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Risk Aversion, Financial Stress and Their Non-Linear Impact on Exchange Rates

Tomáš Adam, Soňa Benecká, and Jakub Matějů *

Abstract

This paper shows how the reaction of selected emerging CEE currencies to increased uncertainty depends on market sentiment in a core advanced economy or even on the global scale. On the example of the Czech koruna, a highly stylized model of portfolio allocation between EUR- and CZK-denominated assets suggests the presence of two regimes characterized by different reactions of the exchange rate to increased stress in the euro area. The "diversification" regime is characterized by appreciation of the koruna in reaction to an increase in the expected variance of EUR assets, while in the "flight to safety" regime, the koruna depreciates in response to increased variance. We suggest that the switch between regimes may be related to changes in risk aversion, driven by the actual level of strains in the financial system as captured by financial stress indicators. Using the Bayesian Markov-switching VAR model, the presence of these regimes is identified in the case of the Czech koruna and to a lesser extent in the case of the Polish zloty and the Hungarian forint. We find that a slight increase in euro area financial stress causes the koruna to appreciate, but as financial market tensions intensify (and investors' risk aversion increases), the Czech currency depreciates in response to a financial stress shock.

Abstrakt

Článek ukazuje, jak měny vybraných rozvíjejících se trhů ve střední a východní Evropě reagují na zvýšenou nejistotu v závislosti na tržním sentimentu v jádrové vyspělé ekonomice nebo v globálním měřítku. Vysoce stylizovaný model alokace portfolia na bázi aktiv denominovaných v eurech a české koruně ukazuje na existenci dvou režimů, které jsou charakterizovány rozdílnou reakcí měnového kurzu na zvýšený finanční stres v eurozóně. V „diverzifikačním" režimu dochází k posílení kurzu koruny v návaznosti na zvýšený očekávaný rozptyl výnosů aktiva denominovaného v eurech. V režimu „útěk do bezpečí" zase koruna oslabuje po zvýšení rozptylu eurového aktiva. Přechod mezi těmito režimy může být spojen se změnami averze k riziku, která je ovlivněna napětím na finančních trzích zachyceným indexy finančního stresu. Pomocí bayesovského Markov-switching VAR modelu identifikujeme existenci těchto režimů u české koruny a do menší míry také u polského zlotého a maďarského forintu. Docházíme k závěru, že mírný nárůst finančního stresu v eurozóně působí na posílení koruny; při vyšším stresu na finančních trzích (které u investorů působí na růst averze k riziku) ale koruna oslabuje v reakci na šokový nárůst finančního stresu.

JEL Codes: E44, F31, G12, G20.
Keywords: Asset allocation, exchange rates, financial stress, Markov-switching.

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Nontechnical Summary

According to standard theories of exchange rate determination, exchange rate movements should be driven primarily by the macroeconomic environment, yet the global financial crisis showed that changes in risk aversion can also have an impact on emerging currencies. A change in portfolio managers' risk attitude caused outflows of funds from emerging economies and subsequent depreciations of their currencies.

In this paper, we show that an increase in uncertainty does not lead to emerging currency depreciation in all circumstances; in our view, the reaction of emerging currencies (e.g. the Czech koruna, the Polish zloty, and the Hungarian forint) to increased uncertainty depends on the level of risk aversion in the core advanced economy (the euro area in our case). Risk aversion therefore causes regime switching in exchange rate behavior. When risk aversion is low and portfolio managers operate in standard mode, the Czech koruna or other emerging currency may be used for "diversification" when uncertainty in the euro area increases. On the contrary, if risk aversion rises, the regime switches to "flight to safety," where the koruna reacts to increased euro area uncertainty by depreciating.

We start by presenting a simple model based on modern portfolio theory where endogenously selected optimal weights of euro area and Czech assets in the portfolio respond to changes in the variance (uncertainty) of euro area assets. Based on this model, we show how the portfolio allocation responds to an increase in euro area financial stress under different degrees of risk aversion and different portfolio management strategies. Since portfolio rebalancing results in capital flows, it is reflected in the expected reactions of relative exchange rates.

Unfortunately, risk aversion and uncertainty are not directly observable, so in empirical testing we concentrate on one particular driver of risk aversion – the actual level of strains in the financial system as measured by financial stress indicators. Impaired market conditions are marked by a higher degree of perceived risk (a wider distribution of probable losses) as well as by uncertainty (decreased confidence in the shape of that distribution), and can alter the risk aversion of traders, as the literature shows.

To identify the regime switching proposed by the theoretical model, we opt for the Markov-switching vector autoregression model, estimating the probability of occurrence of each regime in each period. In the basic setup, we estimate the model for the case of the Czech koruna, and use two endogenous variables: a financial stress index and the exchange rate against the euro. The regime switching is driven endogenously by an unobserved Markov process, so the regimes are not determined by the threshold of financial stress. This is because of path dependency, i.e., investors may react to a rise in the level of stress in a different way when stress has been at elevated levels for a long time than they do when it rises by the same amount in calm times, for example. Substantial or prolonged increased volatility of asset prices may alter the risk aversion of traders or even change the credit constraints, which are unobserved variables to be treated.

To maintain the robustness of our model, we use several financial stress indicators (the CISS and FSI for the euro area, a global measure, and the VIX). As for the results, in all cases we identified at least two regimes – the "diversification" and "flight to safety" regimes as suspected. An increase in financial stress in the "diversification" regime leads to appreciation of the koruna due to diversification motives. A substantial further increase in financial stress coupled with increased risk aversion (a risk-off period) can cause a switch to the "flight to safety" regime and lead to a depreciation of the Czech currency. When the CISS is used, the data suggest the presence of another "calm regime" where the reaction of the exchange rate to financial stress is only marginally significant and short-lived.

The results for the other two Central European currencies (the Polish zloty and the Hungarian forint) seem to support the presence of regime switching in currency reactions, but the effect of the financial stress shock is less pronounced and sometimes even insignificant. We suspect this was due to intervention policies offsetting market pressures, especially during the financial crisis.

1. Introduction

While a sharp drop in capital inflows (a "sudden stop") after a deterioration in the economic or political climate in emerging economies is a well-documented phenomenon, a similar episode occurred in advanced countries during the global financial crisis as a result of increased risk aversion. The lesson learned from the global financial crisis is that a change in portfolio managers' risk attitude can cause outflows of funds from emerging economies and depreciation of their currencies. This indicates the importance of financial instability (domestic or even foreign) for asset markets, whereas according to the standard theory market movements should be driven mainly by the macroeconomic environment.

As increased risk aversion can play quite a substantial role in exchange rate dynamics, the nature of this relationship is worth further investigation. Nevertheless, this topic has so far attracted little attention in the literature. Only carry trades, as a specific case of trade between low- and high-yielding currencies, have been comprehensively discussed in this respect. There are two major difficulties for studying the link between exchange rate dynamics and risk aversion.

First, risk aversion is an unobserved variable, and there are only estimates and proxies available. We do not aim to propose a new measure, but rather concentrate on a particular factor that can affect risk aversion. Traders' attitude toward taking risks shifts during periods of extreme market volatility, when the smooth functioning of financial markets is interrupted. This situation (known as financial stress) is marked by higher uncertainty and perceived risk, impairing the price discovery process. So, in this paper, we employ financial stress indicators to capture changing conditions in financial markets that can alter risk aversion. We refrain from using other, broader measures of financial stability or macroeconomic variables to test the effect of changing financial conditions only. We also do not aim to build the best model of exchange rate dynamics, but rather stress the importance of financial variables and investigate the relationship in more detail.

Second, the existing literature has often suggested a simple link: an increase in risk aversion causes funds to be withdrawn from emerging economies and their currencies to depreciate. In contrast to this finding, we suggest that the reaction of emerging currencies (e.g. the Czech koruna, the Polish zloty, and the Hungarian forint) to increased uncertainty depends on the level of risk aversion in the core advanced economy (the euro area in our case). When euro area financial markets are calm and hence risk aversion is low, the search-for-yield effect drives trades in emerging currencies. This may lead to emerging currencies appreciating in response to a mild increase in uncertainty in the euro area. On the other hand, when advanced markets become turbulent, funds start to be withdrawn from emerging economies. Any increase in financial stress causes their currencies to depreciate. As a result, the link can be non-linear.

We therefore provide both a theoretical background and empirical evidence. To start with, we present a simple model based on modern portfolio theory where the endogenously selected weights of euro area and Czech assets in the optimal portfolio respond to changes in the variance (uncertainty) of euro area assets. In this model we identify two regimes (related to the degree of risk aversion and portfolio management strategy) based on the different reactions of the exchange rate to increased uncertainty. The "diversification" regime is characterized by the koruna appreciating in response to increasing uncertainty of euro asset returns, while the "flight to safety" regime is characterized by the koruna depreciating in response to increasing uncertainty of euro asset returns. Using the Markov-switching model we manage to identify different exchange rate reaction regimes in the case of the Czech koruna, while the evidence for the other two currencies (the Hungarian forint and the Polish zloty) is not as supportive.

The paper is structured as follows. First, it defines the concepts of risk aversion and financial stress and proposes several indicators suitable for measuring financial stress. Next, based on a model of portfolio rebalancing, it provides a theoretical motivation for the link between the exchange rate and risk aversion. Finally, it estimates how the Czech koruna has reacted to the evolution of financial stress in the euro area in the various regimes identified. Results for several types of financial indicators are presented along with an additional analysis using data for the Hungarian and Polish currencies.

2. Risk Aversion and Financial Stress and Its Spillovers

Changes in market sentiment or financial conditions are often cited by financial practitioners as drivers of asset market movements. Terms like "risk aversion", "risk appetite," and "financial stress" are used interchangeably. In economics, though, these notions have specific definitions.

To start with, risk aversion is a term used to describe a characteristic of an economic agent – it is the agent's attitude toward taking risk. It can be inferred from choices in dilemmas or lotteries (gambles) as well as operationalized using scales in specific decision situations. In this sense, risk aversion is a part of the intrinsic makeup of consumers or investors that defines their behavior under uncertainty. Traditionally, risk aversion is assumed to be constant over time, but Kandasamy et al. (2014), for example, suggests that it can be time-varying.

On the other hand, risk appetite is defined as the willingness of investors to bear risk and depends "on both the degree to which investors dislike such uncertainty and the level of uncertainty" (Gai and Vause, 2005). In this definition, risk appetite has two underlying forces – risk aversion, which defines the degree to which investors dislike uncertainty, and the macroeconomic environment, influencing the level of uncertainty about consumption prospects. So, unlike risk aversion, risk appetite varies over time (Misina, 2003). A large set of indices have been constructed to capture changing risk appetite. Some of them are atheoretical – these have mostly been constructed by commercial banks such as UBS, JP Morgan, and Merrill Lynch. Other indices have been built on the basis of theory (CSFB, GRAI, ICI). The survey by Illing and Aaron (2005) offers a comparison of risk-appetite indices.

Some empirical studies also use the VIX index to capture market sentiment in a similar way as risk-appetite indices. The VIX measures the implied volatility of options in the S&P 500 index and it is often cited as a gauge of fear on U.S. stock markets. For example, De Bock and Carvalho Filho (2013) use the VIX to identify risk-off episodes, i.e., episodes of increased global risk aversion. Unfortunately, as Bekaert et al. (2013) has shown, the VIX is driven not only by risk aversion. It also contains specific information on the U.S. stock market (or economic) uncertainty, which complicates its use as an indicator of risk aversion.

In parallel to the efforts to measure risk appetite, attempts to capture changing conditions only in financial markets have given rise to a financial stress literature. Financial stress can be described as a situation where the normal (smooth) functioning of financial markets is severely impaired or interrupted. Under these conditions, the financial system is threatened by substantial losses. Financial stress is marked by a higher degree of perceived risk (a wider distribution of probable losses) as well as uncertainty (decreased confidence in the shape of that distribution), according to Misina and Tkacz (2008). The uncertainty leads to increased volatility of asset prices, which can then alter the risk aversion of traders. As a recent study by Kandasamy et al. (2014) shows, during periods of extreme market volatility traders' attitude toward taking risks changes. This study changed the common perception of risk aversion as a stable trait, moving it closer to a varying attitude toward risk. Impaired market conditions seem to alter the risk aversion of traders. We make use of this link when exploring the reaction of a selected currency to increased uncertainty in foreign financial markets. As the risk aversion of traders, identified by our theoretical model as a key driver, is not directly observable, we test the outcomes empirically using financial stress indicators.

2.1 Measuring Financial Stress

Financial stress indicators aggregate a set of stress measures, such as volatilities and spreads, from various market segments, such as the money market, bond market, stock market, and foreign exchange market,[1] into a single time series. Even early papers on financial stress, which used simply constructed stress indicators (in terms of the aggregation methods or variables used), were able to capture most stressful events as perceived by experts (Illing and Liu, 2006). But over time, more sophisticated indices have been constructed. In particular, the global financial crisis gave a strong impulse to research in this field, highlighting the importance of financial stress for real economic activity.

The construction of indices varies both in the stress measures included and in the methods used to aggregate them. To the best of our knowledge, there is no theoretical background for modeling financial stress, so these choices are often arbitrary. Several indicators have been constructed for individual economies (such as the U.S., the euro area, and Canada) as well as more general ones to be used across countries (Cardarelli et al., 2009). A number of studies have shown the impact of financial stress on real or financial variables as well as on monetary policy, but the financial stress indicators themselves seem difficult to predict according to Slingenberg and de Haan (2011) and their potential use in forecasting so far seems to be limited.

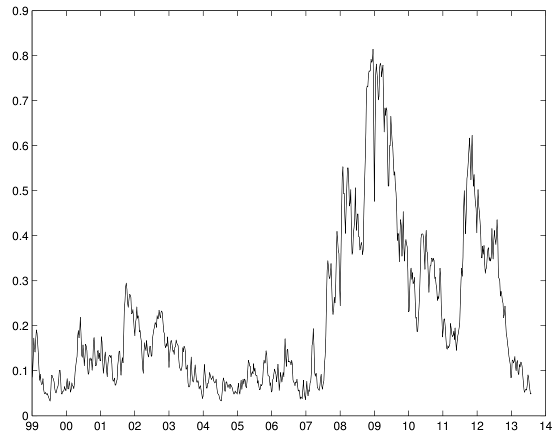
In the post-crisis period, the focus has shifted to the construction of financial stress indicators to capture systemic risk. The contagion effect is an import element of systemic risk, so these indices should reflect situations where stress materializes simultaneously in several interconnected markets. Brave and Butters (2012) constructs a state-space representation of the level of systemic stress. This approach takes into consideration the cross-correlations of a large number of financial variables (100 indicators) and the past development of the index to set the weights for each sub-index. Standard portfolio theory is used by Holló et al. (2012), who aggregate sub-indices in a way which reflects their cross-correlation structure. This approach has been applied to Czech data (Adam and Benecká, 2013) and Hungarian data (Holló, 2012), but generally the attention paid to the role of financial stress in the Central European region (CEE) has been relatively limited.[2]

In this paper, we build on the financial stress literature and use two financial stress indices for the euro area in our analysis. The Composite Indicator of Systemic Stress (CISS) by Holló et al. (2012) will be employed first. Its construction not only incorporates information about conditions in individual markets, based primarily on volatility, but also captures the effect of simultaneous stress in each of them. As an alternative, we will use the Financial Stress Indicator (FSI) for the euro area,

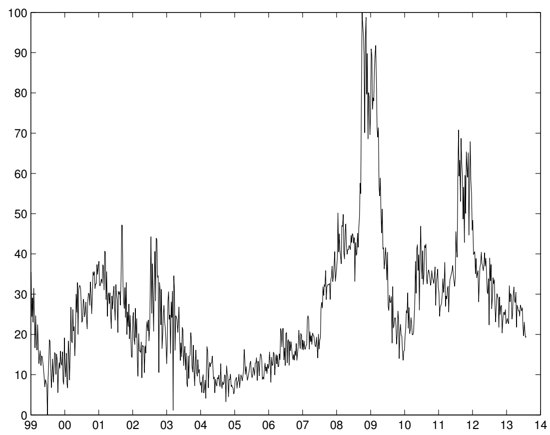
[1] Some studies additionally include macroeconomic or financial stability indicators (such as private credit) to capture the overall economic conditions. We stick to the financial markets context as we intend to assess the impact of financial stress only.
[2] Due to the importance of banking sectors in CEE compared to other financial segments, the focus has been on developing banking-oriented or broader financial stability indices.

as proposed by Cardarelli et al. (2009),[3] which is based mainly on spread indicators and conditional volatilities.

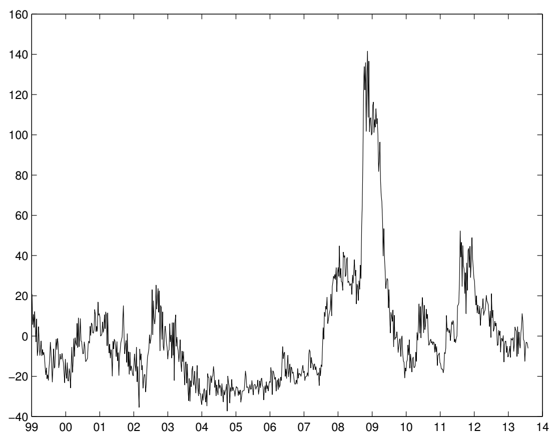
Figure 1: Financial Stress Indicators



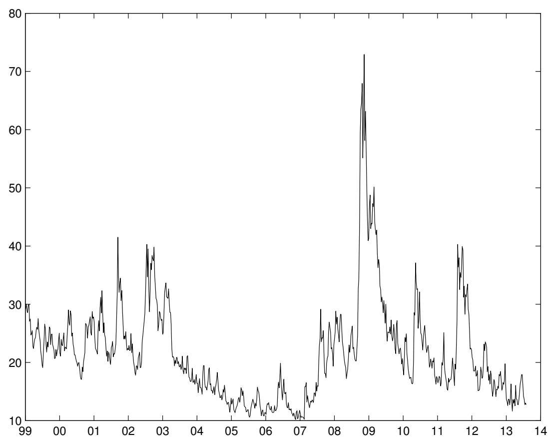
(a) Composite Indicator of Systemic Stress (CISS)



(b) FSI for the euro area



(c) The first principal component of FSIs in the biggest financial centers (FSI PCA)



(d) VIX index

Figures 1a and 1b show the evolution of both indicators starting from the launch of the euro area in 1999. In several periods (e.g. during early 2011), the FSI is higher than the CISS, as the increase in financial stress occurred only in some markets and did not spread through the entire financial system. As the stress was limited to some markets and was not systemic, the CISS shows lower values.

2.2 Financial Stress Spillovers and Their Global Nature

Financial stress should in essence reflect domestic financial market conditions, but with increasing financial integration the domestic conditions have also become affected by external developments. Financial interlinkages facilitate risk diversification at country level, but at the same time they also enhance the transmission of adverse financial shocks. As Appendix A shows on the example of

[3] We adjusted the original index slightly by using weekly data on exchange rates and other variables instead of monthly data as proposed by the original paper.

two interconnected economies (the Czech Republic and the euro area), financial stress transmission is complex (the links between segments are not fixed) and dynamic (they increase in periods of elevated stress). This is due to the complexity and opacity of financial markets and to imperfect information, which lead to herd behavior by investors, increase turbulence, and induce transmission of stress.

Financial stress spillover effects, now well recognized, are therefore regularly monitored by the IMF (e.g. in Spillover Reports), among other institutions. Global shocks, such as those in 2008/2009, originate mainly in advanced countries and the most important financial centers, giving rise to synchronization of their financial markets, and have major impacts on emerging markets. We suspect that the observed volatility in interconnected markets influences exchange rate behavior, but for comparison we construct a global stress indicator to test it as well. It is measured as a common factor of the FSIs for a selected group of economies (or financial centers): the euro area, the UK, Japan, and the USA. We employ the methodology by Cardarelli et al. (2009) and construct a financial stress indicator for each of the above-mentioned financial centers. To obtain the common component, we use Principal Component Analysis (PCA), which filters out the main component. The resulting global financial stress indicator is shown in Figure 1c.

Despite the high degree of co-movement, there are several differences between the CISS and the global financial stress indicator (common factor). The sovereign debt crisis in Europe did not translate fully into the global measure as its spillovers remained contained. In fact, at the peak of the crisis in 2012, after the Greek default, the CISS in the euro area exploded to levels close to those of 4 years before, when the U.S. financial system was collapsing. On the other hand, the VIX index (the implied volatility of S&P 500 index options, Figure 1d), increased far less during the same period, as this fear gauge mainly reflects the situation on U.S. markets.

2.3 Exchange Rate Dynamics and Their Financial Determinants

A number of studies investigate the role of traditional exchange rate determinants, but financial measures such as risk aversion or even financial stress have attracted relatively little attention from researchers. The link between exchange rate movements and risk aversion (measured by the VIX index) is investigated, for example, in De Bock and Carvalho Filho (2013). During risk-off episodes, when risk aversion dominates globally, the Japanese yen, the Swiss franc, and the U.S. dollar appreciate against other G-10 and emerging market currencies. A low-volatility environment stimulates carry trades, i.e., investments in high-yielding currencies funded by low-yielding ones, while an increase in risk aversion causes rapid unwinding.

As for financial stress, Molodtsova and Papell (2012) include spreads between money market rates and the overnight index swap rate (as measures of market tensions) in the Taylor rule. This specification assumes that the central bank responds not only to inflation pressures (expected inflation) and the output gap, but also to financial conditions. This in turn determines the expected interest rate differential, which drives exchange rate movements according to theories of exchange rate determination (uncovered interest rate parity, UIP). The modified Taylor rule model performs better in real-time forecasting of the EUR/USD exchange rate than other common models (based on the UIP alone, on purchasing power parity, or on monetary fundamentals), particularly at the outset of the financial crisis and in 2009 and 2010.

The question of how the conditions in financial markets affect portfolio decisions has been treated to some extent in the literature. According to Raddatz and Schmukler (2012), both investors and fund managers relocate their portfolios when facing a stressful event either in the domestic country or in a foreign country where their investment is exposed. As a result, major institutional investors, and in particular their fund managers, have a substantial impact on capital flows during periods of financial stress. These capital flows then have a direct impact on the exchange rates under scrutiny. Closer to our approach, Lo Duca (2012) discusses the time-varying nature of capital flows, where push and pull factors have a different impact based on market conditions. When market tensions are elevated, investors pay attention to regional developments in emerging economies. But when panic occurs, uncertainty and risk aversion start to drive flows and regional developments play a marginal role.

To sum up, the literature suggests that risk aversion or even financial stress plays some role in exchange rate dynamics. In the traditional view, calm conditions in advanced countries' financial markets stimulate carry trades to high-yielding currencies of emerging economies, which then tend to appreciate. An increased level of risk aversion leads to appreciation of safe haven currencies, while emerging markets are hit by capital outflows and their currencies depreciate vis-à-vis the U.S. dollar (with carry trade reversal too). In the following section, we show that emerging market currencies can operate i several regimes – they appreciate in response to increased external financial stress in the "diversification" regime, and secthey depreciate in response to increased financial stress in the "flight to safety" regime, while a switch from the former to the latter occurs when risk aversion increases. The distinction between safe-haven and high-yielding currency status is therefore no longer time-invariant, but depends on global investors' changing attitude to risk.

3. A Model of Portfolio Rebalancing

In this section we present a highly stylized model of portfolio allocation where investors decide about the composition of a portfolio consisting of CZK- and EUR-denominated assets. The purpose is to investigate the possibly non-linear relationship between risk aversion and the exchange rate, i.e., a different reaction of the relative exchange rate to increased uncertainty based on the level of risk aversion and different portfolio management strategies.

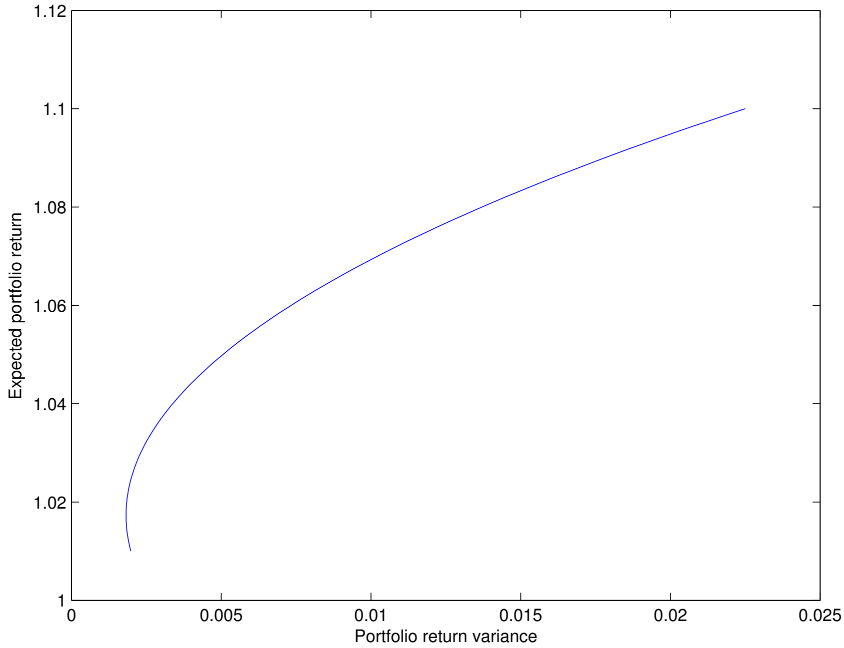
We will consider two types of portfolio management: mean-variance utility maximization and optimization with a constraint on the maximum variance of the portfolio. We decided to include the latter as the value-at-risk indicator has become widely used in portfolio management over the last few decades. Subsequently, two regimes (related to the degree of risk aversion and the portfolio management strategy) can be identified based on the different reactions of the exchange rate to increased uncertainty. The "diversification" regime is characterized by the koruna appreciating in reaction to increasing uncertainty of EUR asset returns, while the "flight to safety" regime is characterized by the koruna depreciating in response to increasing uncertainty of EUR asset returns.

Moreover, we investigate the reasons for regime switching – we suggest that regime switches may occur due to changes in investors' behavior, notably to shifts in the degree of risk aversion, and possibly also to changes in fund managers' objectives related to changes in the perception of risk. In particular, we will show that either an increase in risk aversion or a change from simple mean-variance optimization to value-at-risk-constrained optimization (or both at the same time) causes a switch from the "diversification" to the "flight to safety" regime.

3.1 Portfolio Composition

We model the behavior of an investor deciding about the composition of a portfolio where one class of assets is denominated in EUR (this can be any other core currency), while the other class is

Figure 2: Mean-variance Frontier of the Portfolio



denominated in CZK (this can be any other satellite currency). Matching the stylized facts, we assume that the expected return on CZK-denominated assets is higher than that on EUR-denominated assets,

$$E[R_{CZ}] \geq E[R_{EUR}] \tag{3.1}$$

and the variance of CZK asset returns is higher than that of EUR asset returns.

$$\sigma_{CZ} \geq \sigma_{EUR} \tag{3.2}$$

Assume a portfolio P, composed of CZK- and EUR-denominated assets. The expected return on the portfolio is

$$E[R_P] = \lambda_{CZK} E[R_{CZK}] + (1 - \lambda_{CZK}) E[R_{EUR}] \tag{3.3}$$

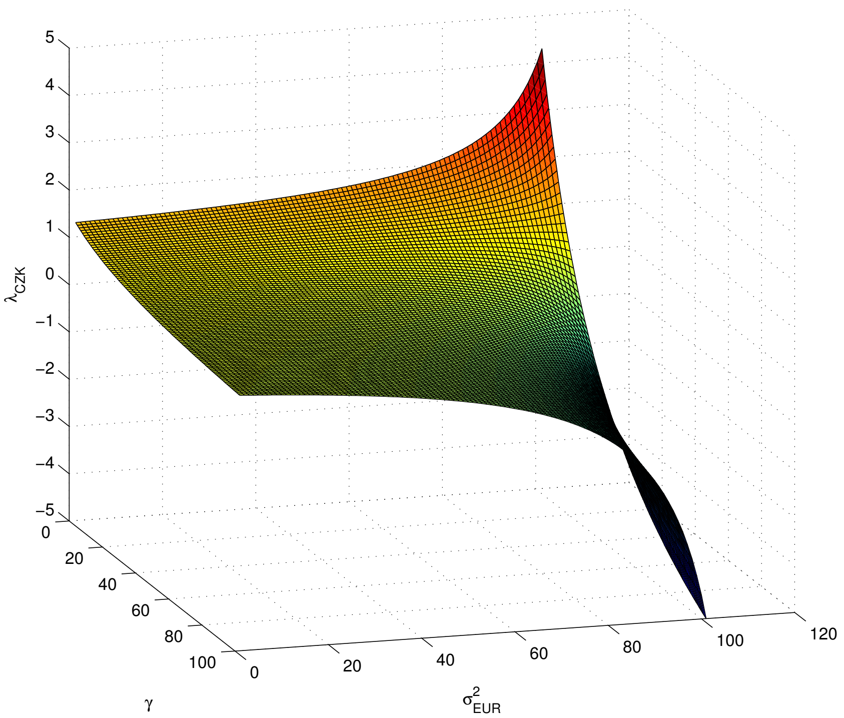
where λ_{CZK} is the weight of CZK assets. The variance of the portfolio returns is then

$$\sigma_P^2 = \lambda_{CZK}^2 \sigma_{CZK}^2 + (1 - \lambda_{CZK})^2 \sigma_{EUR}^2 + 2\lambda_{CZK}(1 - \lambda_{CZK})\sigma_{CZK,EUR} \tag{3.4}$$

The aim is to study the changes in portfolio allocation (particularly the share of CZK-denominated assets λ_{CZK}) in response to increased uncertainty related to the returns on EUR-denominated assets, i.e., an increase in σ_{EUR}. Figure 2 shows the mean-variance frontier[4] of the portfolio for a particular parametrization. The preferences of investors increase toward the north-west of the diagram. It is clear that very low values of λ_{CZK} are strictly dominated by their higher counterparts with equal

[4] Parameter values: $E[R_{CZK}] = 1.1$, $E[R_{CZK}] = 1.01$, $\sigma_{CZK} = 0.15$, $\sigma_{EUR} = 0.08$

Figure 3: Optimal λ_{czk} for Changing σ^2_{eur}, for Different Values of γ



variance but higher returns. The preference schedule also implies that the allocation with minimum variance (the vertex of the mean-variance parabola) is usually not the optimal one, as the investor can achieve higher expected returns with an infinitely small increase in the return variance.

We consider two types of portfolio management: mean-variance utility maximization and optimization with a constraint on the maximum variance. The latter is identical to a constraint on theoretical value-at-risk,[5] a widely used tool for portfolio risk management.

3.2 Mean-variance Utility Maximization

First we consider an investor who maximizes her mean-variance utility derived from the portfolio return. [6] The problem is to choose the share of CZK-denominated assets λ_{CZK} to maximize

$$\max_{\lambda_{CZK}}\{E[R_P]-\frac{\gamma}{2}\sigma_P^2\} \tag{3.5}$$

where γ is the Arrow-Pratt coefficient of absolute risk aversion. The first-order conditions illustrate the optimal allocation. The investors are, in general, allowed to hold negative amounts of any of the assets (short-sell).

[5] Value-at-risk, VaR_α, is defined as the α-quantile of the return distribution and can be interpreted as the loss amount which will not be exceeded with probability $(1-\alpha)$. Under the assumption of return normality, the constraint on the α-quantile is equivalent to the constraint on the variance.

[6] It can be shown that maximizing the exponential utility function $U=-e^{-\gamma R_P}$, where γ is a coefficient of absolute risk aversion, is equivalent to maximizing the mean-variance objective $MV=E[R_P]-\frac{\gamma}{2}\sigma_P^2$.

Figure 4: Optimal λ_{czk} for Changing σ^2_{eur}, Constrained σ^2_p

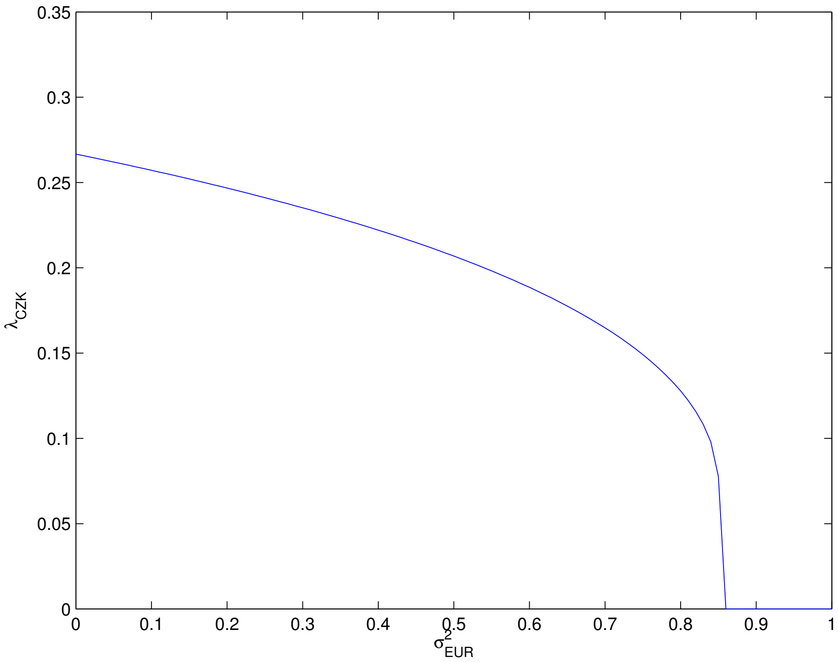


Figure 3 shows the optimal share λ_{CZK} of CZK-denominated assets,[7] with increasing uncertainty in EUR-denominated assets, and for different values of the risk aversion parameter. Most importantly, for low values of the risk aversion parameter γ, the investor optimally reacts to increased EUR uncertainty by switching to CZK assets, increasing the share λ_{CZK}. For higher values of γ, however, the relationship reverses: with increased EUR uncertainty, the investor's optimal response is to reduce the share of CZK assets. This is because CZK asset returns still have relatively higher variance, and an increase in EUR uncertainty in the case of high risk aversion calls for a "flight to safety".

3.3 Optimization with Variance Constraint

The second type of investor behavior is motivated by the widespread use of the Value-at-Risk (VaR) indicator as a risk management tool in the last decade. When risk concerns dominate the portfolio allocation decision, it is reasonable to assume that portfolio managers are forced to pay more attention to VaR-type indicators. The major modeling difference from the previous case is that the portfolio managers have to fulfill the constraint of maximum variance. The objective is the following:

$$\max_{\lambda_{CZK}}\{E[R_P]\} \qquad \text{s.t.} \quad \sigma^2_P \leq \overline{\sigma^2_P} \tag{3.6}$$

Because $E[R_{CZK}] \geq E[R_{EUR}]$, the decision consists of choosing the highest λ_{CZK} such that $\sigma^2_P = \overline{\sigma^2_P}$. Figure 4 presents the variance-constrained optimal choices of the share of CZK-denominated assets in the portfolio with changing EUR asset return variance. When the portfolio manager faces a binding constraint on the portfolio return variance, the share of CZK assets decreases with higher uncertainty of EUR returns. As the variance of EUR assets rises, the manager needs to reduce the exposure to CZK-denominated assets, which are still riskier.

[7] Parameter values: $E[R_{CZK}] = 1.1$, $E[R_{CZK}] = 1.01$, $\sigma_{CZK} = 0.15$, $\sigma_{EUR} \in (0, 0.9\sigma_{CZK})$, $\gamma \in (3, 100)$

Table 1: Results Summary: the Response of Investors to an Increase in the Expected Variance of EUR Assets

	M-V optimization	VaR constraint
low risk aversion	diversification	flight to safety
high risk aversion	flight to safety	flight to safety

3.4 Implications for Exchange Rate Behavior

The results are summarized in Table 1. Based on the risk attitude and objectives of the investors and/or portfolio managers, the share of CZK-denominated assets in the model portfolio can switch between regimes, which we call “diversification” and “flight to safety.” When portfolio managers maximize their mean-variance utility and risk aversion (γ) is low, CZK assets serve as a diversification tool and their share in the representative portfolio increases with increasing uncertainty of EUR asset returns. When risk aversion rises, the attitude toward CZK assets changes to “flight to safety” – the share of CZK assets declines with increased EUR uncertainty. When the portfolio decision is made with a constraint on the portfolio variance (or VaR), the “flight to safety” regime dominates.

We suggest that the described changes in investors’ attitude toward CZK-denominated assets induce international capital flows, which translate into analogous behavior of exchange rates. The simple and stylized model presented above offers an explanation of the regime switches observed in the reaction of the CZK/EUR exchange rate to stress in the euro area. When risk aversion is low and portfolio managers operate in standard mode (mean-variance utility maximization), the Czech koruna may serve for “diversification” when uncertainty in the euro area increases. On the contrary, if risk aversion rises, or portfolio managers start to operate under strictly binding constraints on the portfolio return variance (such as VaR), the regime switches to “flight to safety,” where the koruna reacts to increased euro area uncertainty by depreciating.

4. The Effects of Financial Stress on the Czech Koruna

In this section, we estimate the reaction of the Czech koruna exchange rate to shocks to financial stress. In line with the proposed theoretical model, we believe that the reaction may be non-linear, i.e., the same shock may lead to a different reaction under different regimes. In the first (“diversification”) regime, the koruna appreciates in response to elevated financial stress due to the portfolio diversification motive. However, this behavior may alter in times of financial panic, when investors resort to safe assets in advanced countries (due to increased risk aversion) and thus the koruna depreciates again (the “flight to safety” regime).

We do not assume that the regimes are defined only by the level of financial stress or by its value relative to an estimated threshold. Instead, we assume that regime switching is driven endogenously, by unobserved variables such as risk aversion or credit constraints. The reason why we do not associate regimes with the level of financial stress is path dependency – investors may react to a rise in the level of stress in a different way when the stress has been at elevated levels for a long time than they do when it rises by the same amount in calm times, for example. As mentioned in Section 2, increased volatility of asset prices can alter the risk aversion of traders. Also, after a substantial shock to a financial system the credit constraints change. Investors hence are more sensitive to market volatility, which is an unobserved variable to be treated using endogenous regime switching.

As a result, we opt for the Markov-switching vector autoregression model, where regime switching is driven endogenously by an unobserved Markov process. This is in contrast to threshold VAR, which would define regimes based on the level of stress relative to an estimated threshold. We also assume that the transition probabilities of switching from one regime to another are constant and do not depend on the level of financial stress due to the path dependency mentioned above.

4.1 Bayesian Markov-switching VAR Methodology

Markov-switching VAR is a non-linear variant of the VAR model where two or more VAR models switch over time according to an endogenous unobserved Markov chain process. This model is convenient in our context, as we aim to study the response of an endogenous variable (the exchange rate) to shocks to another variable (a financial stress index) and we assume that the reaction is state contingent, with the regime depending on the state of an unobserved variable.

We estimate the model in the Bayesian setting, since we want to include our prior information regarding the nature of the exchange rate and financial stress (they should be close to a random walk). In addition, we have strong prior information that shocks to the Czech koruna exchange rate do not affect financial stress in the euro area (or on the global scale), but the exchange rate itself reacts to changes in financial stress. Finally, this estimation method allows us to draw impulse response functions easily and does not suffer from convergence problems as in the case of MLE.

Let y_t be an (m x 1) vector of endogenous variables at time t and let N be the number of regimes. In our case, we have $m = 2$, $y_t = (ind_t, czk/eur_t)$, and $N = 2$ or $N = 3$. A Markov-switching vector autoregression model can be written as follows:

$$y_t = \mu_{s_t} + B_{1,s_t} y_{t-1} + \ldots + B_{p,s_t} y_{t-p} + (\Sigma_{s_t})^{\frac{1}{2}} \varepsilon_t \tag{4.1}$$

where $\varepsilon_t \sim i.i.d.N(0, I_m)$. We assume that the unobserved state variable s_t indicating the realization of the regime at time t follows a first-order Markov chain with N regimes and transition probabilities

$$p_{ij} = Prob(s_{t+1} = j | s_t = i), \quad \forall i, j \in \{1, \ldots, N\}, \quad \sum_{j=1}^{N} p_{ij} = 1 \tag{4.2}$$

This means that both the coefficients in the VAR model and the variances of shocks are governed by the same endogenous Markov process (some studies assume that the coefficients are governed by one process and the variances by another – see Krolzig (1997) for example; this reference also provides models where only the coefficients or covariance matrices are regime-dependent).

In the Bayesian setting, the parameters of the model are regarded as random variables. Let us define the vector of parameter blocks to be estimated as $\Theta = \{B_1, B_2, B_3, \Sigma_1, \Sigma_2, \Sigma_3, P, S_t, t = 1, \ldots, T\}$, where T is the number of observations, S_t is the state variable indicating the regime at time t, and P is the transition matrix:

$$P = \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1N} \\ p_{21} & p_{22} & \cdots & p_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ p_{N1} & p_{N2} & \cdots & p_{NN} \end{pmatrix} \tag{4.3}$$

The method of estimating Bayesian Markov-switching VAR models can be seen as an extension of estimating Markov-switching univariate autoregressive processes to a multivariate setting. The former, in the two- and three-regime cases, is described in Kim and Nelson (1999), for example, while the multivariate extension is described in Krolzig (1997).

In order to draw further inferences regarding the model parameters and impulse response functions, we need to choose the number of regimes to be estimated, to impose priors on the parameters, and to simulate approximations of the marginal posterior distributions of each parameter. The choice of the number of regimes was done informally – we ran the estimation using three regimes and if only a few periods were identified in one of the regimes, we decreased the number of regimes to two. The latter two steps – setting the priors and simulating draws from the posterior distribution by means of Gibbs sampling – are described in Appendix B.

4.2 Data

We use weekly data since the introduction of the euro (1 January 1999) in the bi-variate Markov-switching VAR model. The two endogenous variables in the model are a financial stress index and the exchange rate of the Czech koruna against the euro. We choose four possible financial stress indices (described in Section 2), and therefore we estimate four different models, which we call the CISS model, the FSI EA model, the FSI PCA model, and the VIX model.

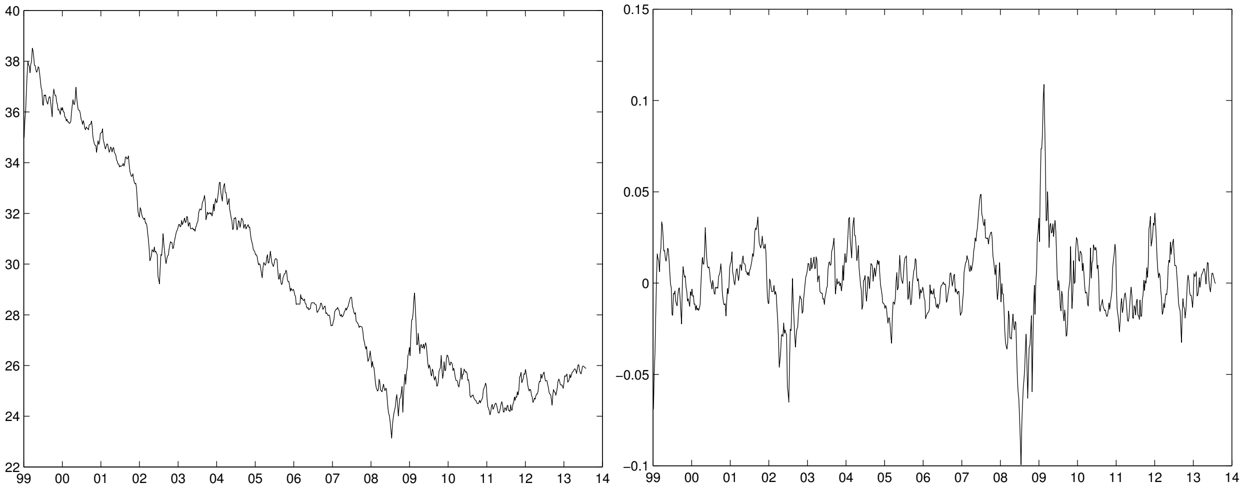
The CISS indicator time series was downloaded from the ECB Statistical Data Warehouse and the CZK/EUR exchange rate from Thomson Reuters Datastream. Other financial stress indicators were replicated by the authors according to the literature, again with the use of data downloaded from Thomson Reuters Datastream and Bloomberg.

The time series of the exchange rate was transformed into logarithms and the gap (from the trend extracted using the Hodrick-Prescott filter) was taken to isolate the effect of trend appreciation and the effects of fundamental variables, which are not included in our model. The level of the resulting time series can be interpreted as percentage deviations of the level of the Czech koruna from its trend. The end of the estimation sample was set to August 31, 2012, because in the following months the Czech National Bank started to verbally intervene on the foreign exchange market and we believe that this date could coincide with a structural break in the relationship we are trying to estimate. The exchange rate time series used for the analysis can be seen in Figure 5.

4.3 Results

Using the Markov-switching model, we identified two or three regimes for the reaction of the exchange rate to changes in financial stress, depending on the choice of financial stress indicator. The main estimation results are summarized in Table 2, which reports the posterior means of the drawn parameters of the four models considered. For each regime, the standard deviations of the structural residuals and the correlation coefficients of the reduced-form residuals are shown, as well as the

Figure 5: Exchange Rate of the Czech Koruna Against the Euro



(a) CZK/EUR in levels

(b) CZK/EUR logarithmic gap

transition matrix elements and the expected durations of staying in a given regime. As we stated above, the ordering of the regimes was chosen with respect to the variance of the reduced-form shocks to the respective stress indicator, i.e., the last regime corresponds mostly to periods of high volatility, when the financial turbulence was large and risk aversion was probably the highest.

Several features can be observed from these results. First, for each index, the probability of staying in the same regime is lowest for the high-stress regime, except for the VIX index model, which has the highest probability of staying in the second stress regime. This result translates to the expected duration of staying in the high-stress regime, which is lowest for all indicators except the VIX index.

In addition, transitions between regimes tend to be "smooth" in the case of the CISS index, i.e., switches from Regime 1 to Regime 3 and vice versa are very unlikely. By contrast, in the VIX model, switches are more likely from Regime 2 to Regime 3 than from Regime 2 to Regime 1. In other words, switches from the middle-stress regime to the high-stress regime are more likely than switches from the middle to the low regime.

Regarding the volatility of shocks to the exchange rate, these have the same ranking across regimes as the shocks to the stress indices, i.e., they are lowest in Regime 1 and highest in Regime 3. One exception is the first model (where the CISS index is used), which has the lowest volatility of residuals in the exchange rate equation in Regime 2. Finally, the correlations are highest in Regime 1 and their values are relatively low in absolute terms, thus the ordering of variables should not matter much for the identification of shocks and the impulse response analysis, the results of which are presented in the following text.

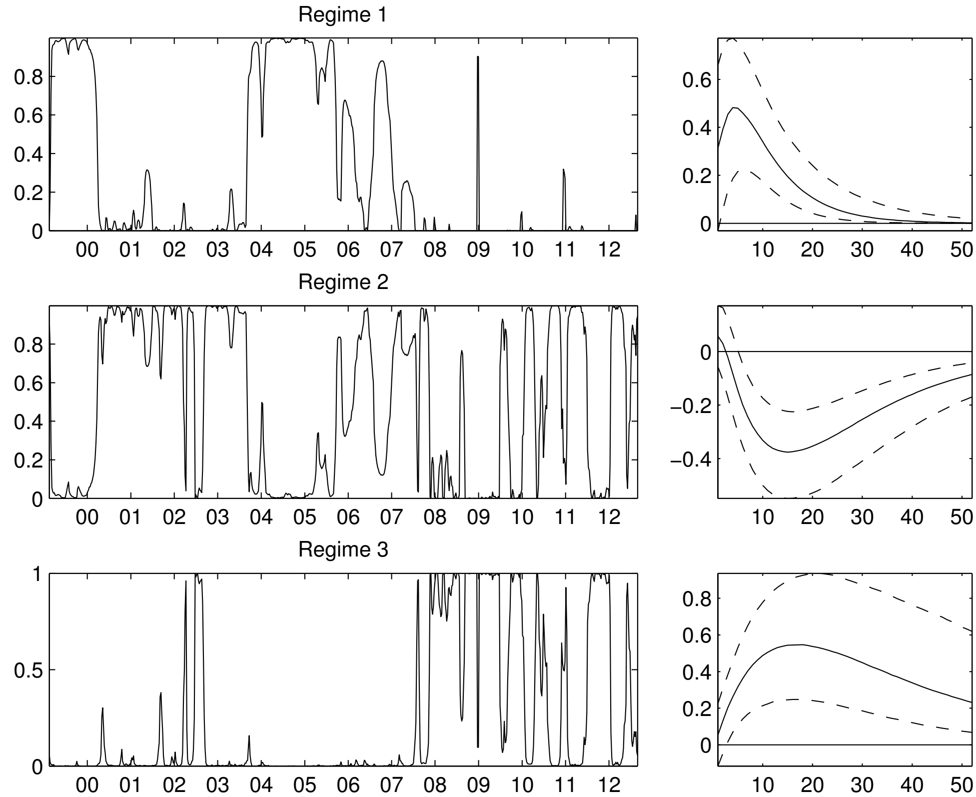
4.3.1 Results: Euro Area Financial Stress Indicators

The estimated regime probabilities and impulse responses in the CISS model can be seen in Figure 6a. The response in the figure represents the reaction of the exchange rate to a one standard deviation shock to the stress indicator (where a downward movement means appreciation of the exchange rate).

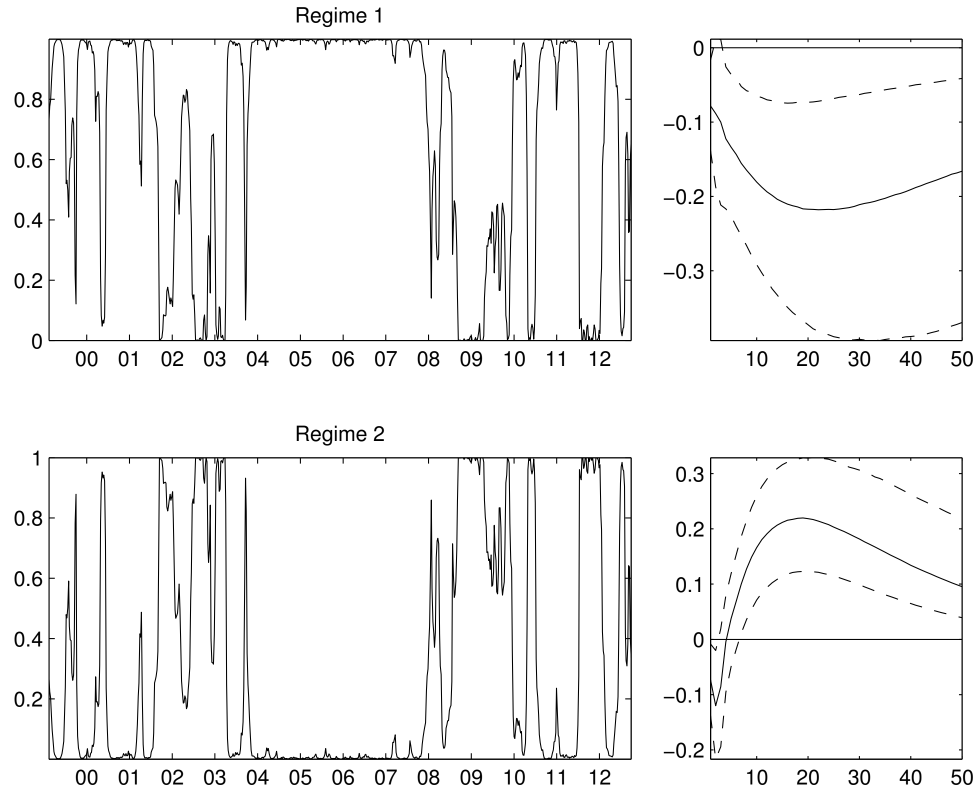
Table 2: Estimation Results: Sample Mean Values of Draws From the Posterior Distribution of the Model Parameters

		CISS model	FSI EA model	FSI PCA model	VIX model
σ_ind	Regime 1	0.060	0.206	0.193	0.082
	Regime 2	0.116	0.501	0.399	0.213
	Regime 3	0.251			0.574
σ_czk	Regime 1	0.268	0.245	0.251	0.230
	Regime 2	0.219	0.457	0.500	0.296
	Regime 3	0.553			0.650
corr(czk,ind)	Regime 1	0.055	-0.067	-0.092	0.040
	Regime 2	0.034	-0.079	-0.112	-0.105
	Regime 3	0.027			-0.096
Expected duration	Regime 1	12.57	28.59	31.02	7.08
	Regime 2	12.37	11.91	8.62	10.43
	Regime 3	9.01			7.60
Transition matrix	p_11	0.920	0.965	0.968	0.859
	p_12	0.061	0.035	0.032	0.130
	p_13	0.018			0.011
	p_21	0.037	0.084	0.116	0.076
	p_22	0.919	0.916	0.884	0.904
	p_23	0.044			0.020
	p_31	0.016			0.019
	p_32	0.095			0.113
	p_33	0.889			0.869

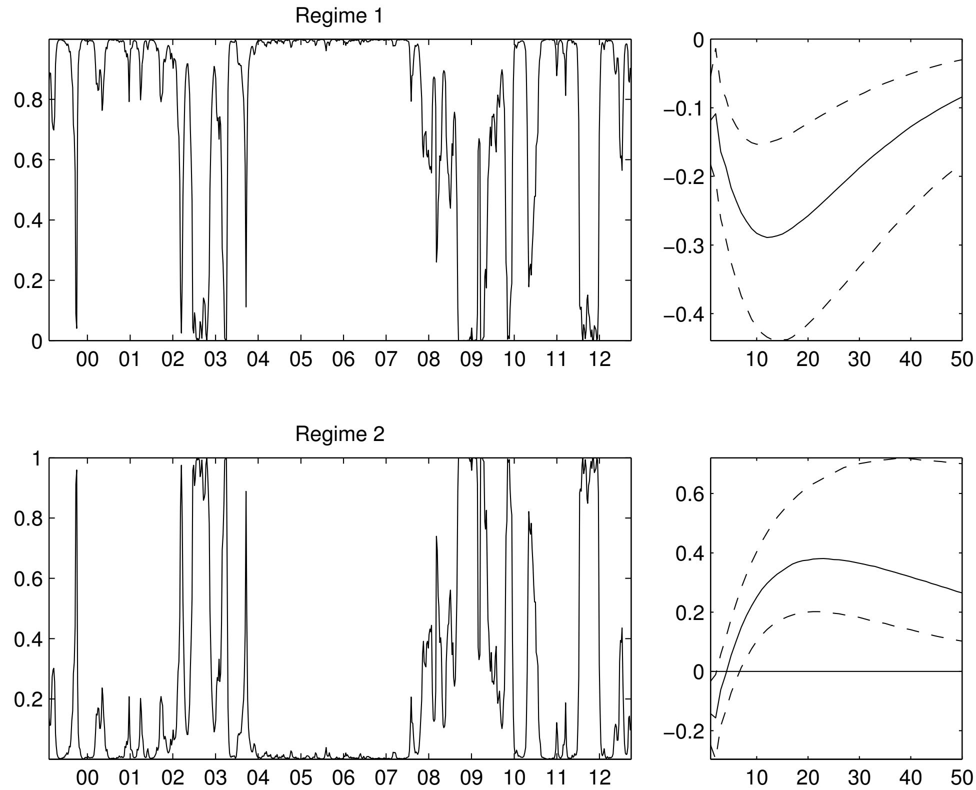
Figure 6: Results: Estimated Probabilities of Regimes and Responses of the CZK/EUR Rate to a one s.d. Shock to a Financial Stress Index (Higher Values Mean Depreciation of the Koruna)



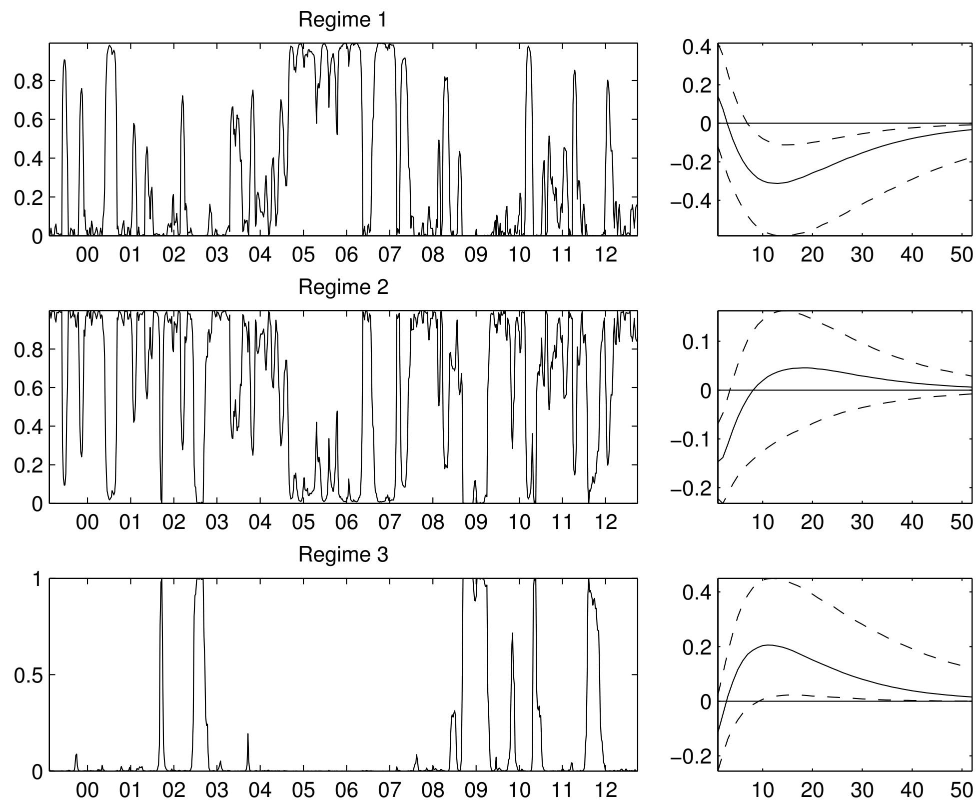
(a) CISS model



(b) FSI EA model



(c) FSI PCA model



(d) VIX model

Regime 1 was identified roughly in the periods between 1999 and 2000 and between 2004 and 2005, that is, in periods of steady appreciation with no large deviations from the trend. The response of the koruna to (systemic) financial stress shocks appears to be a marginally significant depreciation on average, with a peak after about five weeks, after which the impact dies out.

The same depreciation effect, albeit much larger and more significant and persistent, appears in Regime 3. This regime corresponds to periods of high (systemic) financial stress in the euro area stemming from two sources: the U.S. subprime crisis in 2008 and 2009 and the euro area debt crisis after mid-2011. These periods were marked by a sudden withdrawal of funds from emerging economies as a result of financial market tensions, liquidity strains, and increased risk aversion. This result is in line with the findings from the literature, i.e., funds start to be withdrawn from emerging countries following a panic in financial markets. The risk profile of investors changed sharply, which caused a shift in demand toward safe assets and depreciation of the Czech currency.

In contrast to these two regimes, Regime 2 is characterized by appreciation of the Czech currency vis-à-vis the euro in response to shocks to (systemic) financial stress in the eurozone. This intermediate regime is the most prevalent and covers long periods between 2001 and 2003, as well as the pre-crisis period and the period between 2010 and early 2011, before the sovereign debt crisis intensified. In these periods, as our theoretical motivation suggests, diversification motives drove the inflow of funds into Czech assets. This behavior (which is at odds with previous literature, but in line with the "diversification" regime suggested in the theoretical part) of emerging market currencies in periods of slightly elevated stress is called the "local safe haven effect" by financial practitioners. The actual response of the currency also depends on pull factors determined by fundamental developments in the domestic economy. In this view, the stable macroeconomic environment in the Czech Republic, including sound fiscal and credible monetary policy, certainly contributed positively to this effect.

In the FSI EA model, only two regimes were identified (see Figure 6b), i.e., the third regime was identified for a low number of periods, which was insufficient for estimating the parameters in each regime. In the first regime the Czech koruna appreciates as the euro area FSI increases, while in the second regime it depreciates. This corresponds to the second and third regimes found in the estimation with the CISS. If we compare the periods with the highest variance for the CISS and the FSI (Regime 3 in the case of the CISS and Regime 2 in the case of the FSI), in both cases there is a high probability of this regime during the 2008/2009 financial and sovereign debt crisis. In contrast, there is far lower correspondence between the models during 2002–2003.

4.3.2 Results: Global Financial Stress Measures

The global nature of financial stress, which we discussed above, raises the natural question of whether a broader indicator could be a better measure of financial stress relevant to movements of the exchange rate. Figure 5c reports the outcomes of the FSI PCA model. The estimation with the PCA measure yields only two regimes, characterized again by both an appreciation and depreciation effect on the Czech koruna. Interestingly, the number of regimes and impulse responses identified are comparable to the FSI model. Similarly to the previous case, there is also uncertainty about the actual response to a one s.d. shock to financial stress, this time more in Regime 2.

In contrast to the FSI PCA model, the results for the VIX model are slightly different from those described in the previous section. They indicate three regimes as in the case of the CISS (Figure 5d). In the first regime the koruna responds to a VIX shock by appreciating and in the two remaining regimes by depreciating. However in Regime 2, the depreciation effect seems to be weak (almost insignificant). This may be a direct consequence of the fact that the VIX measures stress in U.S. markets while the dependent variable is the CZK-EUR exchange rate, without controlling for the USD-EUR exchange rate.

Overall, the results provide supportive evidence for our theoretical motivation. The emerging market currency can have different responses to increased stress based on actual financial market conditions. When the financial stress to the euro intensifies, low risk aversion leads to an increase in diversification motives and currency appreciation. A panic on financial markets causes risk aversion to increase, leading to capital withdrawals and depreciation of emerging market currencies.

Unfortunately, we are not able to select the best model, as this exercise would require us to choose an optimization criterion, such as the MSE. This, however, could be misleading due to the nature of stress indices, which are constructed arbitrarily. Major differences arise between the models for a number of regimes (CISS versus FSI EA). The estimations with the CISS show the presence of one more regime with a depreciation response to a financial stress shock (Regime 1).

In our view, these differences can be attributed to the construction of the two indices. While the CISS incorporates volatility measures directly, the FSI relies on spread and conditional volatility measures only. Moreover, the CISS reflects whether stress occurred on multiple markets simultaneously and hence it is our preferred indicator. Eventually, Regime 1 for the CISS corresponds to periods when the markets are particularly calm and the systemic stress measured by the CISS is lower than the financial stress as approximated by the FSI.

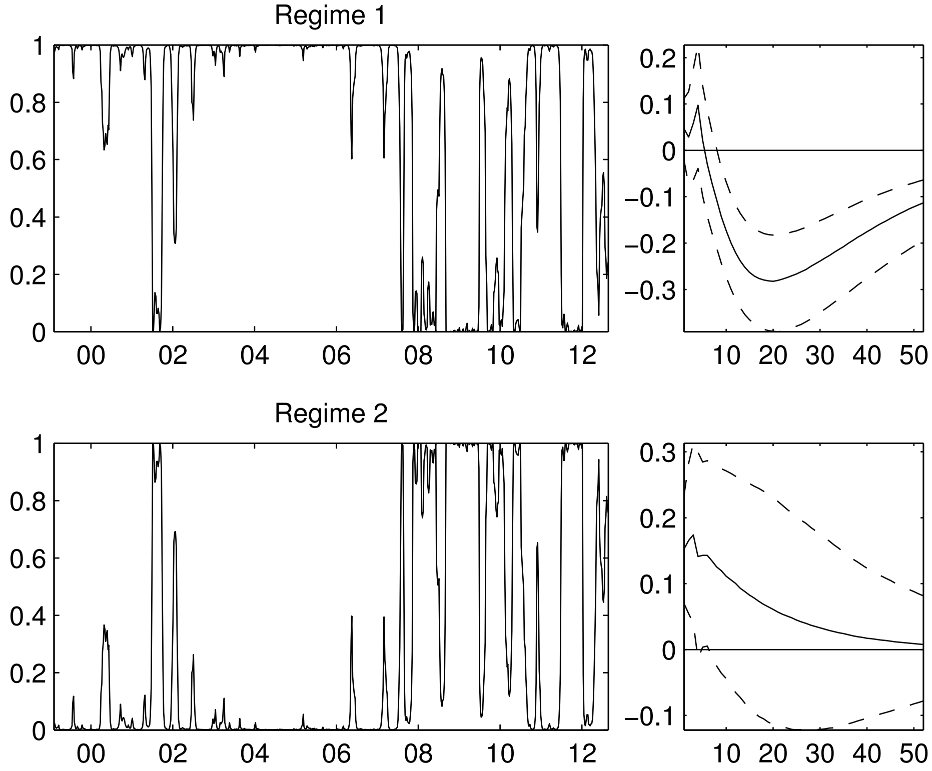
5. Extension: the Polish Zloty and the Hungarian Forint

We perform a similar analysis using two other exchange rates in the CEE region: the Polish zloty and the Hungarian forint. Our main focus is on the Czech koruna, so the analysis here is less comprehensive and we do not report diagnostics either. As a measure of financial conditions in the euro area we use only the CISS (systemic) stress indicator. The estimated regime probabilities and impulse responses are plotted in Figure 7. As in the previous section, the response in the figure represents the reaction of the exchange rate to a one standard deviation shock to the stress indicator (where a downward movement means appreciation of the exchange rate).

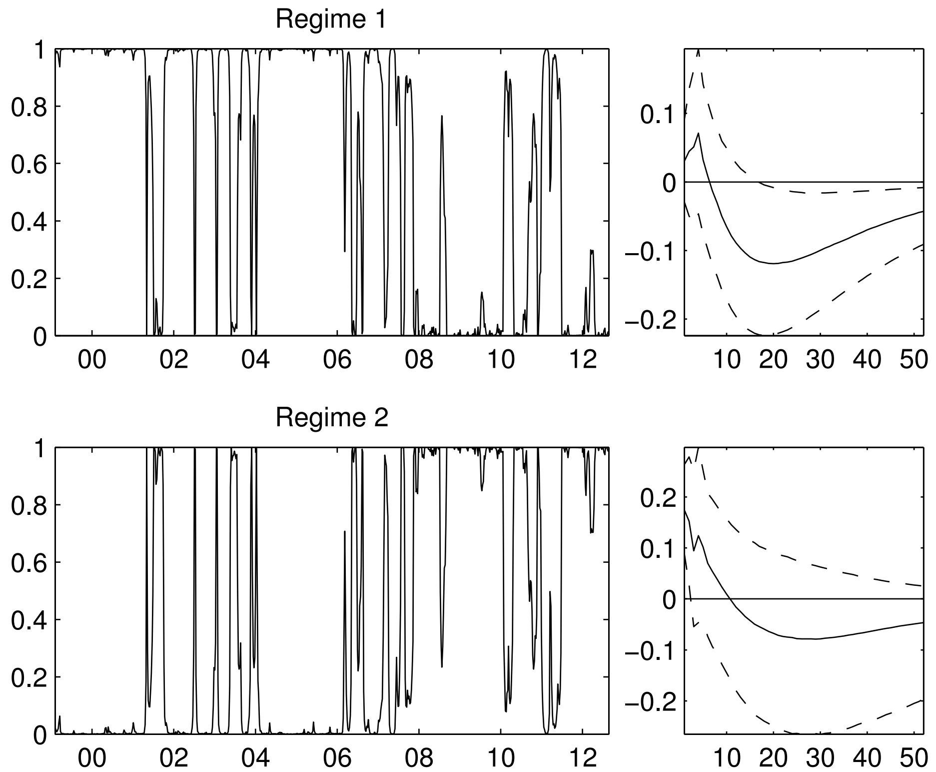
Looking at the Polish zloty, we again identify two regimes with different reactions of the currency to a (systemic) financial stress shock. In the first regime, the currency significantly appreciates, peaking after about 20 weeks, although a marginal and insignificant depreciation occurs first. As in the case of the Czech koruna we find some evidence of a "local safe haven" effect. In the second regime, the Polish zloty depreciates in response to the same shock, albeit insignificantly. The periods identified as Regime 2 correspond broadly to periods of substantial market tensions, including the U.S. subprime crisis in 2008 and 2009, as well as the euro area debt crisis after mid-2011. The insignificant reaction of the currency may be due to foreign exchange interventions. Unfortunately, we do not have data on official currency interventions, but anecdotal evidence (Mohanty et al., 2013) as well as comments in the press suggest that this may be the case. It seems that the authorities intervened during the peak of the financial and sovereign debt crisis to stem currency depreciation, mainly due to a high level of debt denominated in foreign currency.

The results for the Hungarian forint are broadly similar but less convincing. In Regime 1, the currency appreciates weakly in response to a financial stress shock, while the depreciation in the second regime is not significant. It seems that financial conditions in the euro area have only a limited impact on the Hungarian currency. This may again be due to intervention policy as well as to structural problems of the economy (including foreign currency loans on a far larger scale than in the case of Poland). The country even experienced a currency crisis in 2008–2009 (Dapontas, 2009) that required international financial assistance. On the other hand, the Czech National Bank intervened only once in 2002, for a short period of time to lower market volatility.

Figure 7: Extension: Responses of Two Other CEE Countries



(a) Responses of the zloty/euro exchange rate



(b) Responses of the forint/euro exchange rate

6. Conclusion

In this paper, we analyzed how changes in financial stress on the euro area or global level can affect the CZK/EUR exchange rate, conditionally on different degrees of risk aversion. Using a highly stylized model of portfolio allocation, we showed that an increase in uncertainty can cause the koruna either to appreciate (in the “diversification" regime) or to depreciate (in the “flight to safety" regime). A regime switch may occur as a result of an increase in risk aversion or because of a risk-related change in portfolio management strategy.

Estimations with the Markov-switching VAR model identified up to three regimes using real data. In addition to the “diversification" and “flight to safety" regimes, the data suggest the presence of a “calm" regime where the reaction of the exchange rate to financial stress is less significant. An increase in financial stress in the “diversification" regime leads to appreciation of the koruna due to diversification motives. A substantial further increase in financial stress coupled with increased risk aversion (a risk-off period) can cause a switch to the “flight to safety" regime and lead the Czech currency to depreciate. Compared to our estimates for the Czech koruna the effect of changing financial conditions on the Polish and Hungarian currencies is smaller and sometimes even insignificant. We suspect that intervention policies may have influenced the results. Still, even in these two cases there is some supportive evidence of regime switching in exchange rate behavior.

The movements of the Czech currency seem to be driven to a large extent by swings in euro area financial conditions, which poses new challenges to policy makers. With financial integration, markets are becoming increasingly interconnected and shocks can be amplified by spillovers in periods of elevated stress. Exchange rate dynamics can therefore be driven chiefly by external factors, rather than reflecting domestic macroeconomic fundamentals. This paper thus sketches a potential avenue for future research: the questions to be answered include issues of incorporating financial stress indicators into exchange rate forecasting and into practical monetary policy decision making.

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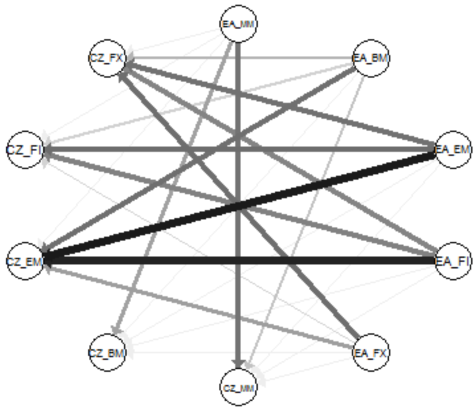
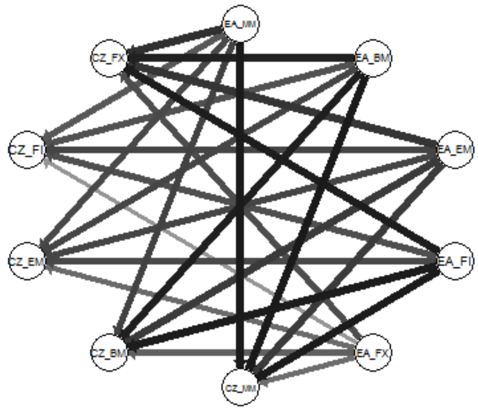
Appendix A: Spillovers Between The Czech And Euro Area Financial Markets

To illustrate the complexity and dynamics of financial stress transmission between financially interconnected economies such as the Czech Republic and the euro area, we show a network graph of the linkages and volatility spillovers not only between the two economies, but also between the individual segments of their financial markets. Figure A.1 shows the strength of transmission as measured by the quarterly averages of the time-varying correlations (computed using the exponentially weighted moving average estimator) between the Czech and euro area financial markets as estimated in Adam and Benecká (2013). In the tranquil period (2006 Q1) the strongest links were observed between the equity markets (EM), while the spillovers in other markets intensified during the first quarter of 2009, when they were present across the entire financial system. The sovereign debt crisis, on the other hand, led to increased spillovers between financial intermediaries in the euro area and the Czech Republic and to a certain extent between bond and money markets.

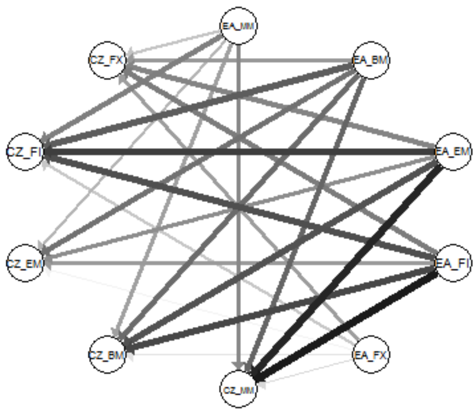
Figure A.1: The Transmission of Financial Stress Among Financial Markets in the Czech Republic and the Euro Area



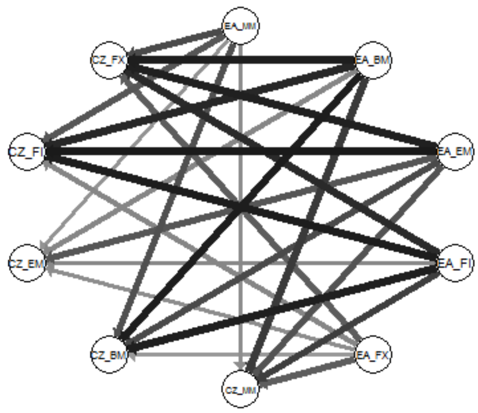
(a) 2006 Q1



(b) 2009 Q1



(c) 2010 Q1



(d) 2011 Q4

Note: The strength of a line represents the degree of correlation between sub-indices in the markets (mm = money market, em = equity market, fi = financial intermediaries, bm = bond market, fx = foreign exchange market).

Appendix B: Setting the Priors and Gibbs Sampling

B.1 Priors

We want to produce results that are as independent of our priors as possible, so we set most of the priors as non-informative. The only block of parameters which we set as informative is the block regarding the regression parameters, matrices B_S. All the priors are described subsequently.

B.1.1 VAR Regression Coefficients: B_S, Σ_S

For the coefficients in the VAR models in each regime, we specify relatively standard priors. Also, since we do not want to make any specific assumptions regarding the regimes, we assume the same priors for each regime.

We assume an independent normal-inverse-Wishart prior for the VAR coefficients. The VAR coefficients B_S ($S \in \{1,...N\}$) have Minnesota prior form as described in Bańbura et al. (2009), for example. Therefore, we assume the following prior $B_{S_t} \sim N(\underline{B}, \underline{V_B})$:

$$(\underline{B}_k)_{ij} = \begin{cases} b_i, & \text{if } i = j, k = 1 \\ 0 & \text{otherwise} \end{cases} \tag{B.1}$$

$$V_{(\underline{B}_k)_{ij}} = \begin{cases} \left(\frac{\lambda_1}{k^{\lambda_3}}\right)^2, & \text{if } i = j \\ \left(\frac{\sigma_i \lambda_1 \lambda_2}{\sigma_j k^{\lambda_3}}\right)^2 & \text{otherwise} \end{cases} \tag{B.2}$$

$$\mu_S \sim N(0, c) \tag{B.3}$$

The AR coefficients are set very close to one (the priors are estimated using univariate AR(1) regression), which is a very plausible prior for exchange rates and also stress indicators. The prior covariances between the regression parameters were set to zero, which is common practice. The variances are assumed to be distributed according to the inverse-Wishart distribution with scale matrix $\underline{S}$ and prior degrees of freedom $\underline{T}$ (in our case, $\underline{S}^{-1} = 0$ and $\underline{T} = 0$, which is a non-informative prior as described in Koop and Korobilis (2010)):

$$\Sigma_S^{-1} \sim W(\underline{S}^{-1}, \underline{T}) \tag{B.4}$$

In addition, as we have a prior belief that shocks to the Czech koruna do not affect the level of stress in the eurozone (and thus the value of stress indices), we incorporate a tight prior on the parameters reflecting the effect of the exchange rate on the stress index: $b_{ik} \sim N(0, c)$ (where i is the equation for the stress index and k indicates all parameters pertaining to the lagged exchange rate values), where c is a very small constant.

The number of lags in the VAR model in each regime was chosen using the information criteria in the frequentist VAR model. Although a more rigorous way would be to select the number of lags using the marginal likelihood, we opted for the approach based on the information criteria due to its simplicity. In addition, changing the number of lags does not change the results dramatically.

As for the prior hyperparameters on the B coefficients in each VAR model, we chose the ones suggested in Canova (2007) (which are very loose in our case). The prior on the constants in the VAR model is also set as very loose ($c = 10,000$).

Finally, one more prior assumption was imposed to alleviate the so-called label switching (identification) problem (Frühwirth-Schnatter, 2006), which Markov-switching models suffer from when the priors are symmetric, as in our case. A possible solution is to assume a ranking of some coefficients across regimes and order the draws accordingly (as applied in Billio et al. (2013), for example). A plausible way to choose such a ranking is to order the regimes according to the variance of some shocks. This is the solution we chose. In our case, we assume that $\sigma_{ind,1} < \sigma_{ind,2} < \sigma_{ind,3}$, that is, the reduced-form shocks to financial stress indicators have the lowest volatility in Regime 1 and the highest volatility in Regime 3.

B.1.2 Priors on Transition Matrix P

In the case where the state variable has two states, we follow Kim and Nelson (1999) and assume a beta prior on the diagonal elements of the transition matrix (due to the adding-up property, one needs to impose only one prior in each row of the transition matrix). Specifically, $p_{ij} \sim \text{beta}(u_{ij}, \bar{u}_{ij})$. We opt for a non-informative version of the prior beta(0.5,0.5). In the case of three regimes, we assume a non-informative Dirichlet distribution prior (which is an extension of the beta distribution to multivariate random variables) for each row of the transition matrix: $p_i \sim Dir(0.5, 0.5, 0.5)$.

B.1.3 Priors on State Variable S_t

Similarly to the algorithm by Carter and Kohn (1994), it can be shown that due to the Markov property, all posterior distributions of S_t depend on S_0 (Kim and Nelson, 1999). Since we draw the parameters conditionally on other parameters, we assume an ergodic solution for the initial S_t for a given draw of transition matrix P.

B.2 Gibbs Sampling

Since no analytical solution of the model exists, we employ the Gibbs sampling algorithm to draw samples from the joint posterior distribution of the parameters:

$$\Theta = \left\{B_S, \Sigma_S, S_t, t\left\{\in 1, \ldots, T\right\}, p_{ij}, i, j\left\{\in 1, \ldots, N\right\}\right\} \tag{B.5}$$

We can draw from the conditional distributions of each block of parameters, which, after a sufficient number of iterations, converges to draws from the joint posterior distribution. The steps are similar to those sketched in Krolzig (1997):

1. Filtering and smoothing step: draw indicators of state (regime) S_t for each t. This is done using multi-move sampling, which first employs the Hamilton filter to obtain the posterior distribution of the state variable at time T and then samples backward states at each time t given a draw at $t+1$. This procedure is in principle very akin to the Carter and Kohn algorithm in linear state-space models (Carter and Kohn, 1994).

2. Hidden Markov chain step: draw the elements of transition matrix P from the posterior beta (Dirichlet) distribution as in Kim and Nelson (1999).

3. Regression step: given the draws of the state variable, the whole sample can be split into N sub-samples. For each sub-sample, parameter B_s can be drawn from the same conditional posterior distribution (multivariate normal) as in the standard Bayesian VAR model, e.g. Koop and Korobilis (2010).

4. Similarly to the previous step, covariance matrices can be drawn for each sub-sample from its conditional posterior distribution, which is from the inverse-Wishart family.

5. Draw impulse response functions: given the draws of B and Σ, we draw impulse response functions identified using recursive identification (where we assume that the shock to stress comes first, so the shock from the koruna does not affect it contemporaneously).

We iterated this procedure 80,000 times, threw out the first 50,000 draws as a burn-in sample, and retained every 3rd draw of the remaining draws. Thus the posterior quantiles were taken from 10,000 samples from the marginal distribution functions.

Appendix C: Convergence Diagnostics

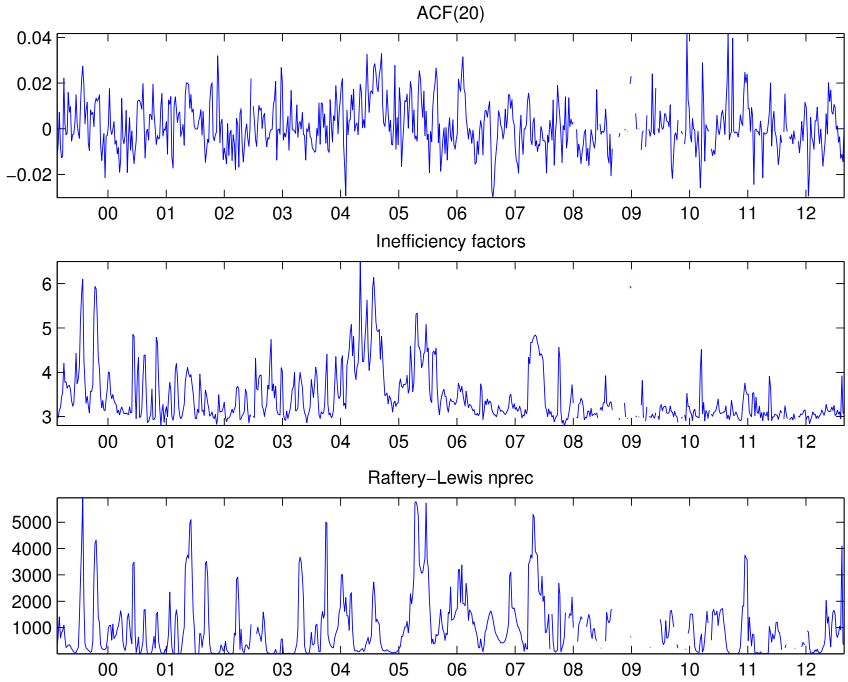
To assess the convergence of Markov chains simulated using the Gibbs sampler, we use several measures commonly employed in the literature. First, the low autocorrelation coefficients of each of the parameters drawn indicate that the Gibbs sampler draws the parameters efficiently. Therefore, we present the following two measures: the autocorrelation coefficient at lag 20 (which should be small because the autocorrelation coefficients of efficiently drawn samples die out quickly) and the inefficiency factors, defined as $IF = 1 + 2\sum_{k=1}^{\infty} \rho_k$, where ρ_k is the autocorrelation coefficient of a Markov chain at lag k. Primiceri (2005) suggests that values of the inefficiency factor above 20 would indicate problems with convergence.

Besides these two autocorrelation measures, we use Raftery-Lewis statistics (Raftery and Lewis, 1992), which suggest how many draws one needs to achieve a given precision of estimates of a given quantile of a statistic. We use two sets of parameters, as LeSage (1998) suggests – one for the draws of the parameters of S_t and the elements of the transition matrices ($p = 0.95, q = 0.025, r = 0.025$), which are characterized by short tails, and the other for the remaining parameters ($p = 0.025, q = 0.01, r = 0.95$).

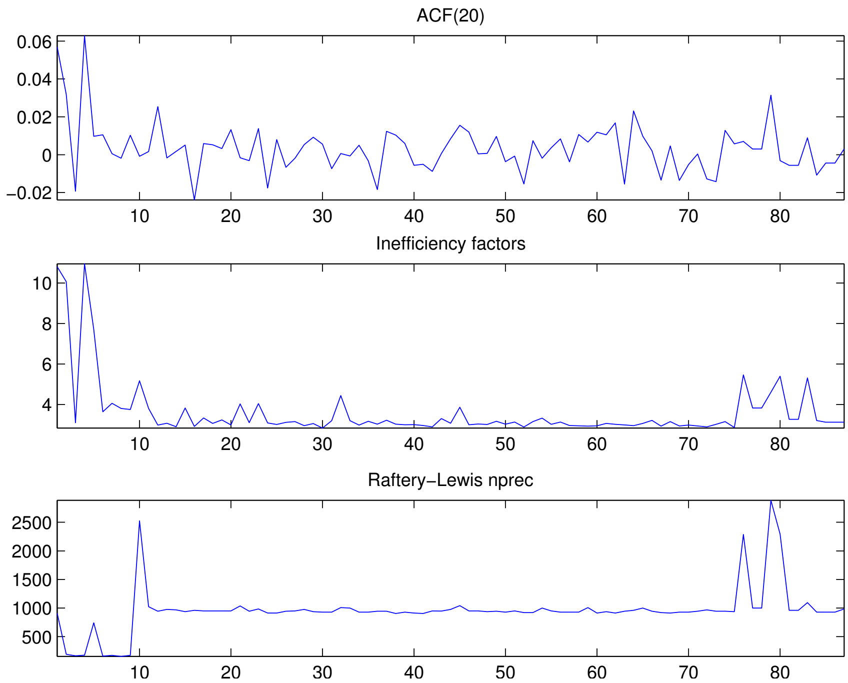
Finally, we examine potential pathologies in the histograms of the posterior draws. For illustration, we include the histograms of the elements of the transition matrices.

The convergence diagnostics do not indicate problems with convergence in any of the models considered. Nevertheless, it should be noted why the elements in S_t are not plotted for some t. This is because after the burn-in period, which was chosen as very long (50,000 draws), the probabilities of some regimes were estimated as 1 for some periods, which means that S_t is constant across draws for each of these periods. As a result, neither the autocorrelation coefficients nor the Raftery-Lewis statistics can be calculated.

Figure C.1: Convergence Diagnostics, the CISS Model: Autocorrelation at Lag 20, the Inefficiency Factor, and the Minimum Number of Runs Suggested by Raftery-Lewis Statistics

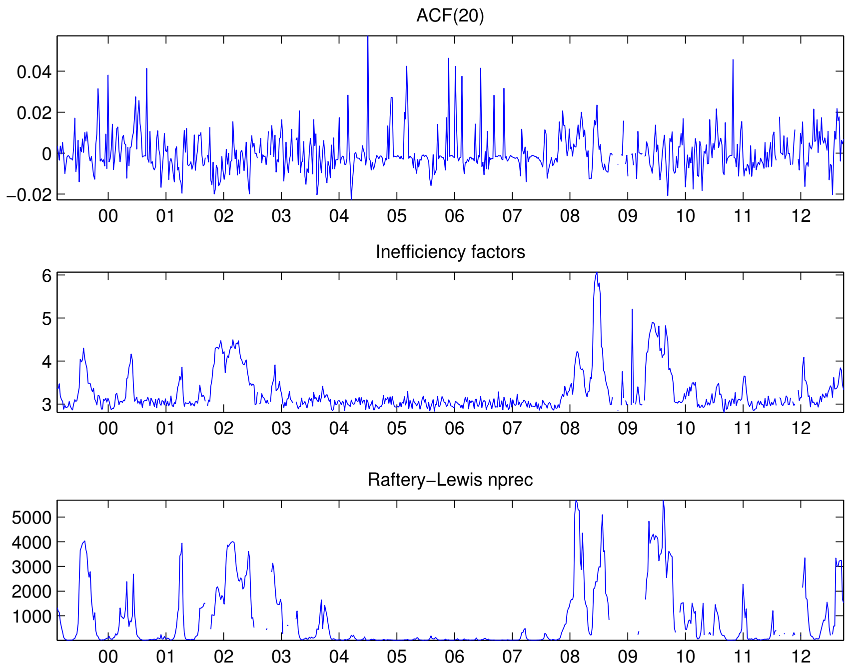


(a) State indicator variable (S_t)

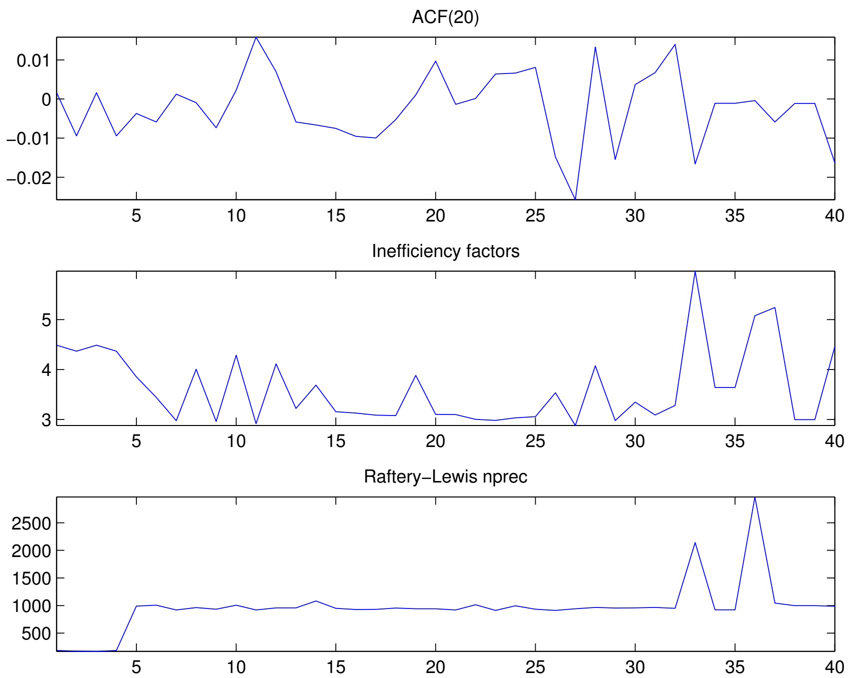


(b) Other variables: B_S, Σ_S, $S = 1,2,3$, P

Figure C.2: Convergence Diagnostics, the FSI EA Model: Autocorrelation at Lag 20, the Inefficiency Factor, and the Minimum Number of Runs Suggested by Raftery-Lewis Statistics

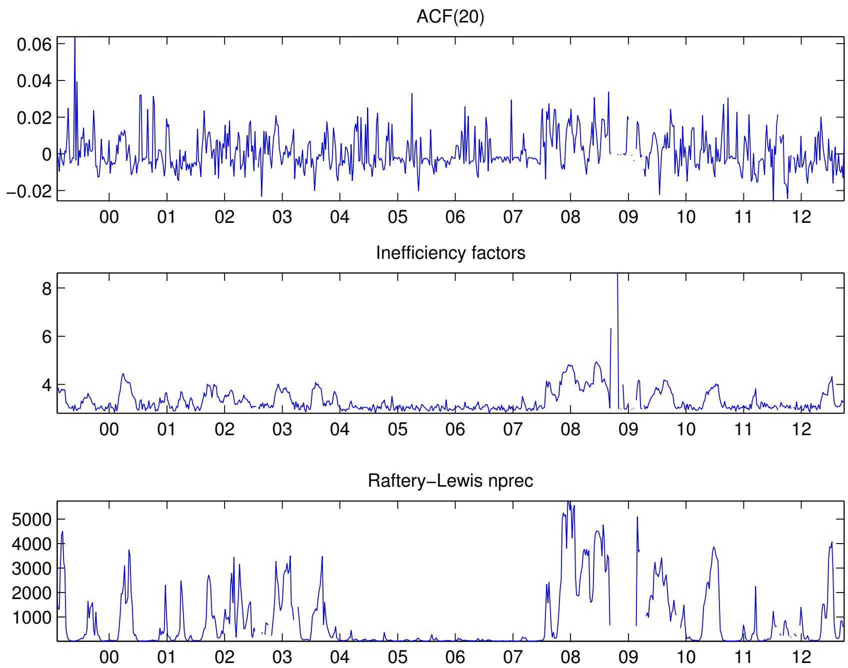


(a) State indicator variable (S_t)

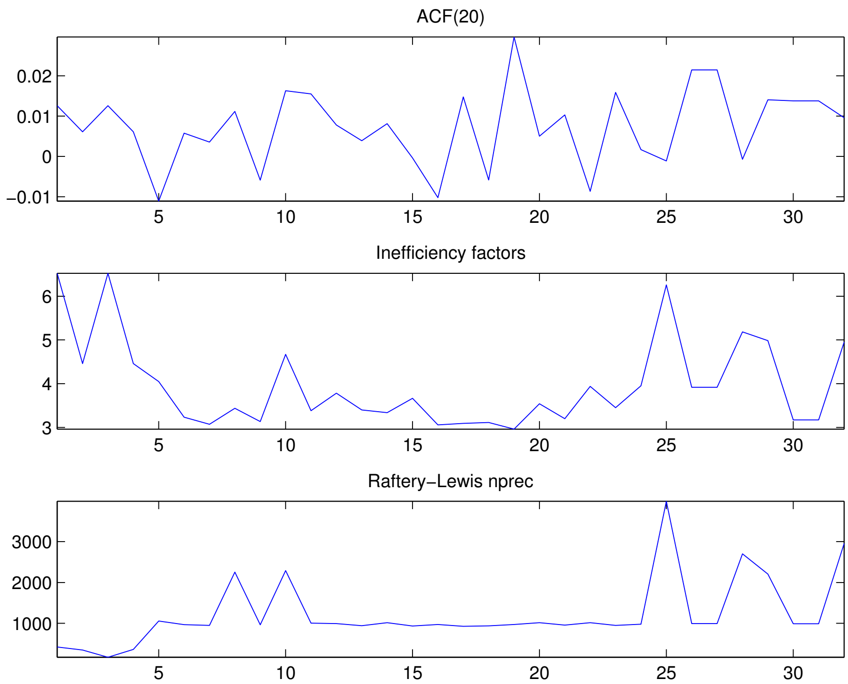


(b) Other variables: B_S, Σ_S, $S = 1, 2$, P

Figure C.3: Convergence Diagnostics, the FSI PCA Model: Autocorrelation at Lag 20, the Inefficiency Factor, and the Minimum Number of Runs Suggested by Raftery-Lewis Statistics

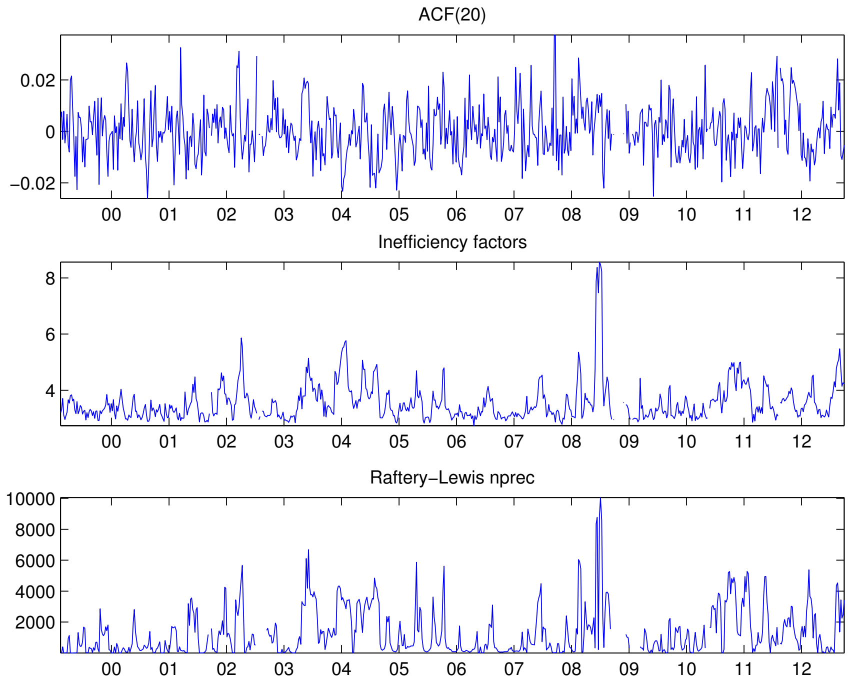


(a) State indicator variable (S_t)

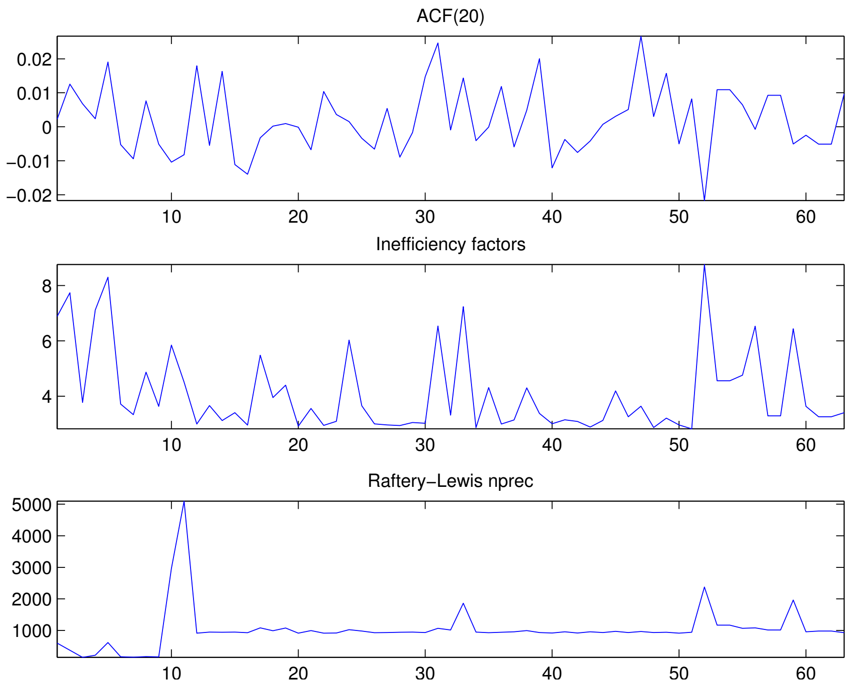


(b) Other variables: B_S, Σ_S, $S = 1, 2$, P

Figure C.4: Convergence Diagnostics, the VIX Model: Autocorrelation at Lag 20, the Inefficiency Factor, and the Minimum Number of Runs Suggested by Raftery-Lewis Statistics

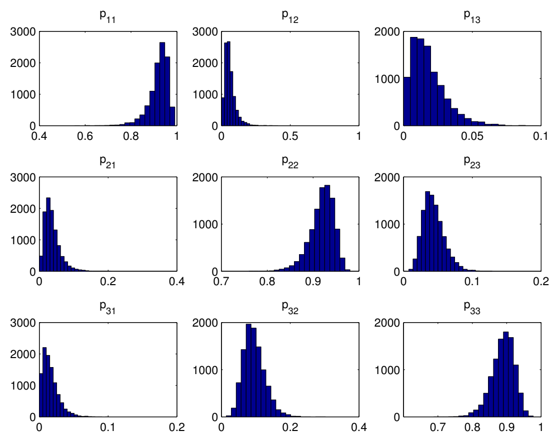


(a) State indicator variable (S_t)

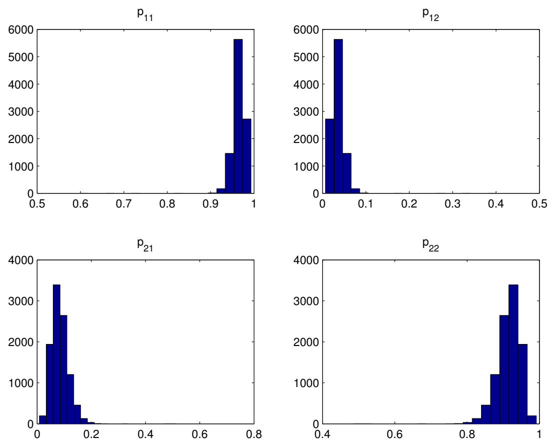


(b) Other variables: B_S, Σ_S, $S = 1,2,3$, P

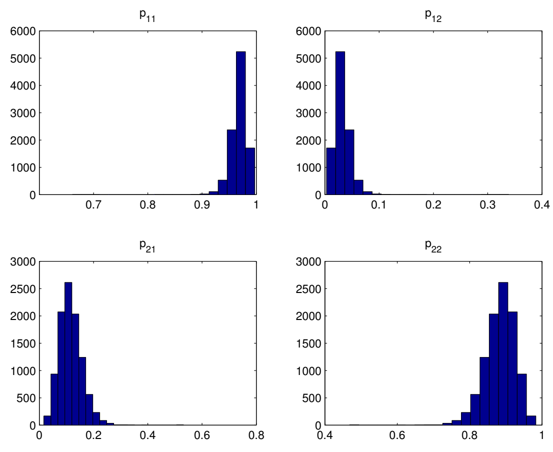
Figure C.5: Histograms of Draws from the Posterior Marginal Distribution of the Transition Matrix Elements. p_{ij} Stands for the Probability of Transition from State i to State j



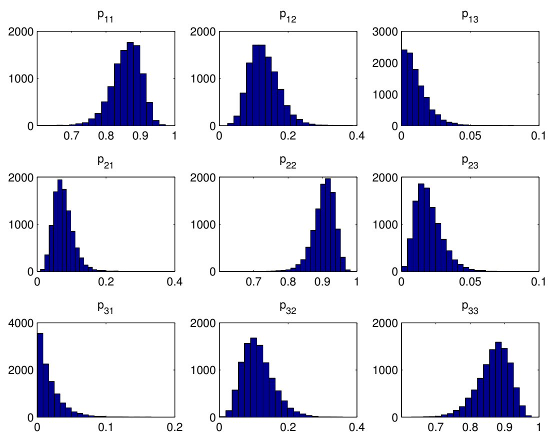
(a) CISS model



(b) FSI EA model



(c) FSI PCA model



(d) VIX model

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