allotment
The last day of a RMP at which underbidding occurred
The next to last day of a RMP at which underbidding occurred
Two days before the end of a RMP at which underbidding occurred

NOTE: See table 4.11 for a detailed description of the abbreviations used. The variable D_t takes value zero unless otherwise specified. H0: D_t is correctly omitted from the original model specification.

4.6.4 Figures

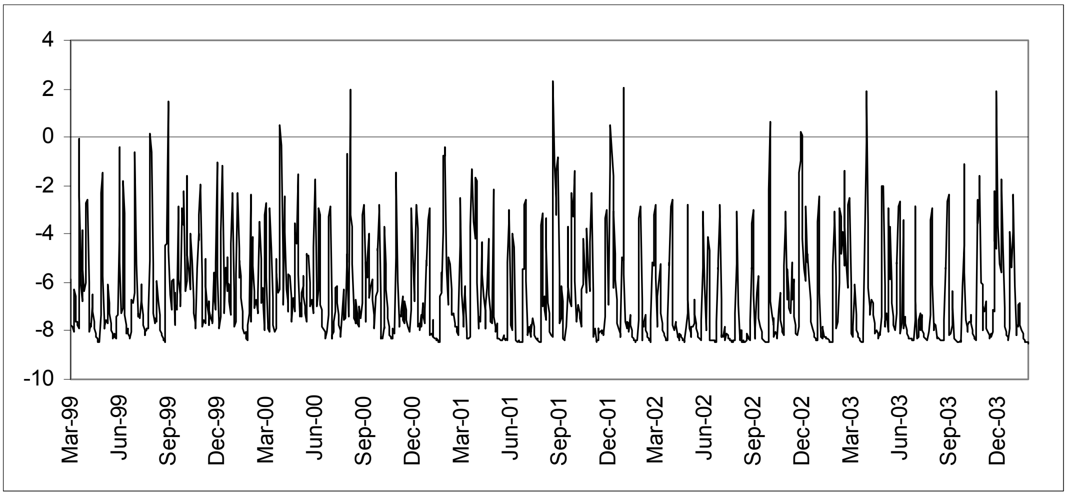

Figure 4.1: Logarithm of Conditional Volatility of the EONIA rate. Estimated with the model as described in table 4.5.

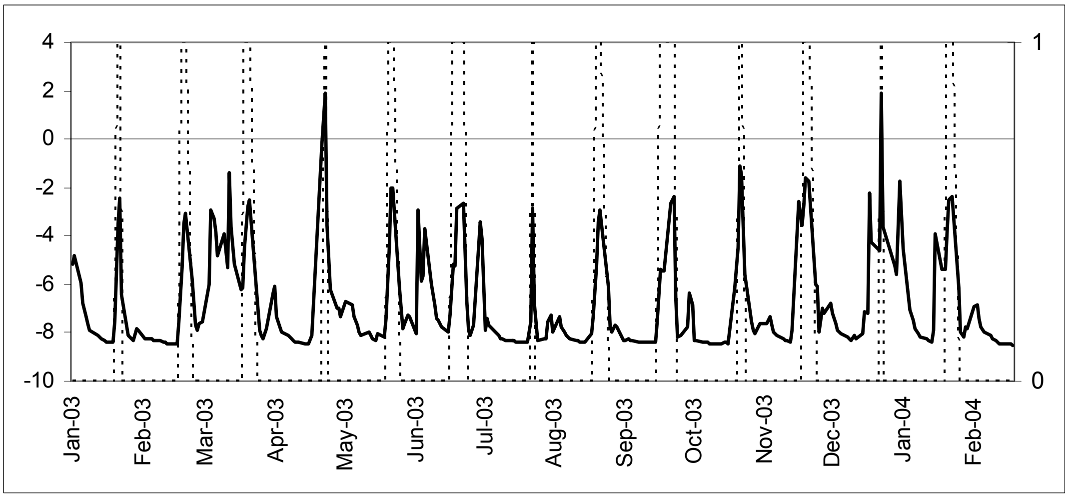

Figure 4.2: Logarithm of Conditional Volatility of the EONIA rate (left scale). Estimated with the model as described in table 4.5. Dotted lines represent a dummy variable taking value one on all days after the last allotment day until the last day of a reserve maintenance period and value zero otherwise (right scale).

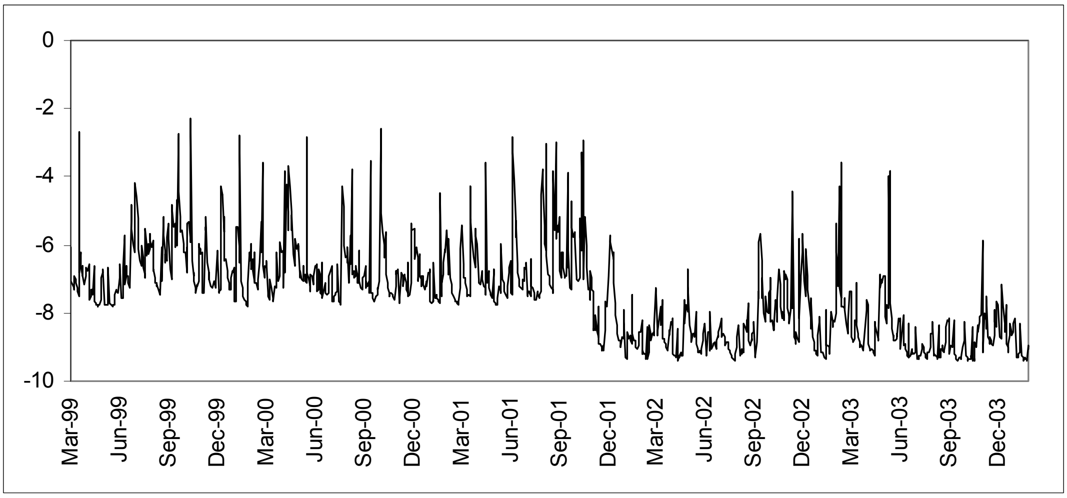

Figure 4.3: Logarithm of Conditional Volatility of the One-month EONIA Swap Rate. Estimated with the model as described in table 4.7.

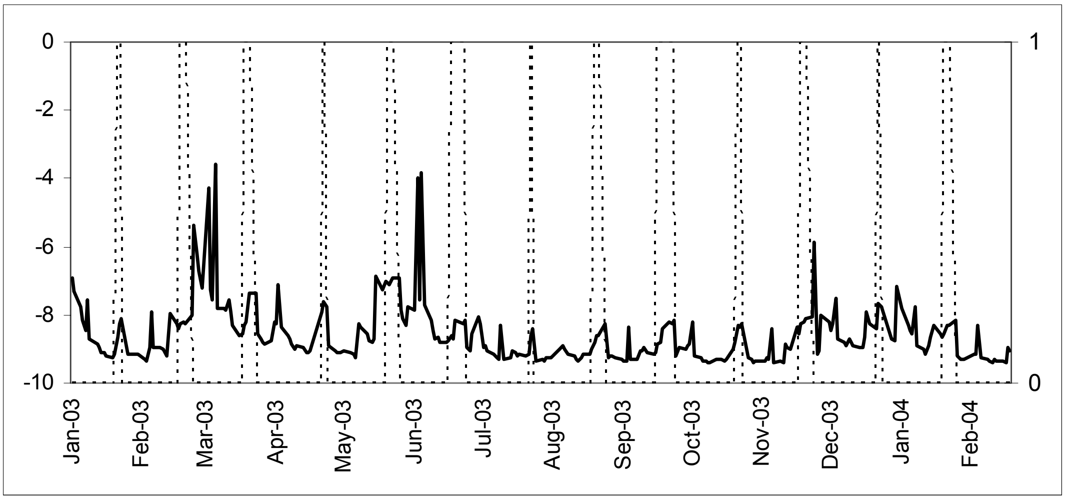

Figure 4.4: Logarithm of Conditional Volatility of the One-month EONIA Swap Rate (left scale). Estimated with the model as described in table 4.7. Dotted lines represent a dummy variable taking value one on all days after the last allotment day until the last day of a reserve maintenance period and value zero otherwise (right scale).

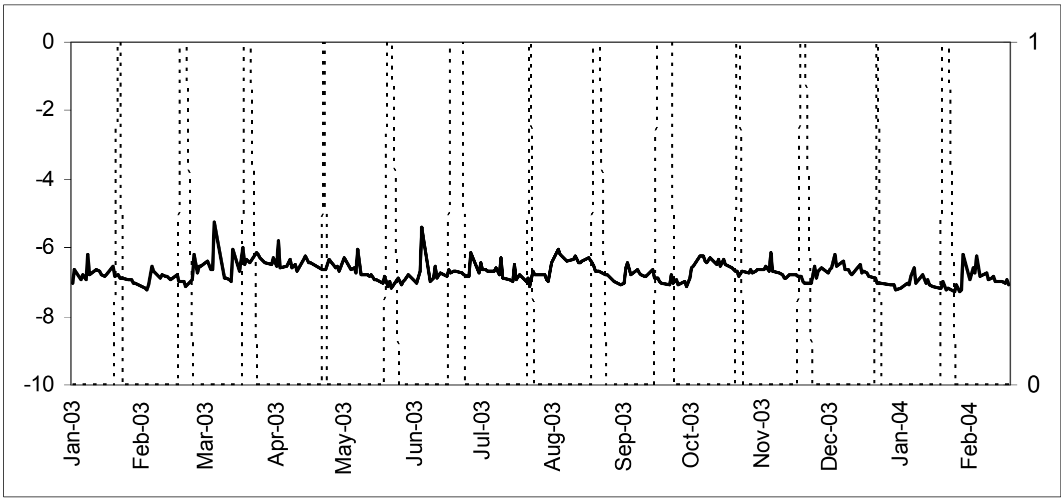

Figure 4.5: Logarithm of Conditional Volatility of the Twelve-month EONIA Swap Rate (left scale). Estimated with the model as described in table 4.10. Dotted lines represent a dummy variable taking value one on all days after the last allotment day until the last day of a reserve maintenance period and value zero otherwise (right scale).

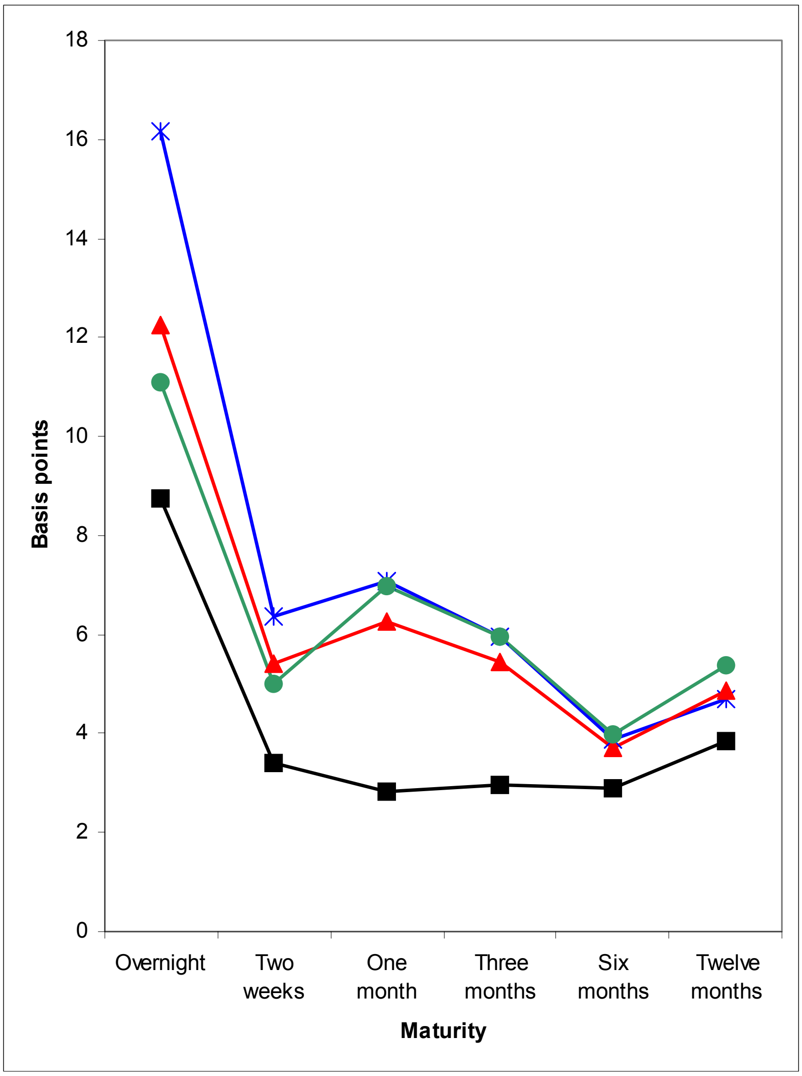

Figure 4.6: Volatility curves for different days of the reserve maintenance period. The blue line (with ★) represents the volatility curve at the ECB's Governing Council (GC) meeting days, before November 2001. Up to this date monetay policy decisions were made (in general) at every GC meeting. From November 2001 onwards monetary policy decisions were made (in general) only at the first GC meeting of each month, coinciding with the press conference (PC). The volatility curve for days of the press conference is given by the green line (with •). The volatility curve for all policy meetings, i.e. all GC meetings before November 2001 and the first GC meeting in each month afterwards, is plotted in red (with ▲). The volatility curve for days which are not policy meeting days is shown as a black line (with ■). Volatility is measured as the average conditional standard deviation, as estimated from models outlined in tables 4.5 to 4.10.

Bibliography

[1] Andrews, D. 1993. Tests for parameter instability and structural change with unknown change point. Econometrica, 61(4), 821-856.

[2] Angeloni, I., A. Kashyab, B. Mojon, and D. Terlizzese. 2002. Monetary transmission in the Euro area: where do we stand? ECB Working Paper No. 114.

[3] Ayuso, J., A. Haldane, and F. Restoy. 1997. Volatility transmission along the money market yield curve. Weltwirtschaftliches Archiv, 133, 56-75.

[4] Bartolini, L., G. Bertola, and A. Prati. 2001. Banks' reserve management, transaction costs, and the timing of federal reserve management. Journal of Banking and Finance, 25, 1287-1317.

[5] Bartolini, L., G. Bertola, and A. Prati. 2002. Day-to-day monetary policy and the volatility of the federal funds rate. Journal of Money, Credit and Banking, 34, 137-159.

[6] Bernanke, B., and I. Mihov. 1997. What does the Bundesbank target? European Economic Review, 41, 1025-1053.

[7] Bernanke, B., and I. Mihov. 1998a. Measuring monetary policy. Quarterly Journal of Economics, 113, 869-902.

[8] Bernanke, B., and I. Mihov. 1998b. The liquidity effect and long-run neutrality. NBER Working Paper No. 6608.

[9] Bindseil, U. 2002. Equilibrium bidding in the eurosystem's open market operations. ECB Working Paper No. 137.

[10] Bindseil, U., and F. Seitz. 2001. The supply and demand for eurosystem deposits the first 18 months. ECB Working Paper No. 44.

[11] Bollerslev, T., R. Chou, and K. Kroner. 1992. ARCH modeling in finance. Journal of Econometrics, 52, 5-59.

[12] Borio, C. 1997. The implementation of monetary policy in industrial countries: a survey. BIS Economic Papers No. 47.

[13] Campbell, J., and R. Shiller. 1991. Yield spreads and interest rate movements: A bird's eye view. Review of Economics Studies, 58, 495-514.

[14] Cassola, N., and C. Morana. 2003. Volatility of interest rates in the euro area. Evidence from high frequency data. ECB Working Paper No. 235.

[15] Cassola, N., and C. Morana. 2004. Transmission of volatility in the euro area money market. ECB, mimeo.

[16] Christiano, L. 1991. Modeling the liquidity effect of a monetary shock. Federal Reserve Bank of Minneapolis, Quarterly Review, Winter, 3-34.

[17] Christiano, L., M. Eichenbaum, and C. Evans. 1998. Monetary policy shocks. What have we learned and to what end? NBER Working Paper 6400.

[18] Ciccarelli, M., and A. Rebucci. 2002. The transmission mechanism of European monetary policy: Is there heterogeneity? Is it changing over time? IMF Working Paper 02/54.

[19] Clarida, R., and M. Gertler. 1996. How does the Bundesbank conduct monetary policy? NBER Working Paper 5581.

[20] Cochrane, J. 2001. Asset pricing. Princeton University Press, New Jersey.

[21] Cohen, B. 1999. Monetary policy procedures and volatility transmission along the yield curve. BIS Study Group.

[22] De Arcangelis, G., and D. Di Giorgio. 1999. Monetary policy shocks and transmission in Italy. A VAR analysis. Universitat Pompeu Fabra, Economics and Business Working Paper No. 466.

[23] Deutsche Bundesbank, 1995. Geldnachfrage und Währungssubstitution in Europa. Monatsbericht, Januar 1995.

[24] Deutsche Bundesbank. 1997. Überprüfung des Geldmengenzieles. Monatsbericht, August 1997.

[25] Diebold, F. 1993. The effect of seasonal adjustment filters on tests for a unit root. Discussion. Journal of Econometrics, 55, 99-103.

[26] ECB. 2002. Monthly Bulletin. January 2002.

[27] ECB. 2004. The monetary policy of the ECB. Frankfurt am Main, Germany.

[28] Ejerskov, S., C. Martin Moss, and L. Stracca. 2003. How does the ECB allot liquidity in its weekly main refinancing operations? A look at the empirical evidence. ECB Working Paper No. 244.

[29] Ericsson, N. 1998. Empirical modeling of money demand. Empirical Economics, 23(3), 295-315.

[30] Ewerhart, C. 2002. A model of the eurosystem's operational framework for monetary policy implementation. ECB Working Paper No. 197.

[31] Fabozzi, F., and F. Modigliani. 1996. Capital Markets. Prentice-Hall, London.

[32] Galí, J. 1992. How well does the IS-LM model fit postwar U.S. data? Quarterly Journal of Economics, May, 709-738.

[33] Gaoitti, E. 1999. The transmission of monetary policy shocks in Italy: 1967-1997. Termi di discussione 363, Banca d'Italia.

[34] Gaspar, V., G. Pérez-Quirós, and J. Sicilia. 2001. The ECB monetary policy strategy and the money market. International Journal of Finance and Economics, 4(6), 325-342.

[35] Ghysels, E. 1990. Unit root tests and the statistical pitfalls of seasonal adjustment: the case of US postwar real gross national product. Journal of Business Economics and Statistics, 8, 145-153.

[36] Ghysels, E., and P. Perron. 1993. Seasonal adjustment filters and unit root tests. Journal of Econometrics, 55, 57-90.

[37] Gilchrist, S. 2001. Commentary to "Identifying the liquidity effect at the daily frequency". Federal Reserve Bank of St. Louis Review, July/August, 79-82.

[38] Green, W. 1997. Econometric Analysis. 3rd Edition. Prentice Hall, Upper Saddle River, New Jersey.

[39] Hall, A., H. Anderson, and C. Granger. 1992. A co-integration analysis of treasury bill yields. Review of Economics and Statistics, 74, 116-126.

[40] Hamilton, J. 1994. Time Series Analysis. Princeton University Press.

[41] Hamilton, J. 1996. The daily market for federal funds. Journal of Political Economy, 104(1), 26-56.

[42] Hamilton, J. 1997. Measuring the liquidity effect. American Economic Review, 87, 80-97.

[43] Hansen, B. 1992. Testing for Parameter Instability in Linear Models. Journal of Policy Modeling, 14(4), 517-533.

[44] Hansen, B. 1997. Approximate Asymptotic P Values for Structural-Change Tests. Journal of Business and Economic Statistics, 15(1), 60-67.

[45] Harvey, A., and G. Collier. 1977. Testing for functional misspecification in regression analysis. Journal of Econometrics, 6, 103-119.

[46] Hatanaka, M. 1996. Time-Series-Based Econometrics. Unit Roots and Co-integrations. Oxford University Press.

[47] Issing, O. 1997. Monetary Targeting in Germany: The stability of monetary policy and of the monetary system. Journal of Monetary Economics, 39(1), 67-79.

[48] Johansen, S., and K. Juselius. 1990. Maximum likelihood estimation and inference on co-integration - with application to the demand for money. Oxford Bulletin of Economics and Statistics, 52, 169-210.

[49] Johansen, S. 1991. Estimation and hypothesis testing of co-integration vectors in Gaussian vector autoregressive models. Econometrica, 59, 1551-1580.

[50] Juselius, K. 1998. Changing monetary transmission mechanisms within the EU. Empirical Economics, 23, 455-481.

[51] Kim, B., and N. Ghazali. 1998. The liquidity effect of money shocks on short-term interest rates: some international evidence. International Economic Journal, 12, 4, 49-63.

[52] Kim, S., and N. Roubini. 2000. Exchange rate anomalies in the industrial countries: a solution with a structural VAR approach. Journal of Monetary Economics, 45, 561-586.

[53] Leeper, E., and D. Gordon. 1992. In search of the liquidity effect. Journal of Monetary Economics, 29(3), 341-369.

[54] Lütkepohl, H. 1993. Introduction to Multiple Time Series Analysis. 2nd Edition. Springer Verlag, Berlin.

[55] Lütkepohl, H., and P. Saikkonen. 2000. Testing for the co-integrating rank of a VAR process with a time trend. Journal of Econometrics, 95, 177-198.

[56] Mojon, B. and G. Peersman. 2001. A VAR description of the effects of monetary policy in the individual countries of the euro area. ECB Working Paper No. 92.

[57] Nyblom, J. 1989. Testing for the constancy of parameters over time. Journal of the American Statistical Association, 84, 223-230.

[58] Osterwald-Lenum, M. 1992. A note with quantiles of the asymptotic distribution of the maximum likelihood co-integration rank test statistics. Oxford Bulletin of Economics and Statistics, 54, 460-462.

[59] Panigirtzoglou, N., J. Proudman, and J. Spicer. 2000. Persistence and volatility in short-term interest rates. Bank of England Working Paper No. 116.

[60] Pérez Quirós, G., and H. Rodríguez Mendizábal. 2003. The market for funds in Europe: What has changed with the EMU? Forthcoming Journal of Money, Credit and Banking.

[61] Perron, P. 1989. The great crash, the oil price shock and the unit root hypothesis. Econometrica, 57(6), 1361-1401.

[62] Perron, P. 1990. Testing for a unit root in a time series with a changing mean. Journal of Economics and Business Statistics, 8(2), 153-162.

[63] Piazzesi, M. 2003. Bond yields and the federal reserve. Forthcoming Journal of Political Economy.

[64] Poole, W., and R. Rasche. 2000. Perfecting the market's knowledge of monetary policy. Journal of financial services research, 18(2-3), 255-298.

[65] Saikkonen, P., and H. Lütkepohl. 2000. Testing for co-integrating rank of a VAR process with structural shifts. Journal of Business and Economic Statistics, 18(4), 451-464.

[66] Sarno, L., and D. Thornton. 2003. The dynamic relationship between the federal funds rate and the Treasury bill rate: An empirical investigation. Journal of Banking and Finance, 27, 1079-1110.

[67] Shapiro, M., and M. Watson. 1988. Sources of Business Cycle Fluctuations. NBER Working Paper 2589.

[68] Strongin, S. 1995. The identification of monetary policy disturbances: explaining the liquidity puzzle. Journal of Monetary Economics, 35(3), 463-497

[69] Thornton, D. 2001a. Identifying the liquidity effect at the daily frequency. Federal Reserve Bank of St. Louis Review, July/August, 59-78.

[70] Thornton, D. 2001b. The federal reserve's operating procedure, non-borrowed reserves and the liquidity effect. Journal of Banking and Finance, 25, 1717-1739.

[71] Uctum, M. 1999. European integration and asymmetry in the EMS. Journal of International Money and Finance, 18, 769-798.

[72] Välimäki, T. 2002. Variable rate liquidity tenders. Bank of Finland Discussion Paper No. 24.

[73] Walsh, C. 1998. Monetary theory and policy. MIT Press, Cambridge, Massachusetts.

[74] Wetherilt, A. 2003. Money market operations and short-term interest rate volatility in the United Kingdom. Applied Financial Economics, 13, 701-719.

[75] Wolters, J., T. Teraesvirta, and H. Lütkepohl. 1998. Modeling the demand for M3 in the unified Germany. Review of Economics and Statistics, 399-409.

[76] Würtz, F. 2003. A comprehensive model on the euro overnight rate. ECB Working Paper No. 207.