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**Exchange rate pass-through to various price  
indices: empirical estimation using vector error  
correction models**

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**DISCUSSION PAPERS**

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# Exchange rate pass-through to various price indices: empirical estimation using vector error correction models

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## Abstract

The extent to which exchange rate fluctuations are passed through to domestic prices is of high relevance for open economies and for monetary authorities targeting price stability. Existing empirical studies estimating the exchange rate pass-through for Switzerland are based on either single equation estimation or on VAR models. However, these approaches feature some major drawbacks. The former cannot account for dynamic interactions between the time series and both methods disregard long-run equilibrium relations between the variable levels. This paper contributes to the evidence on the exchange rate pass-through in Switzerland by using a vector error correction model, which has the advantage of incorporating both short-run dynamics and long-run equilibrium relations among variables. The results reveal a significant impact of exchange rate shocks on various price (sub-)indices. Pass-through to import prices is substantial both in the short-run and in the long-run and occurs relatively quickly. It is slower, but still considerable in the long-run for the consumer price index and some of its sub-indices. Producer prices react significantly to exchange rate shocks as well. In contrast, consumer price inflation for services and for goods of domestic origin show hardly any significant response. The findings of this paper indicate a decline in the pass-through over time.

*JEL classification:* E31, F31, F41

*Keywords:* Exchange rate pass-through, consumer prices, import prices, cointegration, vector error correction models, new open economy macroeconomic model

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# 1 Introduction

Exchange rates are of crucial importance for open economies. Due to their impact on the relative prices between domestic and foreign goods, exchange rates affect the demand for these goods. As a consequence, both aggregate production and price levels of an open economy depend on exchange rates. The influence of exchange rates on domestic prices has long been of interest in the international macroeconomics literature because it matters for the international transmission of shocks and international policy spillovers. The extent to which prices change in response to exchange rate fluctuations, henceforth referred to as exchange rate pass-through (ERPT), is of particular importance for monetary policy. Central banks aiming at stabilizing prices need to know about the inflationary effect of exchange rate movements. This knowledge is essential for both their inflation forecasts and the monetary transmission mechanism. In recent years, there has been extensive research, theoretical as well as empirical, on the determinants, the dynamics and the extent of the ERPT. The massive exchange rate fluctuations in the aftermath of the recent financial crisis and international debt crisis have reinforced the interest in the ERPT.

Theoretical papers have revealed a variety of factors influencing the ERPT, such as international price discrimination (Krugman, 1986), openness of an economy, degree of competition (Dornbusch, 1987), transportation and distribution costs (Burstein et al., 2003a,b, 2005; Corsetti and Dedola, 2005), the currency pricing decision (Bacchetta and van Wincoop, 2005) in combination with the degree of price stickiness, stability of monetary policy (Devereux and Engel, 2001; Devereux et al., 2004), the perceived persistence of exchange rate movements (Froot and Klemperer, 1989; Taylor, 2000), and exchange rate volatility (Corsetti and Pesenti, 2004). Thus, the ERPT to prices has been recognized as an important and complex transmission mechanism.

Given this variety of country-specific factors that affect the pass-through, empirical estimations for one country do not apply to other countries. Instead, separate estimations have to be conducted for different countries. Based on the methods applied, the empirical papers can be classified into three groups: studies based on single equation models, vector autoregressive (VAR) models and cointegration analysis (including vector error correction (VEC) models).

In single equation models, a price or inflation measure is regressed on the exchange rate and further explanatory variables (see Menon, 1995, for a survey of early contributions; more recent examples of studies applying this method are Gagnon and Ihrig, 2004, and Campa and Goldberg, 2005). The findings of these papers show substantial variation in the estimated degree of ERPT across countries.

Many studies based on VAR models (e.g. McCarthy, 2000; Hahn, 2003; Choudhri et al., 2005; Cavaliere, 2007) find evidence for significant ERPT to import prices and limited pass-through to producer and consumer prices. Moreover, the results indicate

that the magnitude of the ERPT and the speed of price adjustments decrease along the distribution chain.

Evidence on the ERPT based on the analysis of cointegrating relations or VEC models is rather scarce. Both Kim (1998) and Billmeier and Bonato (2004) find a relatively small long-run impact of exchange rates on price levels. In contrast, the findings of Masten (2004), who analyzes depreciation and inflation rates instead of exchange rates and price levels, suggest a high ERPT.

For Switzerland, evidence on the ERPT indicates a decreasing degree of pass-through along the distribution chain. Import prices react more quickly and to a larger extent to exchange rate shocks than consumer prices. The estimated degree of pass-through varies substantially between studies. The evidence for Switzerland is based on both single equation models (Gagnon and Ihrig, 2004; Campa and Goldberg, 2005) and VAR models (McCarthy, 2000; Cavaliere, 2007; Stulz, 2007).

However, the ERPT to Swiss prices has not yet been analyzed in the framework of a VEC model. Moreover, evidence on the ERPT using VEC models is in general scarce, despite the advantages of this estimation method. In particular, VEC models feature the advantage of incorporating both short-run dynamic interactions between the variables and long-run equilibrium relations contained in the variable levels. Since both the dynamics and the short- and long-run degree of ERPT are of interest, VEC models appear to be appropriate for estimating the ERPT.

Many studies on the ERPT have restricted their analysis to the impact of exchange rate shocks on aggregate price indices such as the import or consumer price index. However, a better understanding of the complex ERPT mechanism might be achieved by additionally estimating the pass-through to various price sub-indices, such as consumer price sub-indices for imported goods, for domestically produced goods or for services. Up to now, little research has been devoted to the ERPT to price sub-indices.

This master thesis estimates the ERPT to various price (sub-)indices for Switzerland. The purpose of the paper is twofold. Firstly, it contributes to the existing evidence on the ERPT by using a more complex and more appropriate model for estimation, namely a VEC model. Based on the estimated VEC models, this master thesis analyzes the degree of pass-through (both in the short- and in the long-run) as well as the dynamics of the price adjustments over time. Secondly, by estimating the ERPT to prices for specific categories of goods, this paper aims to shed some more light on the complex transmission mechanism from exchange rates to prices. The estimated responses of price sub-indices to exchange rate shocks may promote the understanding of the determinants, the degree and the dynamics of the ERPT to the aggregate consumer price index.

The results of this master thesis reveal a significant impact of exchange rate shocks on aggregate import, producer and consumer price indices. In the short-run, the ERPT decreases along the distribution chain: The pass-through is much higher for import prices

than for producer and consumer prices. Moreover, the ERPT to import and producer prices occurs more quickly than the pass-through to overall consumer prices. The analysis of the price adjustment dynamics shows that, with some lag, the response of import prices to exchange rate shocks resembles the response of the exchange rates. In contrast, producer and consumer prices mostly converge steadily to their new long-run values. The comparison of the long-run price adjustment due to exchange rate shocks to the long-run change in exchange rates shows substantial pass-through to import, producer and consumer prices. However, the long-run pass-through estimates are very imprecise. Therefore, the findings for the long-run need to be interpreted with care. Nevertheless, some long-run ERPT estimates are significantly different from zero, indicating that exchange rate shocks have a considerable long-run impact on import and consumer prices. Thus, the ERPT is important for any institution that forecasts inflation, in particular for central banks. Overall, the findings of this thesis are consistent with previous ERPT estimates for Switzerland.

In addition, the results of this paper show that pass-through varies considerably between different consumer price sub-indices. Consumer price inflation both for services and for goods of domestic origin show hardly any significant response to exchange rate shocks, whereas the consumer price sub-indices for goods and for goods of foreign origin react significantly. An analysis of several subsamples indicates that the ERPT has declined over time for all price (sub-)indices. Robustness checks show that many results of the VEC models are rather similar to results obtained from a VAR model, but that the VAR model tends to find somewhat lower pass-through estimates to many price indices.

The remainder of this paper is structured as follows. Section 2 reviews theoretical and empirical literature on the ERPT. A theoretical model of the ERPT in a framework of international strategic price setting and the implications of the theoretical analysis are presented in section 3. Section 4 describes the methodology, the model and the identification strategy used for the empirical analysis. Section 5 contains the description of the data. In section 6, the estimation and the empirical results are presented. Some comparisons and robustness checks are discussed in section 7. Section 8 concludes.

## **2 Literature review**

### **2.1 Theoretical literature**

This section contains an overview of theoretical papers about the ERPT to prices. Subsection 2.1.1 briefly introduces two basic economic relations between exchange rates and prices. The main focus of this section is on the importance of strategic price setting and imperfect competition for the ERPT (subsection 2.1.2). Other branches of the literature are briefly reviewed in subsection 2.1.3.

### 2.1.1 Purchasing power parity and the law of one price

A fundamental relation between exchange rates and prices is given by the purchasing power parity (PPP), which states that once converted to a common currency, national price levels should be equal. International arbitrage is the main justification why this relation should hold. The same relation on a more disaggregated level is called the law of one price. For each good  $j$ , the price in domestic currency ( $P_j$ ) is equal to the foreign price ( $P_j^*$ ) converted to the domestic currency:

$$P_j = SP_j^*. \quad (1)$$

$S$  denotes the nominal exchange rate, defined as the price of foreign currency in terms of domestic currency. The law of one price, which is motivated by international arbitrage, is an important requirement for PPP to hold.<sup>1</sup>

Even in this simple framework of PPP and the law of one price, the relation between prices and exchange rates may differ across countries. For a small country with no influence on world market prices, the law of one price would imply unitary pass-through of exchange rates to prices (i.e. a depreciation of the domestic currency by one percent would lead to an increase of the domestic price by one percent). However, if the exchange rate of a large economy depreciates, the upward pressure on domestic prices is partly offset by a reduction in the world price resulting from lower world demand. This reduces the measured pass-through for large economies. Hence, the size of an economy is one determinant of the extent of the ERPT to prices (McCarthy (2000), p.3).

### 2.1.2 Pricing to market and imperfect competition

Models with deviations from the law of one price provide further insight into the ERPT to prices. The reasons for these deviations often reveal important determinants of the ERPT. One important factor is imperfect competition. With absence of international arbitrage, firms can price discriminate between different locations. A theoretical basis for the relation between exchange rates and prices in the context of international price discrimination is provided by Krugman (1986) and Dornbusch (1987).

Krugman (1986) discusses several static and dynamic models with respect to *pricing to market*, a term henceforth extensively used in the literature. Pricing to market describes the (non-competitive) pricing behaviour of firms to strategically choose prices in different markets and to incompletely adjust prices to exchange rate movements, but to adjust profit margins instead. Comparing static models, Krugman finds that pricing to market

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<sup>1</sup>However, the law of one price holding does not necessarily imply that PPP holds. One particular reason is the existence of non-tradable goods. Prices of non-tradable goods may differ across countries, causing a violation of PPP. According to the Balassa-Samuelson model, differences in the prices of non-tradable goods arise because of productivity differentials (Asea and Corden (1994)).

behaviour can arise in case of limited competition (Cournot oligopoly and monopolistic price discrimination), but not in a simple competitive framework. To get pricing to market behaviour, the competitive model needs to be enlarged by transportation or distribution costs.

In the discussion of some dynamic models, Krugman argues that if the adjustment of a firm's service and distribution infrastructure is costly, the expected persistence of exchange rate changes plays an important role for the ERPT. A firm is not willing to bear the adjustment costs if the exchange rate change is expected to reverse soon. Using other models, Froot and Klemperer (1989) and Taylor (2000) obtain similar conclusions: The more persistent an exchange rate change is perceived to be, the larger is the price adjustment.

Moreover, Krugman (1986) argues that if the adjustment costs are increasing in the speed of adjustment, prices would only gradually be adjusted even in the case of a permanent exchange rate change. Hence, the time elapsed after the exchange rate change is of importance. Krugman concludes that dynamic models of imperfect competition might be the most suitable models to explain pricing to market. Such a model is used in section 3.1 to analyze the ERPT to prices.

The paper of Dornbusch (1987) is another seminal theoretical contribution that emphasizes the role of imperfect competition for the ERPT. Similar to Krugman (1986), Dornbusch (1987) adopts a partial-equilibrium approach in the sense that movements in the exchange rate are assumed to be exogenous. The Cournot oligopoly model with a homogeneous good, a linear demand function and a number of domestic and foreign firms is able to explain the whole range of exchange rate induced price changes between the two limiting cases of unchanged prices on the one hand and complete ERPT (i.e. price adjustments proportional to the exchange rate change) on the other hand. Two factors determine the magnitude of the ERPT: the number of foreign firms relative to the total number of firms and the ratio of marginal costs of foreign firms to the price (the inverse of the mark-up). The former can be considered as a proxy for the share of imports; the latter is a measure of the degree of competition. According to this model, the ERPT is higher for countries with a large import share because, in this case, more firms face a change in their marginal costs when exchange rates change. Moreover, the ERPT increases with the degree of competition because this reduces the ability of firms to absorb exchange rate induced cost shocks by adjusting profit margins instead of changing prices.

Dornbusch (1987) discusses several additional models and concludes that all these models predict a reduction of import prices after an appreciation. Whether and to what extent the domestic firms adjust their prices depends on the specific model.



### 2.1.3 Review of theoretical considerations

The preceding subsection discussed the ERPT to prices in the context of imperfect competition. This subsection gives a summary of alternative approaches to the ERPT. Following Engel (2004), there are two distinct branches of the literature modelling the phenomenon that import prices react less than proportionally to exchange rate movements. One consists of mostly partial equilibrium models with flexible prices and imperfect competition. The other part of the literature is general equilibrium in nature and emphasizes the role of nominal price stickiness. Thus, it is mainly focussing on the ERPT in the short-run. When prices are sticky, it is important whether the foreign firms set their prices in their own currency (producer currency pricing, PCP) or in the currency of the economy to which they export their goods (local currency pricing, LCP). In the former case, import prices change one to one with the exchange rate in the short-run. In the latter case, the short-run ERPT is zero. Hence, the resulting short-run pass-through in a sticky price model depends on the firms' choice between LCP and PCP.

Bacchetta and van Wincoop (2005) try to endogenize the ERPT by modelling the currency pricing decision. They find two main factors determining this choice. The higher the market share of foreign firms in the domestic market, and the higher the differentiation between foreign and domestic products, the more likely foreign firms choose PCP. High market shares or highly differentiated products are associated with low competition. Thus, the competitive conditions influence the pass-through. Since the ERPT is high when many firms choose PCP, low international competition tends to increase the ERPT.<sup>2</sup>

In the paper of Corsetti and Pesenti (2004), the decision between LCP and PCP is linked to the exchange rate volatility. In their model, the degree of pass-through and the monetary policy are jointly determined. There are two equilibria: If firms choose PCP, the optimal policy of the monetary authorities is inward-orientated and consists in closing the national output-gap. This means that the countries choose different monetary policies, which leads to exchange rate volatility. But when exchange rates are volatile, the optimal decision of the firms is indeed to adopt PCP, which stabilizes their export mark-ups and implies a high ERPT. In the second equilibrium, the firms use LCP, implying a low ERPT. In that case, the optimal policies of the authorities of different countries coincide, leading to exchange rate stability. But if the exchange rate is stable, LCP is indeed one possible optimal pricing decision of the firms.

The relation between exchange rate volatility and ERPT is also addressed in Chang and Lapan (2003). Their paper is partial equilibrium in nature and studies a price competition game. Exchange rate variability affects the pricing strategies of the firms and thereby the ERPT. High exchange rate uncertainty creates incentives for the firms to de-

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<sup>2</sup>Thus, the influence of competitive pressure on the ERPT is quite different from that in Dornbusch (1987) or Benigno and Faia (2010), where a more intensive competition increases the pass-through to import prices.

fer the price setting to be able to adjust prices to unexpected exchange rate fluctuations. This corresponds to PCP. Hence, similar to the result obtained by Corsetti and Pesenti (2004), Chang and Lapan (2003) find that the ERPT to prices is higher when exchange rates are volatile, because the firms more likely choose PCP in this case.

Another attempt to endogenize the ERPT consists in the analysis of the relation between monetary policy and the currency pricing decision. In a two-country general equilibrium model, Devereux and Engel (2001) find that monetary stability is a crucial factor determining the currency choice. With complete financial markets, prices are set in the currency of the country with the more stable monetary policy. With incomplete financial markets, there is an equilibrium in which all firms choose LCP. This is the case if the monetary policies of the two countries are similarly stable. But if there is a large difference in the volatility of monetary policy, goods are priced in the currency of the country with the more stable monetary policy. This analysis yields considerable implications for the ERPT: Countries with a stable monetary policy are likely to have their import prices set in their own currency, thus facing a low ERPT, whereas countries with an unstable monetary policy tend to have their import prices set in foreign currencies, which results in a high ERPT. This result is confirmed in the paper of Devereux et al. (2004). They stress the relevance of viewing the ERPT as endogenous. Changes in monetary policy can cause changes in the ERPT by affecting the firms' currency pricing decisions. A country that stabilizes its money growth rate in order to stabilize domestic prices creates incentives for foreign exporters to set their prices in domestic currency. Therefore, such a country faces a low ERPT and its import prices become less sensitive to exchange rate shocks, which enhances overall price stability. As a consequence, Devereux et al. (2004) conclude that monetary authorities which take the ERPT as a given factor miss an important channel through which monetary policy works, namely the impact of monetary policy on the degree of the ERPT.

A further part of the literature deals with the fact that the ERPT is index specific. In particular, the ERPT to import prices may differ from the ERPT to consumer prices due to the presence of transportation and distribution costs on the one hand and of domestically produced goods and non-tradable goods on the other hand. Burstein et al. (2003a, 2005) demonstrate the underlying reasoning. The consumer price index (CPI) contains both prices of tradable and prices of non-tradable goods. Tradable goods can be divided into imported goods and domestically produced goods. Both domestic and imported goods rely on transportation and distribution services. The costs of these services describe the sum of expenditures which are necessary to sell a tradable good to a consumer, such as transportation costs, wages and rents in the wholesale and retail sector and advertising costs. Burstein et al. (2003b) document that distribution costs are substantial. Thus, the ERPT to the CPI can be regarded as an aggregated response of prices to exchange rate shocks, which depends on the ERPT to the prices of imported

goods, domestically produced tradable goods, distribution and transportation services, and non-tradable goods. These considerations illustrate potential reasons for incomplete pass-through to consumer prices. For instance, if non-tradable goods represent a large part of the CPI and if the prices of these goods are relatively insensitive to exchange rate movements, then pass-through to the CPI will be low.

Allowing for distribution costs and non-tradable goods, Burstein et al. (2005) find that the substantial declines in real exchange rates after large devaluations are mainly due to slow adjustment of the prices for non-tradable goods and services. Corsetti and Dedola (2005) integrate distribution services in a two-country general equilibrium model. If non-tradable goods are required to distribute tradable goods to consumers, the price elasticity of demand becomes country-specific. As a consequence, monopolistic producers of tradable goods optimally charge different prices to domestic and foreign retailers. This dampens the response of both import and consumer prices to exchange rate movements, since the firms optimally adjust their mark-ups when faced with demand fluctuations. A different, but complementary approach is chosen by Bacchetta and van Wincoop (2003) who connect the firms' currency pricing decision to the presence of non-tradable goods. In their model, imports are intermediate goods. Domestic firms use the intermediate goods to produce final goods. Competitive pressure on final goods producers is higher because they compete with all the goods bought by consumers (including non-tradable goods), whereas intermediate goods producers only compete among themselves. If the non-tradable sector is large enough, it is likely that intermediate goods producers choose PCP and final goods producers choose LCP. As a consequence, the ERPT to import prices is higher than the ERPT to consumer prices. Hence, this model highlights a complementary aspect since non-tradable goods do not matter because they are necessary to distribute imported goods to consumers, but because their presence affects the demand of consumers.

Finally, the study of Choudhri et al. (2005) explores the ability of a variety of new open economy macroeconomic models to explain the ERPT to different prices. Quantitative versions of the models are used to predict dynamic responses of prices to exchange rate shocks, which afterwards are compared with the empirical evidence. The models investigated in the study feature different combinations of aspects highlighted by the literature, such as sticky wages and prices, the currency pricing decision (LCP versus PCP) and distribution costs. The results indicate that the model which is most suitable to fit the data incorporates all these features: a combination of LCP and PCP (with roughly equal weights), sticky prices and wages, and distribution costs.

## 2.2 Empirical literature

The growing theoretical literature on the ERPT to prices has been accompanied by many empirical studies. This section presents an overview of some empirical papers using dif-

ferent methodologies for the estimation of the ERPT. A particular emphasis is put on results for Switzerland. Studies using single equation models for estimation are summarized in subsection 2.2.1. Subsection 2.2.2 presents papers estimating the ERPT with VAR models. The empirical literature that incorporates cointegration relations is addressed in subsection 2.2.3. Finally, the empirical evidence for Switzerland is summarized in subsection 2.2.4.

### 2.2.1 Single equation models

Single equation models have been extensively used in order to estimate the ERPT to prices. They consist of a single equation with a price or inflation measure as dependent variable. The explanatory variables comprise the exchange rate (in level or first-differenced) and usually further control variables. To introduce dynamics into the model, lagged values of the exchange rate can be added as regressors.

Menon (1995) provides a survey of early contributions to the empirical literature on the ERPT. Most of these studies apply ordinary least squares (OLS) to estimate the ERPT. They have been criticized by Menon (1995) and more recent papers because they do not properly address the time series properties of the data. Many variables used to estimate the ERPT are non-stationary<sup>3</sup> and the regression of an integrated variable<sup>4</sup> on another integrated variable can be problematic. Such regressions can indicate a relation between the variables, although they are actually independent. This phenomenon is known as spurious correlation.

As a consequence of this criticism, more recent studies attempt to adequately incorporate the time series properties of the data. Gagnon and Ihrig (2004) estimate the ERPT to consumer price inflation in 20 industrial countries. Since they use first-differenced data for prices and exchange rates, non-stationarity can be rejected for a majority of countries. Hence, the estimates of the ERPT should not be subject to spurious correlation for most of the countries. The results of Gagnon and Ihrig (2004) suggest that the pass-through to consumer prices is low. On average, a one percent depreciation of the local currency leads to an increase of consumer prices by 0.23% in the long-run. There is substantial variation across countries. The estimate for Switzerland is smaller than the average (the point estimate suggests a CPI change by 0.15% in the long-run) and not significantly different from zero. The overall results of the study show that the ERPT to consumer prices has declined over time.

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<sup>3</sup>A time series process  $X_t$  is stationary if the expectation of  $X_t$  is constant, the variance of  $X_t$  is finite and the covariance between  $X_t$  and  $X_s$ ,  $Cov(X_t, X_s)$ , is equal to the covariance between  $X_{t+r}$  and  $X_{s+r}$ ,  $Cov(X_{t+r}, X_{s+r})$ , i.e. the covariance depends on the time lag between  $t$  and  $s$ , but is independent of the specific points in time  $t$  and  $s$  (Neusser (2006), p. 12).

<sup>4</sup>A time series process  $X_t$  is integrated of order  $d$  if the  $d$ -times differenced time series is stationary. For a formal definition see Neusser (2006), pp. 99-100. According to this definition, a trend-stationary process, i.e. a process that is non-stationary because its expectation is a function of the time and that becomes stationary if the time trend is subtracted, is not an integrated process.

Campa and Goldberg (2005) estimate the ERPT to import prices for 23 OECD countries and analyze its determinants. Because tests indicate that most of the time series may have a unit root but are not cointegrated, they choose to apply OLS with variables in log differences. Price changes are regressed on current and lagged exchange rate changes, the domestic GDP growth rate and the current and lagged changes in the costs of foreign exporters. The ERPT to import prices is defined as the elasticity of import prices with respect to the exchange rate, keeping the change of foreign exporters' costs and domestic GDP growth constant. On average, the estimated ERPT amounts to 0.46 over one quarter and to 0.64 over five quarters. The estimates for Switzerland are larger: The elasticities amounts to 0.68 and to 0.93, respectively. The latter is not significantly different from one. Thus, full pass-through to Swiss import prices over the long term cannot be rejected. Using disaggregated data, Campa and Goldberg (2005) show that the ERPT differs across goods, but is stable over time for the separate product categories. Therefore, they conclude that changes in the composition of imports are an important explanation for changes in the ERPT to overall import prices over time.

Single equation models have the advantage of being relatively easy to estimate and to interpret. However, there are some substantial drawbacks of these models. Firstly, they consider only one price index at a time. Since only a single equation is estimated, it is impossible to jointly analyze the behaviour of import and consumer prices in the aftermath of an exchange rate shock. Secondly, they rely on the strong assumption that exchange rate changes and the other explanatory variables (for example GDP) are exogenous. These models feature an endogeneity problem because price changes may affect GDP and future exchange rate changes. Therefore, it is more adequate to use models allowing for extensive dynamic interactions between the variables of interest, such as VAR models.

### **2.2.2 Vector autoregressive models**

In recent years, structural VAR models have been extensively used in order to estimate the ERPT to prices. In contrast to single equation models, VAR models can contain several price indices and allow for complex interrelations between the variables. Moreover, they are more suitable to capture the dynamics of the ERPT. A large majority of the studies using VAR models applies a recursive scheme (Cholesky decomposition) for the structural identification of the model.

McCarthy (2000) examines the impact of exchange rate and import price fluctuations on producer and consumer prices in nine industrialized economies. He uses a structural VAR model with a distribution chain of pricing, incorporating three stages of inflation (import, producer and consumer price inflation). This framework allows tracking the ERPT to each stage of prices, which may give additional insight into the complex transition mechanism from exchange rates to final consumer prices. Oil price inflation, output gap, money growth and the short-term interest rates are included as additional variables.

The results show that while an appreciation of the exchange rate has a negative short-run impact on import prices, there is no significant effect on producer and consumer prices in most of the economies (including Switzerland).

Using a slightly different model, Hahn (2003) finds a significantly negative response of euro area prices to an appreciation shock. The size of the response and the speed of adjustment decrease along the distribution chain of pricing; they are largest for import and lowest for consumer prices. An appreciation shock of one percent reduces import, producer and consumer prices by about 0.5%, 0.3% and 0.16%, respectively.<sup>5</sup>

There are further studies documenting that the ERPT decreases along the distribution chain. Faruqee (2004) presents additional evidence on the ERPT to euro area prices. The hypothesis of full pass-through to import prices in the long-run cannot be rejected. The response of producer and consumer prices is much lower: An appreciation shock of one percent decreases these price indices by roughly 0.2% and 0.1%, respectively. Core inflation and wages show hardly any reaction to an exchange rate shock. The response of export prices is considerable, but less pronounced than the reaction of import prices. Consequently, the terms of trade increase with a currency appreciation. Similar findings are reported in Choudhri et al. (2005) for six major industrial countries. The responses of import and export prices are stronger than those of producer and consumer prices. Wages show no significant response. Since the reaction of import prices exceeds the one of export prices in the short- and medium-term, the terms of trade temporarily increase in the aftermath of an appreciation shock. Ito and Sato (2006) analyze the ERPT for East Asian countries. They find a huge ERPT to import prices. The response of producer prices is lower, but still sizable, whereas the reaction of consumer prices is moderate and for some countries not significantly different from zero.

A few studies analyze the transmission mechanism from exchange rates to prices in more detail by estimating the ERPT to prices of specific categories of goods. Belaisch (2003) uses VAR models to estimate the ERPT to various price indices in Brazil. The study explicitly distinguishes between tradable and non-tradable goods. The findings reveal that prices of the former react more quickly. However, in the long-run, the price change is similar for both types of goods. Overall, the estimates indicate incomplete pass-through to all price indices except wholesale prices. The ERPT declines along the distribution chain. In a study using Swiss data, Stulz (2007) finds evidence for significant but incomplete ERPT to import and consumer prices. The impulse response functions reveal a quick and somewhat hump-shaped reaction of import prices to an exchange rate shock whereas consumer prices slowly converge to their new long-run level. The long-run ERPT elasticities amount to 0.37 and 0.18 for import and consumer prices, respectively. Furthermore, consumer prices are divided into prices of imported goods and the remaining

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<sup>5</sup>These price changes are the accumulated impulse responses measured three years after the shock occurred. The reaction of import prices is already accomplished after three quarters.

goods. The ERPT to consumer prices of imported goods is estimated. The results indicate a long-run ERPT elasticity of 0.34. Interestingly, this is very close to the pass-through to import prices, suggesting that rigid import prices rather than distribution costs are the main reason for incomplete ERPT to consumer prices of imported goods. However, this result does not hold in a more recent subsample which is characterized by an environment of low and stable inflation. In this subsample, the ERPT is lower for all price indices and, especially, consumer prices of imported goods barely react to exchange rate shocks. As a consequence, the ERPT to overall consumer prices is virtually zero.

Finally, Cavaliere (2007) analyzes the ERPT to different price indices in 20 industrialized economies, including Switzerland. The results show a significant reaction of import prices to exchange rate shocks for all countries. There is an immediate jump in import prices followed by a quick adjustment to the new long-run level. For most of the economies, including Switzerland, the long-run elasticity of import prices with respect to the exchange rate is close to one, indicating almost full pass-through. The responses of consumer prices are considerably lower and, for some countries, not significantly different from zero. The long-run ERPT elasticity is smaller than 0.5 for many countries, but it is larger for Switzerland. The adjustment process of consumer prices is slower and more prolonged compared to that of import prices. The results of the study reveal that high ERPT to import prices does not necessarily imply high pass-through to consumer prices. The responses of producer prices are an intermediate case; for some countries, the reaction is more similar to that of import prices, for other countries (including Switzerland), the response function resembles the one of the CPI.

Overall, the empirical evidence on the ERPT from VAR models can be summarized as follows. Firstly, the magnitude of the ERPT and the speed of adjustment decrease along the production and distribution chain. Secondly, the pass-through to producer and consumer prices seems to be incomplete and sometimes not significantly different from zero. Third, the ERPT to import prices is significant, but the results are mixed whether there is full or limited pass-through.

Structural VAR models are suitable for the consistent estimation and the analysis of dynamic adjustments of interrelated variables to various shocks. However, there is a substantial drawback of these models. Since many variables involved in the analysis of the ERPT are non-stationary, they have to be first- or even second-differenced in order to achieve stationarity. This way of proceeding results in the loss of the information contained in the level of the variables. This can be problematic if there are long-run equilibrium relations between the variable levels, which are neglected when the analysis is restricted to changes in the variables.

### 2.2.3 Cointegration analysis and vector error correction models

Cointegration analysis has the advantage of incorporating short-run dynamics without disregarding long-run equilibrium relations among variables. Hence, it comprises the advantages of VAR models and in addition incorporates the information contained in the level of the time series. In the light of these features, it is somewhat surprising that there are only few studies estimating the ERPT in a cointegration framework. While some studies are not able to find evidence for cointegrating relations and, as a consequence, use single equation or VAR models, there are several empirical studies that disregard cointegrating relations without even testing for them. The concept of cointegration is described in subsection 4.1.1. A frequently used model in this context, the VEC model, is introduced in subsection 4.1.2.

The empirical analysis by Kim (1998) uses cointegration analysis with a VEC model to estimate the ERPT to US producer prices. He finds one cointegrating relation between US producer prices, exchange rates, money supply, income and interest rates. The exchange rate has a significant, but rather small long-run impact on prices; keeping the other variables constant, an appreciation of the US dollar by one percent decreases producer prices by only 0.24%.

Billmeier and Bonato (2004) use both a VAR model and a cointegration approach to assess the ERPT to prices in Croatia. The test for cointegration indicates one cointegrating relation between the exchange rate, the manufacturing and the retail price index. The cointegrating relation reveals a significant but incomplete ERPT to retail prices: A devaluation of one percent increases retail prices by about 0.3% in the long-run.

A more detailed study is presented by Masten (2004), who explicitly addresses the issue of identification of the equilibrium pass-through effect in a cointegration framework. His work is based on the paper of Johansen (2002) about the interpretation of cointegrating coefficients. Johansen (2002) shows that, under certain conditions, a method similar to the instrumental variables approach can be applied to cointegrating relations. Instead of using a change in the exogenous instrumental variables to produce the desired changes in the endogenous variables, there may be changes in the current values of the time series that will induce long-run changes of the desired form. For example, in the context of the ERPT to prices, the desired modifications would be a long-run change in the exchange rate by one percent and the resulting percentage price change, keeping the other variables in the cointegrating relation constant. Johansen (2002) proves the conditions under which such a counterfactual experiment is possible and, hence, under which the cointegrating coefficients can be interpreted as long-run elasticities (provided that the variables are measured in logarithms). Masten (2004) uses these findings in order to estimate the ERPT for Hungary, Poland, Slovenia and the Czech Republic. The long-run equilibrium pass-through derived from the cointegrating coefficients is remarkably high. For Slovenia



and Hungary, the ERPT to consumer price inflation is virtually one, meaning that CPI inflation changes one to one with the growth of the nominal exchange rate. The estimate for Poland is somewhat smaller, but not significantly different from one either. The results for the Czech Republic suggest a long-run ERPT of about 0.6.

#### 2.2.4 Summary of the empirical evidence for Switzerland

Table 1 summarizes the results of some empirical studies estimating the ERPT for Switzerland. The empirical evidence suggests that the degree of pass-through decreases along the distribution chain. Regarding import prices, the estimates vary between a long-run pass-through elasticity of roughly 0.2 and 1. The response of import prices seems to happen rather quickly and to be mostly accomplished one year after the shock occurred. The ERPT to producer and consumer prices is either incomplete or not significantly different from zero. With regard to consumer prices, the estimates range from a pass-through of virtually zero to a long-run ERPT elasticity of more than 0.5. The CPI adjusts more slowly than import prices to exchange rate shocks. The instantaneous reaction is very small. Afterwards, the accumulated impulse response function converges to the new long-run level. Some studies present evidence for a decrease in the ERPT over time. This decline is rather small with regard to import prices, but it is substantial regarding the ERPT to the CPI.

| study                     | method          | findings  |
|---------------------------|-----------------|---|
| Gagnon and Ihrig (2004)   | single equation | The results indicate that a depreciation of 1% leads to an increase in consumer prices by 0.15% in the long-run. However, this increase is not significantly different from zero.   |
| Campa and Goldberg (2005) | single equation | Import prices change by 0.68% over one quarter and by 0.93% over five quarters given a 1% change in exchange rates. Both estimates are significantly different from zero. The latter is not significantly different from one.   |
| McCarthy (2000)           | VAR             | The ERPT to import prices is significant in the first year after the exchange rate shock. The pass-through to producer and consumer prices is not significantly different from zero.  |
| Stulz (2007)              | VAR             | An exchange rate shock of 1% leads to a change in import prices of 0.35% after one quarter and of 0.37% two years after the shock occurred. Consumer prices change by 0.09% and 0.18%, respectively. The ERPT to consumer prices for imported goods amounts to 0.27% and 0.34% after one quarter and two years, respectively. |
| Cavaliere (2007)          | VAR             | The long-run ERPT elasticity with respect to exchange rate shocks is close to one for import prices, amounts to about 0.5 for producer prices and lies between 0.5 and one for consumer prices.   |

Table 1: Summary of the findings of some empirical studies estimating the ERPT for Switzerland

### 3 Theoretical analysis

#### 3.1 A theoretical model of international strategic pricing

Section 2.1 has shown the importance of imperfect competition for the ERPT. The findings of Krugman (1986) and Dornbusch (1987) have been the basis for further theoretical and empirical studies. This section discusses a more modern model. It is a simplified version of the model presented in Benigno and Faia (2010). The simplification consists in omitting the distinction between different sectors. The original assumption that firms are not small with respect to their sector and that their pricing decision affects the sectoral price index is replaced by the assumption that firms are not small with respect to the economy and that their pricing decision influences the overall price index of the economy. Appendix A shows the details of the derivation of some equations used in this section.

The setup of the model is as follows. There are two countries, labelled *domestic economy* and *foreign economy*. In the domestic economy, there are  $N$  different goods.  $N^h$  goods are produced by domestic firms and the remaining  $N^f$  by foreign firms. There is a representative household maximizing the present discounted value of utility. Utility is a function of a composite consumption good  $C_t$  which is an aggregate of all available goods. The aggregation of the goods occurs according to the Dixit-Stiglitz aggregator:

$$C_t = \left[ \sum_{j=1}^N C_{j,t}^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}}. \quad (2)$$

$C_{j,t}$  denotes the consumption of good  $j$  in period  $t$ .  $\theta$  is the elasticity of substitution across goods. In this model, each firm is a monopolistic supplier of its good. However, households are able to substitute between the goods, which limits the monopoly power of the firms.

Since utility in period  $t$  depends on the composite consumption good  $C_t$ , households choose  $C_{j,t}$  such as to minimize expenditure for the desired amount of  $C_t$ . The solution to this minimization problem yields the following demand function for a generic good  $j$ :

$$Y_{j,t} = \left( \frac{P_{j,t}}{P_t} \right)^{-\theta} Y_t. \quad (3)$$

$Y_t$  is the overall demand of the domestic economy,  $P_{j,t}$  is the price of good  $j$  and  $P_t$  is the overall price index, defined as the minimum expenditure needed to buy one unit of  $C_t$  and given by the following equation:

$$P_t = \left( \sum_{j=1}^N P_{j,t}^{1-\theta} \right)^{\frac{1}{1-\theta}}. \quad (4)$$

The aim of the firms is to maximize profits. For simplicity, the production function is assumed to depend only on labour  $L_t$  and to be of linear form:

$$\text{domestic firm } i: Y_{i,t} = A_t^h L_{i,t}, \quad (5)$$

$$\text{foreign firm } j: Y_{j,t} = A_t^f L_{j,t}, \quad (6)$$

in which  $A_t^h$  and  $A_t^f$  are productivity parameters.

Under flexible prices, each firm chooses its price to maximize profits. The profit function of a domestic firm  $i$  in period  $t$  is characterized by the following equation:

$$\Pi_{i,t} = P_{i,t} Y_{i,t} - W_t^h L_{i,t}. \quad (7)$$

$W_t^h$  is the nominal wage in the domestic economy in period  $t$ . Using the production function (5) to replace  $L_{i,t}$  and replacing  $Y_{i,t}$  by the demand function (3), profits can be rewritten as follows:

$$\Pi_{i,t} = P_{i,t} Y_{i,t} - W_t^h \frac{Y_{i,t}}{A_t^h} = \left( P_{i,t} - \frac{W_t^h}{A_t^h} \right) \left( \frac{P_{i,t}}{P_t} \right)^{-\theta} Y_t. \quad (8)$$

Assuming that foreign firms set their prices in the currency of the country in which the products are sold, profits in foreign currency of a foreign firm  $j$  in period  $t$  are given by the following equation:

$$\Pi_{j,t}^* = \frac{P_{j,t}}{S_t} Y_{j,t} - W_t^{f*} \frac{Y_{j,t}}{A_t^f} = \left( \frac{P_{j,t}}{S_t} - \frac{W_t^{f*}}{A_t^f} \right) \left( \frac{P_{j,t}}{P_t} \right)^{-\theta} Y_t. \quad (9)$$

Variables denoted with a \* are denominated in foreign currency.  $W_t^{f*}$  is the nominal wage in the foreign labour market in period  $t$ .  $S_t$  denotes the nominal exchange rate.

Both domestic and foreign firms maximize their profits with respect to their price, taking into account that they are not small with respect to the market and, as a consequence, that their pricing decision affects the overall price index.<sup>6</sup> The optimal prices set by domestic and foreign firms are characterized by the following equations:

$$\text{domestic firm } i: P_{i,t} = \frac{\theta(1 - \psi_{i,t})}{\theta(1 - \psi_{i,t}) - 1} \frac{W_t^h}{A_t^h} \quad (10)$$

$$\text{foreign firm } j: P_{j,t} = \frac{\theta(1 - \psi_{j,t})}{\theta(1 - \psi_{j,t}) - 1} \frac{W_t^{f*}}{A_t^f} S_t \quad (11)$$

$$\psi_{i,t} \equiv \frac{\partial P_t}{\partial P_{i,t}} \frac{P_{i,t}}{P_t} \quad (12)$$

For the interpretation of these equations, it is important to recognize that the elasticity

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<sup>6</sup>The paper of Benigno and Faia (2010) uses an alternative assumption, namely that the firms are able to influence the sectoral price index.

of the price index with respect to the price of a generic firm  $i$ ,  $\psi_{i,t}$ , is exactly equal to the market share of firm  $i$  (see Appendix A).

Consider the special case that the market share of each firm goes to zero. In this limiting case, firms are small with respect to the market and their pricing decision does not affect the overall price index of the economy. Setting  $\psi_{i,t} = 0$ , equation (10) becomes the familiar mark-up pricing formula<sup>7</sup>:

$$P_{i,t} = \frac{\theta}{\theta - 1} \frac{W_t^h}{A_t^h}. \quad (13)$$

Prices set by domestic firms are a mark-up over marginal costs. The mark-up depends on  $\theta$ , the elasticity of substitution across the goods. A very similar formula is obtained for the prices of foreign firms:

$$P_{j,t} = \frac{\theta}{\theta - 1} \frac{W_t^{f*}}{A_t^f} S_t. \quad (14)$$

The price setting formulas (13) and (14) show that the prices of domestic firms are independent of the exchange rate whereas the elasticity of the prices of foreign goods with respect to the exchange rate is equal to one. Hence, this special case of the model yields the strong prediction that import prices should change one to one with the nominal exchange rate whereas the ERPT to prices of domestically produced goods is zero.

In the general case, in which the firms are aware that their pricing decision influences the overall price index (equations (10) and (11)), the optimal prices of domestic and foreign goods are still a mark-up over marginal costs. However, the mark-up is not constant any more. It depends positively on the market share  $\psi_{i,t}$ . Because of that, the mark-up depends negatively on the price set by a firm: If a firm unilaterally increases its price, it will lose market share and the mark-up decreases.

The dependence of the optimal prices on the market share introduces strategic interaction between domestic and foreign firms. Suppose that there is an appreciation of the domestic currency ( $S_t$  decreases). The direct effect consists in foreign firms lowering their prices, since their marginal costs in domestic currency decline. *Ceteris paribus*, the lower price increases the market share of foreign firms to the detriment of domestic firms. The decline in market share of domestic firms causes a reduction of their mark-up, meaning that domestic firms lower their prices as well in order to limit their loss of market share. The strategic interaction between domestic and foreign firms is crucial for this result. Eventually, both domestic and foreign firms lower their prices in response to an appreciation: foreign firms due to lower marginal costs and domestic firms because they compete with the foreign firms in the domestic market.

To calculate the ERPT that is implied by this general case of the model, a log-linear

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<sup>7</sup>The same formula results if the model is designed as a monopolistic competition model with a continuum of firms.

approximation of the equations (10) and (11) combined with the definition of the market share is taken (see Benigno and Faia (2010), pp.7). This leads to the following equations:<sup>8</sup>

$$\widehat{P}_t^h = \frac{\kappa s^f}{1 + \kappa} \left( \widehat{W}_t^{f*} - \widehat{A}_t^f + \widehat{S}_t \right) + \frac{1 + \kappa s^h}{1 + \kappa} \left( \widehat{W}_t^h - \widehat{A}_t^h \right) \quad (15)$$

$$\widehat{P}_t^f = \frac{\kappa s^h}{1 + \kappa} \left( \widehat{W}_t^h - \widehat{A}_t^h \right) + \frac{1 + \kappa s^f}{1 + \kappa} \left( \widehat{W}_t^{f*} - \widehat{A}_t^f + \widehat{S}_t \right) \quad (16)$$

$$\text{with } \kappa = \frac{\theta - 1}{\theta \left(1 - \frac{1}{N}\right) - 1} \frac{1}{N - 1}, \quad s^h = \frac{N^h}{N} \quad \text{and} \quad s^f = \frac{N^f}{N}$$

Variables with a hat denote log-deviations from the steady state.  $s^h$  and  $s^f$  denote the respective share of domestic and foreign firms relative to the total number of firms. From these equations, it is obvious that the prices of both domestic and foreign firms depend on the exchange rate.

The impact of exchange rate movements on the price of imported goods is given by the term  $\frac{1 + \kappa s^f}{1 + \kappa}$ . Thus, pass-through to import prices is usually less than one. The two exceptions are the absence of domestic firms ( $s^f = 1$ , in which case foreign firms can pass through exchange rate movements without losing market share) and the case of monopolistic competition ( $N$  goes to infinite and therefore  $\kappa$  goes to zero). Hence, this model predicts a higher ERPT to import prices for countries with a larger share of imports and with a higher degree of competition (a higher  $N$ ). These results coincide with those from the Cournot model in Dornbusch (1987).

The analysis of the prices of domestically produced goods (equation (15)) reveals that an increase of  $\widehat{S}_t$  raises  $\widehat{P}_t^h$  by  $\frac{\kappa s^f}{1 + \kappa}$ . Hence, competition from abroad influences domestic prices: They react to exchange rate movements, but the reaction is certainly lower than one. The extent of the price change depends positively on the share of imported goods and negatively on the degree of competition (characterized by  $N$ ).

The implications of this theoretical model can be summarized as follows. Firstly, import prices react to exchange rate movements, but incompletely. Secondly, even the prices of purely domestic goods, i.e. goods not relying on any imported inputs, react to exchange rate shocks because domestic firms compete with foreign firms. This is modelled as actual competition, but potential competition through the threat of market entry might also play a role. Finally, the model confirms the findings of the literature that the share of imports and the degree of competition are important determinants of the ERPT. A higher import share increases the sensitivity of both import and domestic prices with respect to exchange rate changes. A more intensive competition increases the pass-through to import prices, but it reduces the response of domestic prices to the exchange rate.

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<sup>8</sup>Since all domestic firms are equal and face the same problem, they will set the same price. The same is true for the foreign firms. Therefore, the indices indicating the firms are dropped. To distinguish between the price of domestic and foreign goods, the superscripts  $h$  and  $f$  are used.

## 3.2 Implications of the theoretical analysis

The preceding sections 2.1 and 3.1 have analyzed the ERPT to prices theoretically. This section briefly summarizes some of the theoretical implications that arise from the above analysis and that are of importance for this master thesis.

The theoretical models yield several concrete and testable predictions regarding the ERPT. The following issues are addressed for the Swiss economy in the empirical part of this paper (section 6):

- The ERPT to consumer prices is positive, but incomplete. This is suggested by the model of international strategic pricing (section 3.1). Thus, the elasticity of the CPI with respect to the exchange rate should be located strictly above zero and below one.
- The ERPT to import prices is positive. Whether the pass-through is limited or complete depends on the model.
- Although some models claim that the prices of domestically produced goods are independent of the exchange rate, there are two reasons to believe that these prices react to exchange rate movements, albeit to a lower extent than import prices. Firstly, domestically produced goods usually rely partially on some imported inputs. As a consequence, their price depends to some extent on import prices, and since import prices depend on exchange rates, so do the prices of domestic goods. Secondly, the model of section 3.1 shows that even the prices of purely domestically produced goods depend on the exchange rate, because domestic firms compete with foreign firms whose marginal costs (and hence whose prices) hinge on the exchange rate.
- Price stickiness requires a dynamic analysis of the ERPT. With sticky prices, the ERPT to domestic prices is low in the short-run and increases only in the course of time when prices can be adjusted. Moreover, the short-run ERPT to import prices is mostly determined through the currency pricing decision. If LCP dominates, the short-run pass-through tends to zero. In contrast, the ERPT is close to one if PCP dominates. Thus, pass-through in the short-run may be largely determined through price rigidities. A dynamic analysis is necessary in order to assess how the ERPT evolves over time as prices can be adjusted.
- The ERPT is likely to be different for distinct price indices due to the presence of non-tradable goods as well as transportation and distribution costs. Usually, the ERPT is assumed to be largest for import prices at the border level and to decrease along the production and distribution chain down to the lowest pass-through for retail prices, since those prices contain the largest portion of distribution costs.

Moreover, due to the presence of non-tradable and of domestic tradable goods, whose prices are likely to react less than import prices to exchange rate movements, the ERPT to the CPI is lower than the ERPT to import prices.

## 4 Methodology, model and identification

### 4.1 Methodology

This section explains the methodology which is used in the empirical part of this paper. Subsection 4.1.1 describes the concept of cointegration. VAR and VEC models are introduced in subsection 4.1.2. Subsections 4.1.3 and 4.1.4 present the tests for cointegration and unit roots. Particular emphasis is put on the calculation of the impulse response functions (subsection 4.1.5), since the ERPT is essentially given by these functions. Finally, the issues of inference and bias are addressed in subsection 4.1.6.

#### 4.1.1 Cointegration

Many economic time series are non-stationary. As discussed in section 2.2, the problem of spurious correlation may occur in regressions of an integrated variable on another integrated variable. Therefore, time series are usually transformed in order to achieve stationarity, for example by differencing the series. However, this results in the loss of information contained in the level of the variables. This problem can be solved if the time series are cointegrated. This is the case if there is a linear combination of the time series that is stationary, although the series are non-stationary.

Cointegration is defined as follows (Neusser (2006), p. 218):

**Definition: Cointegration** The multivariate time series process  $\{X_t\}$  is *cointegrated* if  $\{X_t\}$  is integrated of order one and if there is a vector  $\beta \in \mathbb{R}^n$ ,  $\beta \neq 0$ , such that  $\{\beta'X_t\}$  is stationary, given an appropriate distribution of the starting value  $X_0$ .

$\beta$  is called *cointegrating vector*. The *cointegration rank*  $r$  is the maximal number of linearly independent cointegrating vectors  $\beta_1, \dots, \beta_r$ . These vectors span a vector space, the so-called *cointegration space*.

These stationary linear combinations of the integrated series, called *cointegrating equations* or *cointegrating relations*, can be interpreted as long-run equilibrium relations between the variable levels. Because the cointegrating equations are stationary, deviations are of temporary nature. Shocks cause deviations from these equilibrium relations, but these deviations cause adjustments of the variables in order to restore the equilibrium relations in the long-run.

If there are cointegrating relations, it is reasonable to include them in the model used for estimation. This does not cause spurious correlation since these relations are station-

ary combinations of the time series. Since VEC models incorporate the cointegrating relations and therefore provide a possibility to allow for level effects, this master thesis uses these models for the estimation of the ERPT. In contrast, differencing the series to achieve stationarity would result in the loss of the information contained in these long-run equilibrium relations between the variable levels.

#### 4.1.2 VAR and VEC models

A large part of the empirical literature uses VAR models to estimate the pass-through to prices (see subsection 2.2.2). These models are of the form

$$X_t = c + \Phi_1 X_{t-1} + \dots + \Phi_p X_{t-p} + Z_t, \quad Z_t \sim \text{WN}(0, \Sigma), \quad (17)$$

with constant column vector  $c$  and coefficient matrices  $\Phi_1, \dots, \Phi_p$ , where  $p$  denotes the order of the model.  $Z_t$  is a white noise process with mean zero and covariance matrix  $\Sigma$ . To avoid the problem of spurious correlations, these models are usually estimated with time series that have been stationarized. As discussed above, this results in the loss of the cointegrating relations.

In contrast, the VEC model preserves the cointegrating equations between the time series. The VEC model can easily be derived from a VAR model which is estimated using variables that are integrated of order one. Subtracting  $X_{t-1}$  from the VAR( $p$ ) model in equation (17) yields a VEC model of order  $p - 1$ :

$$\Delta X_t = c + \Pi X_{t-1} + \Gamma_1 \Delta X_{t-1} + \dots + \Gamma_{p-1} \Delta X_{t-p+1} + Z_t. \quad (18)$$

The coefficient matrices of the VEC model in equation (18) are related to the coefficient matrices of the VAR model in equation (17) as follows:  $\Gamma_i = -\sum_{j=i+1}^p \Phi_j$ .  $\Pi$  is given by  $\Pi = -I_n + \Phi_1 + \dots + \Phi_p$ , where  $I_n$  denotes the identity matrix and  $n$  denotes the number of variables in the model.

The term  $\Pi X_{t-1}$  in equation (18) is crucial since this term makes the difference between a VAR model estimated with differenced data and a VEC model. Suppose that  $\Pi$  is singular with rank  $r$ ,  $1 \leq r < n$ . In this case, there are at least  $n - r$  unit roots and there are two  $n \times r$  matrices  $\alpha$  and  $\beta$  with full column rank  $r$  such that  $\Pi = \alpha\beta'$  (Neusser (2006), p. 219).<sup>9</sup> Using this equality, the VEC model can be rewritten as follows:

$$\Delta X_t = c + \alpha\beta' X_{t-1} + \Gamma_1 \Delta X_{t-1} + \dots + \Gamma_{p-1} \Delta X_{t-p+1} + Z_t. \quad (19)$$

The columns of  $\beta$  are the cointegrating vectors. Thus, the cointegrating equations  $\beta' X_{t-1}$  enter the VEC model. Matrix  $\alpha$  is called loading matrix.

<sup>9</sup>The decomposition of  $\Pi$  in the product of  $\alpha$  and  $\beta'$  is not unique. For any non-singular  $r \times r$  matrix  $R$ ,  $\Pi$  could be decomposed as  $\Pi = (\alpha R'^{-1})(\beta R)'$ .



The representation in equation (19) is useful to understand the mechanisms which gave rise to the term *vector error correction model*<sup>10</sup>. Since  $\beta' X_t$  is stationary,  $\mathbb{E}\beta' X_t$  can be interpreted as steady state of the system or long-run equilibrium relation. Deviations from this equilibrium (*errors*) lead to adjustments (*corrections*) in  $\Delta X_t$ . The loading matrix  $\alpha$  determines how  $\Delta X_t$  adjusts to deviations in the cointegrating relations. These adjustments result in restoring the equilibrium in the long-run.

### 4.1.3 Tests for cointegration

Since the main difference of a VEC model to a VAR model estimated with differenced data consists in the inclusion of the cointegrating relations, these relations should be tested for. If there are none, it is sufficient to use a VAR model. Otherwise, a VEC model might be more appropriate for estimating the ERPT.

This paper uses the Johansen test, a likelihood ratio test, to test for cointegration. There are two types of the test. These types are distinguished by the alternative hypothesis that is applied. Let  $H(j)$  denote the hypothesis that there are at most  $j$  linearly independent cointegrating vectors.

In the *trace* test, the alternative hypothesis is always  $H(n)$ , where  $n$  is the maximal number of cointegrating relations, which is given by the number of time series in the model. A sequence of hypotheses is tested. Firstly, the null hypotheses of zero cointegrating relations ( $H(0)$ ) is tested versus the alternative  $H(n)$ . A failure of rejecting  $H(0)$  indicates that there are no cointegrating relations. If  $H(0)$  is rejected, there is at least one cointegrating relation. Then, the next step of the sequence tests  $H(1)$  against  $H(n)$ . If the test cannot reject  $H(1)$ , there is one cointegrating relation. Otherwise, there are at least two cointegrating relations and  $H(2)$  is tested against  $H(n)$  as a next step. This procedure is carried on until the test fails to reject a null hypothesis.

The *max* test applies a similar sequential testing strategy. In each step of the sequence,  $H(j)$  is tested against  $H(j + 1)$ . The sequence starts with testing  $H(0)$  against the alternative  $H(1)$ . A failure of rejecting  $H(0)$  indicates that there is no cointegrating relation. In contrast, if the test rejects  $H(0)$ , there is at least one cointegrating equation and  $H(1)$  is tested against  $H(2)$  as a next step. This procedure is carried on until the test fails to reject a null hypothesis.

Before the Johansen test can be applied, a model has to be specified because the asymptotic distribution of the test statistics depends on the specification of the deterministic part of the model (Neusser (2006), pp. 227-228). Since the data used in this master thesis exhibit a trend, there are two options. Both of them contain a constant in the cointegrating equation. The difference between the options consists in whether a time trend is included in the cointegrating equation.

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<sup>10</sup>This term goes back to Davidson et al. (1978).

For the models estimated in this paper, a time trend is included in the cointegrating equation for several reasons. First of all, both theoretical considerations and empirical studies show that the ERPT to prices can change over time. Hence, one should allow for time variation also within the cointegrating equation. Secondly, if some of the series are trend-stationary, the cointegrating equation should include a trend. As section 6.1 shows, evidence is unclear whether the exchange rate index has a unit root or is trend-stationary. As a consequence of this potential trend-stationarity, it might be safer to include a time trend in the cointegrating equation. Finally, allowing for a time trend amounts to the estimation of a more flexible model from an econometric point of view. Since there is no empirical or theoretical reason to a priori impose the restriction that there is no time trend, the more flexible model is chosen.

In addition to the deterministic specification of the model, the number of lags of the first-differences of the endogenous variables needs to be determined before the cointegration tests. In this master thesis, the following approach is used. A VAR model is estimated first. Different specifications of the VAR model are analyzed with respect to information criteria<sup>11</sup>, the significance of the coefficients and the residuals. The number of lags chosen for this VAR model is then transformed into the VEC framework<sup>12</sup> used for the cointegration test.

#### 4.1.4 Tests for unit roots

Consider the VEC model as in equation (19). To avoid the problems of regressing an integrated variable on another,  $\Delta X_t$  should be stationary. This means that  $X_t$  should not be integrated of order two or higher. Therefore, the first step of the empirical analysis consists in testing for unit roots. If the tests indicate a higher order of integration, then the time series are transformed before the estimation of the model such that  $X_t$  is integrated of order one and  $\Delta X_t$  is stationary.

This master thesis uses two unit root tests: the augmented Dickey Fuller (ADF) test and the Phillips Perron (PP) test. Both tests are based on the regression of  $X_t$  on  $X_{t-1}$  and some deterministic components. The ADF test includes lags of  $\Delta X_{t-1}$  as additional regressors. In contrast, the PP test addresses the autocorrelation in the data by correcting the estimator or its t value after the estimation in a non-parametric way.

The PP test has several advantages compared to the ADF test. It is more general than the ADF test due to its non-parametric correction for autocorrelation. Moreover, an exact modelling is not necessary. In addition, the PP test is more powerful, i.e. it has a higher probability of rejecting the unit root hypothesis if it is wrong in fact. However,

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<sup>11</sup>The following information criteria are considered: the Akaike Information Criterion (AIC), the Bayesian Information Criterion (BIC) and the Hannan Quinn Information Criterion (HQ)

<sup>12</sup>As shown in the previous subsection, a VAR model of order  $p$  can be rewritten as VEC model of order  $p - 1$ .

the PP test has a more pronounced size distortion, which results in too many rejections of the null hypothesis (Neusser (2006), p. 113).

#### 4.1.5 Impulse response functions

In this master thesis, the ERPT to a particular price index is defined as the percentage change of this price index in response to a one percent exchange rate shock. Thus, the ERPT is basically an impulse response function and is computed accordingly.

As shown in subsection 4.1.2, a VAR model of order  $p$  in levels can be written as a VEC model of order  $p-1$  and vice versa. Hence, the computation of the impulse response functions of a VEC model is analogous to that of a VAR model, for which the impulse response functions are given by the infinite moving average representation of the model (Neusser (2006), pp. 193-194):

$$\begin{aligned} X_t &= Z_t + \Psi_1 Z_{t-1} + \Psi_2 Z_{t-2} + \dots, \\ &= (I_n - A)^{-1} B V_t + \Psi_1 (I_n - A)^{-1} B V_{t-1} + \Psi_2 (I_n - A)^{-1} B V_{t-2} + \dots \end{aligned} \quad (20)$$

The matrices  $\Psi_1, \Psi_2, \dots$  are computed using the estimated coefficients of the VEC model by the method of equating coefficients. The second equation uses the relation between the structural form of the model,

$$X_t = A X_t + \Omega_1 X_{t-1} + \dots + \Omega_p X_{t-p} + B V_t, \quad (21)$$

and the reduced form, which is given by the VAR representation of the model:

$$X_t = \Phi_1 X_{t-1} + \dots + \Phi_p X_{t-p} + Z_t. \quad (22)$$

Subsection 4.3 will discuss the identification strategy used to obtain the coefficients of the structural form given the estimated coefficients of the reduced form. Once the matrices  $A$  and  $B$  are known, the impulse response functions are given by the coefficients of the matrices  $[\Psi_j (I_n - A)^{-1} B], j = 0, 1, 2, \dots$

The impulse response functions show the changes of the time series in response to an exchange rate shock. For the time series in logarithms, the impulse response functions directly measure the percentage change of the time series after an exchange rate shock. Thus, the ERPT is given by the impulse response functions that are normalized such that they represent the response to an exchange rate shock of one percent.

#### 4.1.6 Inference and bias-correction

The previous subsection explained how to compute the ERPT given an estimated VEC model and a suitable identification strategy. To assess the precision of the estimates and

to conduct tests on the ERPT, it is necessary to provide standard errors for the estimates.

There are several methods to compute the standard errors of the ERPT. This master thesis uses bootstrapping methods. Since the VEC model is chosen such that the null hypothesis that the residuals are white noise cannot be rejected, a relatively simple bootstrapping technique can be applied. From the residuals of the estimated VEC model, random draws with replacement are taken and used to compute new realizations of the time series. A new VEC model is estimated and the ERPT is computed for this model. This procedure is repeated 2000 times. The VEC models with the bootstrapped data are estimated with the number of cointegrating relations fixed at the number that is found for the original time series. This is problematic if the number of cointegrating relations for the bootstrapped data frequently differs from the original number of cointegrating relations. Nevertheless, the number is fixed for reasons of practicability, since a flexible number of cointegrating relations would require applying the cointegration test for each of the 2000 bootstrap repetitions.

Bootstrapping has the advantages of being conceptually simple and taking into account the empirical distribution of the residuals instead of imposing a distribution. However, there is a major drawback of this method of inference. As pointed out by Kilian (1998), impulse response estimates can be heavily biased in small samples. Therefore, he suggests a procedure to correct for the bias.

The basic idea is as follows. Let  $\hat{\beta}$  denote the estimator of the VEC model coefficients.  $\beta$  is the true population value. In VAR models,  $\hat{\beta}$  is biased away from  $\beta$ . If the biased  $\hat{\beta}$  is used to generate bootstrapped data, the bootstrap estimates are likely to be even more biased. As a consequence, Kilian (1998) proposes to bias-correct  $\hat{\beta}$  before the bootstrapping procedure. This can be achieved by his *bootstrap-after-bootstrap* method. In a first step, the standard bootstrap technique is used to generate bootstrap estimates  $\hat{\beta}^*$ . The difference between the average of  $\hat{\beta}^*$  and the initial coefficient estimates is taken as an approximate measure of the bias. Then, the initial coefficient estimates are bias-corrected and these bias-corrected estimates are used to generate bootstrapped data. Since the coefficients estimated using these bootstrapped data are again biased, they are bias-corrected as well before they are finally used for the computation of the impulse response functions. The confidence intervals are then based on these impulse response functions.

Unfortunately, there are two major problems regarding the implementation of the bias-correction method suggested by Kilian (1998) for the models of this master thesis. Firstly, the bias-correction may change the number of cointegrating relations. In this case, the question arises as to which number of cointegrating relations to use. Due to small sample bias, the estimates of the original model may be wrong. But since the bias-correction is only an approximation, the bias-corrected estimates could be wrong as well. Secondly, the bias-correction pushes most of the models estimated in this master thesis into the non-stationary region. In principle, Kilian (1998) suggests a solution for this problem, namely

to reduce the estimate of the bias by the lowest extent that is required in order to avoid pushing the bias-corrected model into non-stationarity. However, the implementation of this strategy leads to roots that are pushed very close to a unit root due to the bias-correction. In this case, there is implausibly high persistence of some impulse response functions, i.e. there are impulse response functions that are far from having reached their long-run level even ten years after an exchange rate shock. Thus, the question arises how much to adjust the bias-correction in order to avoid these implausibly high persistence. The answer to this question would be completely ad hoc. For these reasons, no bias-correction will be applied in this master thesis. This might be more appropriate than using a bias-correction that leads to explosive impulse response functions or at least to implausibly high persistence.

## 4.2 Model and variables

This section describes the three models of this master thesis that are used for the estimation of the ERPT to various price (sub-)indices. In addition, it discusses the variables which are included in these models.

Several time series are included in all three models. Since the main objective of this paper is the estimation of the ERPT to prices, all models contain an exchange rate time series, import prices as well as some form of consumer prices. Thus, all models allow for the estimation of the ERPT to both import and consumer prices. The comparison of the pass-through to these price indices may implicitly reveal the importance of some determinants of the ERPT such as non-tradable goods as well as transportation and distribution costs, since these are major reasons causing a gap between the pass-through to import and consumer prices.

Including a variable that accounts for monetary policy is of crucial importance. Suppose that there is an exchange rate shock threatening price stability. Since the Swiss National Bank targets price stability, it is likely to adjust its policy in order to counteract potential inflationary or deflationary pressure due to this exchange rate shock. Thus, the eventual impact of exchange rate shocks on prices depends on how monetary policy reacts to the shock. Therefore, a variable representing monetary policy should be included in the models. This paper uses the three-month Libor as monetary policy variable, because this has been the interest rate that the Swiss National Bank targets for implementing its monetary policy decisions.

Finally, all models contain a real output variable since output is interrelated with both exchange rates and prices. Fluctuations in exchange rates have an impact on GDP, which in turn affects prices. For example, a large appreciation shock to the domestic currency has a direct impact on consumer prices since import prices are likely to decrease. However, there is also an indirect effect. Since imports become cheaper and exports get

more expensive, output tends to decrease which puts additional downward pressure on domestic prices. Thus, output is an important factor in the transmission of exchange rate shocks to price adjustments and, hence, it is important to include real GDP in the model.

In summary, the three models all include an exchange rate time series, real GDP, short-term interest rates, import prices and some form of consumer prices. *Model (I)* includes the overall CPI. Moreover, it adds producer prices to these time series. The ERPT to producer prices is of interest because it shows how much the factory gate prices of domestically produced goods react to exchange rate shocks. Thus, model (I) allows for joint estimation and comparison of the ERPT to import, producer and consumer prices. This comparison enhances the understanding of the complex ERPT mechanism.

*Model (II)* splits the CPI into prices for goods and prices for services. To avoid estimating a too large model, producer prices are not included. *Model (III)* divides the CPI into two sub-indices by origin of the goods, i.e. it distinguishes between consumer prices for goods of foreign origin and for goods of domestic origin. To limit the dimension of the model to six time series, producer prices are not included. The aim of models (II) and (III) is twofold. Firstly, they offer a robustness check to the results of model (I), since they yield estimates for the ERPT to import and consumer prices as well. Secondly, these models provide further insight into the ERPT mechanism. The distinction between prices for goods and services allows analyzing the impact of services and distribution costs. The distinction by origin of the goods is interesting as it reveals the differences in pass-through for goods of foreign origin, i.e. goods that are directly affected by the exchange rate shock by means of higher purchasing costs, and for goods of domestic origin, i.e. goods that are only indirectly affected by the exchange rate shock, for example by means of competition with foreign products, by the response of monetary policy or due to the dependence on imported inputs for production.

### 4.3 Identification strategy

This section presents and justifies the strategy which is used to identify the coefficients of the structural form of the models given the estimated coefficients of the VEC models. The coefficients of the structural form are needed in order to compute the impulse response functions to structural shocks such as exchange rate shocks (see subsection 4.1.5).

First of all, the basic identification strategy needs to be determined. This master thesis uses short-run restrictions, i.e. the structural form is identified by restricting the instantaneous effect of some shocks. Alternatively, restrictions on the long-run effects could be used. However, this strategy would be very difficult to apply to the models in this paper. Since the time series contained in the models are integrated, a shock to a particular series has a permanent effect on the level of this series. Thus, it is very difficult to plausibly argue that a shock to one variable has no long-run impact on the level of

other variables. It seems less restrictive to choose an identification strategy that restricts only the effects on impact, i.e. within the same quarter when the shock occurs.

The number of restrictions which is necessary to identify the structural form of the model can be derived as follows. Solving the structural form (equation (21)) for the multivariate time series process  $X_t$  yields:

$$X_t = (I_n - A)^{-1}\Omega_1 X_{t-1} + \dots + (I_n - A)^{-1}\Omega_p X_{t-p} + (I_n - A)^{-1}BV_t. \quad (23)$$

The comparison of this equation to the VAR representation of the model (equation (22)) shows that the matrices  $\Omega_j$ ,  $j = 1, \dots, p$ , are given by  $\Omega_j = (I_n - A)\Phi_j$  and that the structural shocks,  $V_t$ , are linked to the residuals of the model,  $Z_t$ , as follows:

$$Z_t = (I_n - A)^{-1}BV_t. \quad (24)$$

The identification problem is solved by comparing the covariance matrices. From equation (24), it follows that

$$\Sigma = \mathbb{E}Z_t Z_t' = (I_n - A)^{-1}B\Lambda B'(I_n - A')^{-1}. \quad (25)$$

$\Sigma$  is the covariance matrix that can be estimated using the residuals of the estimated model. It contains  $\frac{n(n+1)}{2}$  distinct elements.  $\Lambda$  is the covariance matrix of the structural shocks. It is assumed to be a diagonal matrix, i.e. the structural shocks are assumed to be uncorrelated. Given this assumption on  $\Lambda$  and the standard assumptions that  $A$  has only zeros on its diagonal and  $B$  has only ones on its diagonal (Neusser (2006), pp. 191-193), there are  $2n^2 - n$  unknowns in the matrices  $\Lambda$ ,  $A$  and  $B$ . Thus, the number of unknowns exceeds the number of estimated elements in  $\Sigma$  by  $\frac{3}{2}n(n-1)$ . This corresponds to the number of restrictions needed for identification.

The models in this master thesis contain six time series ( $n = 6$ ). This yields a total of 45 restrictions necessary for identification. A simple method suggested by Sims (1980) consists in setting  $A = 0$ . Thus, 15 additional restrictions are needed. These restrictions are chosen in line with many empirical papers on the ERPT.

Firstly, real GDP is assumed to need at least one quarter to react to exchange rate, price and monetary policy shocks. As pointed out by Gali (1992), a variety of empirical evidence supports the assumption that aggregate demand needs some time to react to monetary policy shocks. Moreover, the most interesting identification scheme according to Sims and Zha (1998) features a lagged response of real economic activity to most price and financial variables. This is motivated by delays in planning and inherent inertia.

All price indices are assumed not to react instantaneously to monetary policy shocks. These restrictions are motivated by price stickiness. For Switzerland, Kaufmann (2009) finds a median price duration of more than four quarters based on CPI micro data.

Restrictions needed for the identification of the price indices are imposed according to the production and distribution chain. Import price shocks are allowed to exert an immediate impact on downstream producer and consumer prices. Producer price shocks can immediately affect consumer prices, but there is no impact on import prices within a quarter. Consumer price shocks do not immediately affect the upstream import and producer prices. For model (II), in which the CPI is divided into prices for goods and services, consumer price inflation of services is restricted to have no contemporaneous impact on the CPI of goods. For model (III), in which consumer prices are split by origin of the goods, it is assumed that the CPI of goods of foreign origin can immediately affect consumer price inflation of domestic goods, but that the opposite does not hold within the quarter of occurrence of the shock.

In addition, the instantaneous response of exchange rates to some shocks is restricted. McCarthy (2000) states that empirical research in the last decades has suggested that most short-term fluctuations in exchange rates cannot be accounted for by macroeconomic fundamentals. Moreover, in his review of the literature on exchange rate economics, Taylor (1995) finds that although macroeconomic fundamentals are important for the general framework within which exchange rates move in the short-run, they fail to provide a sufficient explanation for short-run movements. As a consequence of these findings, this master thesis assumes that exchange rates do not react on impact to price and monetary policy shocks.

Finally, no restrictions are assumed regarding the interest rate. Since this time series represents monetary policy and since monetary authorities take output, price and exchange rate developments into account when deciding on their policy, it is important to allow for an immediate response of monetary policy to all these shocks.

Using all these restrictions on the matrices  $A$  and  $B$ , the relation between the residuals of the model,  $Z_t$ , and the structural shocks,  $V_t$ , according to equation (24) can be rewritten as follows:

$$\begin{pmatrix} Z_{GDP,t} \\ Z_{IPI,t} \\ Z_{PPI,t} \\ Z_{CPI,t} \\ Z_{ER,t} \\ Z_{IR,t} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ * & 1 & 0 & 0 & * & 0 \\ * & * & 1 & 0 & * & 0 \\ * & * & * & 1 & * & 0 \\ * & 0 & 0 & 0 & 1 & 0 \\ * & * & * & * & * & 1 \end{pmatrix} \begin{pmatrix} V_{GDP,t} \\ V_{IPI,t} \\ V_{PPI,t} \\ V_{CPI,t} \\ V_{ER,t} \\ V_{IR,t} \end{pmatrix}. \quad (26)$$

The subscripts  $GDP$ ,  $IPI$ ,  $PPI$ ,  $CPI$ ,  $ER$  and  $IR$  denote real GDP, import prices, producer prices, consumer prices, exchange rates and interest rates, respectively. Unrestricted coefficients of the matrix  $B$  are indicated by a \*.<sup>13</sup>

<sup>13</sup>Equation (26) applies for model (I). The corresponding equation for model (II) is obtained by replacing *producer prices* with *consumer prices for goods* and by replacing *consumer prices* with *consumer price inflation for services*. To get the corresponding equation for model (III), the variables *consumer prices for goods of foreign origin* and *consumer price inflation for goods of domestic origin* are used instead



Of course, each of these identifying restrictions is open to dispute. However, most of these restrictions are imposed by a large number of empirical studies on the ERPT and, hence, are sort of standard in the empirical ERPT literature. There is one precarious assumption, namely that exchange rates cannot immediately react to interest rate shocks. As financial variable, exchange rates should be allowed to react on impact to any innovation. But monetary policy should be allowed to react on impact to exchange rate shocks as well. However, in order to identify the models, one of these immediate responses has to be restricted. Concerning this matter, there is no clear preference in the literature. However, since exchange rate shocks affect prices and since the Swiss National Bank targets price stability, it seems to be more important to allow for an immediate response of monetary policy to exchange rate shocks than to allow for an instantaneous reaction of exchange rates to interest rate shocks.

Finally, it is important to emphasize again that all these restrictions only limit the effect of shocks on time series within the quarter when the shock occurs. In the subsequent quarter, any time series can react to any shock.

## 5 Data

The estimation of the models described in section 4.2 requires data on consumer, import and producer prices, real GDP, short-term interest rates and exchange rates. This section describes the particular time series that are used for the estimation. Moreover, it states the data sources and explains the transformation of the time series.

Data on consumer prices are given by the Swiss CPI, which is computed by the Swiss Federal Statistical Office and is available on a monthly basis. The CPI measures the development of prices for a wide range of goods and services. The prices are measured at the consumer level, i.e. including taxes or special offers. The CPI is a chained Laspeyres index<sup>14</sup> with a yearly adjustment and re-weighting of the underlying basket in order to account for changes in consumer behaviour.<sup>15</sup> The index can be divided into sub-indices in various ways. This master thesis uses the division into prices for goods and prices for services on the one hand and into prices for goods of foreign origin and prices for goods of domestic origin on the other hand.

Import and producer price data are given by the import price index (IPI) and by the producer price index (PPI). The IPI measures the price development of imported goods. Prices are measured at the boarder level. The PPI measures the price development of domestically produced goods. The index contains both domestically consumed or invested goods and export products. Prices are measured at the producer level (industrial selling

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of *producer prices* and *consumer prices*.

<sup>14</sup>Appendix B contains the definition of different price indices.

<sup>15</sup>More details on the Swiss CPI are available on the webpage of the Swiss Federal Statistical Office, <http://www.bfs.admin.ch/bfs/portal/de/index/themen/05/02.html>.

prices), i.e. excluding value added tax. Both the IPI and the PPI are Laspeyres indices. These indices are computed by the Swiss Federal Statistical Office and are available on a monthly basis.<sup>16</sup>

The data on the price indices (CPI, CPI sub-indices, IPI and PPI) are obtained from the database of the Swiss National Bank.<sup>17</sup> All price indices are transformed before the empirical analysis. Quarterly averages are computed and the logarithm is taken. Moreover, the CPI and all its sub-indices need to be seasonally adjusted due to sales prices which cause a seasonal pattern of prices.<sup>18</sup>

The State Secretariat for Economic Affairs (Seco) provides quarterly estimates of the seasonally adjusted real GDP of Switzerland.<sup>19</sup> This paper used the data release from May 30, 2011. Before the time series is used in the models, the logarithm is taken.

As discussed in section 4.2, data on the short-term interest rate are given by the three-month Libor in CHF. However, these data are only available from 1989 onwards, which would severely reduce the sample size. Therefore, the Libor time series is expanded backwards using the relative changes of the three-month euro market interest rate in CHF. These interest rate series are obtained from the publicly available database of the Swiss National Bank. Data transformation of the interest rate time series is limited to taking the quarterly average.

Finally, the estimation of the ERPT requires data on exchange rates. It is important to realize that only one structural exchange rate shock can be identified. The structural identification of several exchange rate shocks using short-run restrictions would require the restriction that one of the exchange rate shocks has no immediate impact on the other exchange rate. Taking account of the strong interrelations between exchange rates, such an assumption is very implausible. As a consequence, the models of this thesis include only one exchange rate series.

Basically, there are two possibilities to incorporate exchange rates into the model. Either only one particular exchange rate is considered or an index of exchange rates is constructed. The latter option is chosen by many empirical studies on the ERPT. This master thesis, too, constructs an import-weighted exchange rate index that represents a large part of Swiss imports.

The decision on which countries to include in the construction of the exchange rate index is based on the shares of Swiss imports originating from these countries. The import shares by countries of origin are computed on an annual basis, since there are no data of

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<sup>16</sup>For more details, see the webpage of the Swiss Federal Statistical Office, <http://www.bfs.admin.ch/bfs/portal/de/index/themen/05/04.html>.

<sup>17</sup>These time series are publicly available on <http://www.snb.ch/de/iabout/stat/statpub/statmon/stats/statmon>.

<sup>18</sup>Since there are no official seasonally adjusted series for the price (sub-)indices, these time series are seasonally adjusted by applying the X12 method of the US Census.

<sup>19</sup>These time series are publicly available on <http://www.seco.admin.ch/themen/00374/00456/00458/index.html?lang=en>.

higher frequency for the sample period up to 1987. The data on the shares of nominal imports are provided by the Swiss Federal Customs Administration. There is a trade-off regarding the number of countries that are included in the index. A smaller number reduces the import share that is represented by the index, but also reduces the amount of required exchange rate data. In this study, countries with an average import share of at least 0.35% are incorporated for the calculation of the exchange rate index. This threshold is clearly arbitrary, but it turns out to be a reasonable choice since with a relatively small number of countries, a very large part of Swiss imports is covered. There are only 28 countries which fulfil this criterion, but the import shares of these countries sum up to 94% of Swiss imports on average.<sup>20</sup> Excluding the countries with an average import share smaller than 0.35% is not likely to affect the overall results of the empirical study, while it substantially reduces the exchange rate data that has to be collected.

The import-weighted exchange rate index is constructed as a Paasche index.<sup>21</sup> The nominal exchange rate index of each of these 28 countries is weighted by the share of Swiss nominal imports originating from this country. Due to data availability, not all of the 28 countries are included over the whole sample period. Appendix C contains a table indicating for each country the earliest period in which exchange rate data are available and, hence, the period from which onward the respective country is included in the index. Thus, the exchange rate index is sort of a chained index which is consecutively rebased to 100 every time additional exchange rates are available and included. Appendix C contains a figure depicting the import-weighted exchange rate index in comparison to two export-weighted exchange rate indices published by the Swiss National Bank.

Data on exchange rates from the 28 countries are taken from various sources, including the database of the Swiss National Bank, online databases on historical exchange rates or the databases of the central bank of the respective countries. The exchange rates are defined as the price of foreign currency units in terms of domestic currency. Thus, an increase in the import-weighted exchange rate index represents a depreciation of the Swiss franc. The exchange rate index is transformed before the empirical analysis: The quarterly average is computed and the logarithm is taken.

Overall, the data sample ranges from the first quarter of 1980 to the last quarter of 2010. The beginning of the sample is determined by availability of GDP data. The ending is chosen such that the GDP series, which is subject to substantial data revisions, has been revised at least once. Quarterly data frequency is used since there are no GDP data on a higher frequency. The overall sample contains 124 periods of observations. For the

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<sup>20</sup>Arranged according to the magnitude of the average import share over the whole sample period, these countries comprise Germany, France, Italy, the United States, the United Kingdom, the Netherlands, Austria, Belgium, Japan, Spain, Ireland, Sweden, China, the Russian Federation, Denmark, Hong Kong, Finland, Libya, Taiwan, South Africa, Canada, the Czech Republic, Brazil, Thailand, South Korea, Hungary, Portugal and India.

<sup>21</sup>Appendix B contains the definition of different price indices.

models (II) and (III), the sample includes only 112 quarters due to availability of the CPI sub-indices.

## 6 Estimation and results

### 6.1 Model (I): unit root tests, order of the model and cointegrating relations

This section describes the results of the unit root tests for the time series contained in model (I). The choice of the order of the model and the number of cointegrating relations is justified and the cointegrating relations are presented.

The first step of the empirical analysis consists in testing each time series with respect to unit roots. Neither the ADF nor the PP test is able to reject the null hypothesis of a unit root for real GDP, the IPI, the PPI, the CPI and the interest rate. However, the first differences of these series are found to be (trend-)stationary. Thus, the tests indicate that the three price indices contained in model (I), real GDP and the interest rate are integrated processes of order one.

The evidence is less clear regarding the import-weighted exchange rate index. The ADF test rejects the null hypothesis of a unit root at the 5% level, whereas the PP test is not able to do so. For this reason, one should take into consideration that the exchange rate index possibly has a unit root. Regarding the changes in the exchange rate index, the results of the tests consistently indicate that this series is stationary. Hence, the exchange rate index is possibly integrated, but the integration order is at most one.

Before the VEC model is estimated, the order of the model and the cointegration rank have to be determined. Several criteria are used to decide on the order of the model. First of all, the residuals of the model should not be autocorrelated, i.e. they should not be significantly different from a white noise process. Secondly, the decision is based on information criteria such as the AIC, BIC and HQ. AIC tends to overestimate the order, whereas BIC and HQ are consistent and asymptotically yield the correct order (Neusser (2006), p. 183). Finally, a lag exclusion test indicates whether the coefficients of the last lag are jointly significantly different from zero.

A lag order of four is chosen for model (I). The null hypothesis that the resulting residuals are white noise cannot be rejected, while models with a smaller order yield residuals that are significantly autocorrelated. Moreover, the order four lies in the range that is suggested by the different information criteria: The BIC indicates a lower order whereas the AIC suggests a larger order. In addition, a lag exclusion test confirms that the fourth lag is significantly different from zero and, hence, it should be included in the model. By including four lags of the first-differenced series in the model, five observations are lost. Thus, the estimation of model (I) is based on 119 quarters of observations.

Since the unit root tests indicate that the time series of model (I) are integrated, there may be some cointegrating relations between the series. Both types of the Johansen test, the *trace* test and the *max* test, indicate that there are cointegrating relations. However, while the trace test indicates three cointegrating relations at the 5% level, the max test suggests that there is only one cointegrating relation. Thus, any number of cointegrating relations from one to three could be justified. However, including only one cointegrating equation may not be appropriate for several reasons. First of all, an analysis of several sub-periods of the whole sample shows that in many subsamples, both tests indicate at least two cointegrating relations. Moreover, estimating a model with only one cointegrating relation might be missing a relation that is of crucial importance for the purpose of this paper, namely the long-run relation between exchange rates and the price indices. Within the first cointegrating equation, the coefficients of the exchange rate index, the IPI and the PPI are not significantly different from zero. In contrast, the second relation is found between the price indices and exchange rates. Therefore, in order to estimate the ERPT to prices with a VEC model, this second cointegrating equation is included and the model is estimated with two cointegrating relations.<sup>22</sup>

The estimated cointegrating equations are as follows:

$$\begin{aligned} GDP_t + 0.040IPI_t + 0.011PPI_t + 0.488CPI_t - 0.034IR_t - 0.007t &\sim I(0), \\ ER_t - 0.553IPI_t + 0.777PPI_t - 1.267CPI_t + 0.004IR_t + 0.006t &\sim I(0), \end{aligned}$$

where  $GDP_t$ ,  $ER_t$ ,  $IPI_t$ ,  $PPI_t$ ,  $CPI_t$  and  $IR_t$  denote the time series of GDP, the import-weighted exchange rate index, the IPI, the PPI, the CPI and the short-term interest rate, respectively, as described in the data section (section 5).  $I(0)$  signifies integrated of order zero. A likelihood ratio test shows that some restrictions can be imposed on the cointegrating equations. In particular, the hypothesis cannot be rejected that the cointegrating equations are as follows:

$$\begin{aligned} GDP_t + 0.472CPI_t - 0.033IR_t - 0.007t &\sim I(0), \\ ER_t - 0.439IPI_t + 0.818PPI_t - 1.193CPI_t + 0.006t &\sim I(0). \end{aligned}$$

While the first equation describes a relation between output, consumer prices and interest rates, the second equation is important for the estimation of the ERPT, since it describes a relation between exchange rates and various price indices. As section 7.2 will show, including this cointegrating relation in the model makes a substantial difference for the estimated ERPT.

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<sup>22</sup>As a robustness check, the model is also estimated with one and three cointegrating relations and the resulting ERPT is compared. Section 7.2 contains the results of this analysis.

## 6.2 Model (I): exchange rate pass-through to various price indices

This section presents the estimated percentage changes of various price indices in response to a one percent shock in the exchange rate index, namely to a depreciation shock. The estimated ERPT elasticities to consumer, import and producer prices are compared and the results are discussed. Finally, the responses of all time series contained in model (I) to a depreciation shock are jointly analyzed.

There is significant pass-through to consumer prices on impact (figure 1). A depreciation shock of one percent leads to an increase in the CPI of 0.07%. The ERPT elasticity increases to 0.18 one year after the shock occurred, to 0.30 after two years and finally to its long-run value of 0.47. Thus, the initial one percent exchange rate shock finally leads to a change in the CPI of almost half a percent. Consumer prices react slowly to the exchange rate shock. The CPI needs more than four years in order to complete the adjustment. The ERPT to the CPI is significantly different from zero at the 5% level up to 12 quarters after the shock. At the 10% level, the pass-through is significantly different from zero even in the long-run.

The response of import prices to an exchange rate shock is shown in figure 2. Compared to the CPI, the IPI reacts quickly to exchange rate shocks. The estimated elasticity on impact amounts to 0.32. The ERPT quickly increases and peaks at 0.75 in the fifth quarter after the shock. Then, the elasticity decreases to its long-run level of 0.42. The ERPT with respect to import prices is estimated with low precision. It is significantly positive only during the first two years after the shock. Afterwards, it the 95% interval includes both zero and one, meaning that the estimated long-run elasticity is neither significantly different from no pass-through nor from full pass-through.

Figure 3 depicts the estimated pass-through elasticity to producer prices. The PPI reacts by 0.06% to a one percent exchange rate shock within the same quarter. The pass-through elasticity rises to 0.30 two years after the shock occurred. This corresponds to the long-run ERPT elasticity. Thus, producer prices accomplish their adjustment process within two years. The ERPT to the PPI is only significantly different from zero in the first two years after the shock.

For a comparison of the ERPT to import, producer and consumer prices, figure 4 plots the dynamics of the pass-through to these indices in comparison to the evolution of the exchange rate index itself. The dynamics of the exchange rate impulse response function are hump-shaped with a peak one quarter after the shock. During five quarters, the exchange rate index is more than one percent above its pre-shock value. Afterwards, the exchange rate steadily decreases and stabilizes at 0.56% above its initial value. This partial appreciation of the exchange rate index is most easily understood if the response

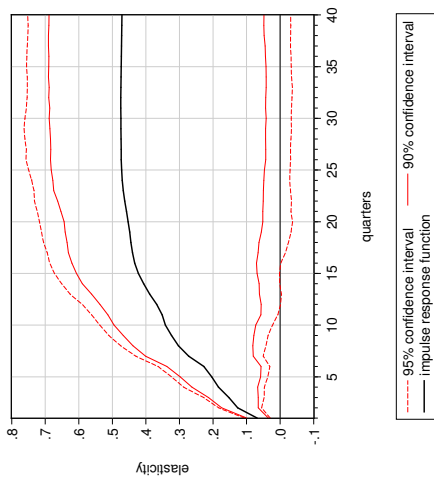


Figure 1: Estimated ERPT to consumer prices

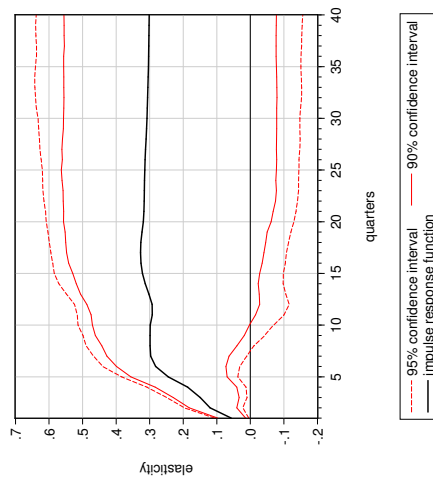


Figure 3: Estimated ERPT to producer prices

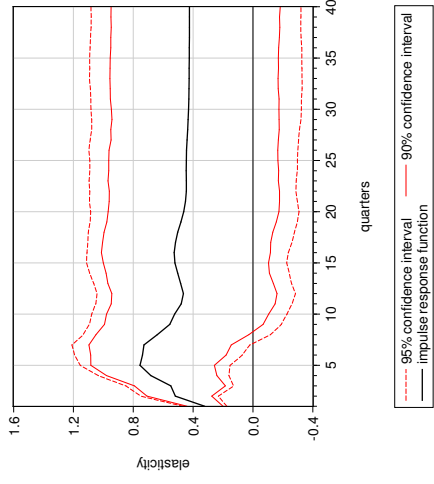


Figure 2: Estimated ERPT to import prices

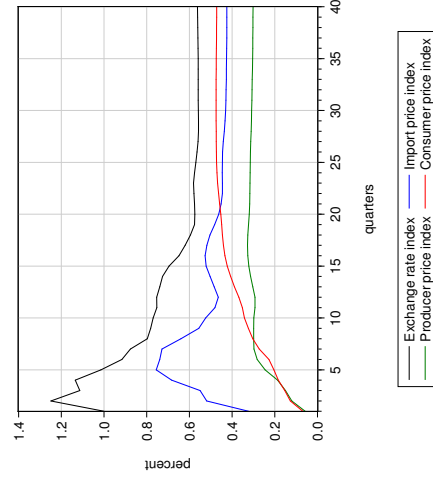


Figure 4: Percentage change of exchange rates, import, producer and consumer prices in response to an exchange rate shock

of monetary policy to the exchange rate shock is taken into account. As this section shows, a depreciation shock leads to significant increases in price levels. Thus, a central bank targeting price stability is likely to react by restricting monetary policy in order to counteract inflationary pressure. This conjecture is in line with the findings of the model, which show that, with a delay of one quarter, there is a significant increase in the short-term interest rate in response to the depreciation shock.<sup>23</sup> This increase in interest rates is one reason for the appreciation of the exchange rates and, thus, for the hump-shaped dynamics.

Figure 4 shows that the response of import prices resembles the impulse response function of the exchange rate index. The ERPT to the IPI is hump-shaped as well. However, there is some delay compared to the exchange rate index as the ERPT peaks three quarters later. The new long-run value of the IPI is 0.42% above the initial value. Comparing this value to the long-run change in the exchange rate of 0.56% indicates that the ERPT to import prices is incomplete, but substantial: The long-run change in the IPI relative to the long-run change in the exchange rate amounts to 0.76. For the PPI, the long-run price change relative to the long-run exchange rate change amounts to 0.54. For consumer prices, this ratio even amounts to 0.84. Thus, the long-run price change compared to the long-run exchange rate change is quite high for all three price indices. However, since the confidence intervals are huge for the long-run estimates, the results for the long-run should be interpreted with caution.

One explanation for the similarity between the responses of import prices and the exchange rate is given by the cointegrating relation between import, producer and consumer prices as well as the exchange rate index. The depreciation shock induces a deviation of this cointegrating relation from its long-run equilibrium. The estimated cointegrating relations and adjustment coefficients reveal that this deviation in turn leads to a positive adjustment of the IPI in order to restore the equilibrium in the long-run.

There are large differences in the dynamics between the ERPT to import prices on the one hand and the ERPT to producer and consumer prices on the other hand (see figure 4). While the ERPT to the IPI features a hump-shaped pattern, the ERPT to the PPI and the CPI mostly converge steadily to their long-run values. Thus, while the IPI follows, with some delay, the dynamics of the exchange rate, the PPI and the CPI seem not to respond to the partial re-appreciation in the exchange rate. A possible explanation is given by differences in the persistence of the price indices. Since the IPI reacts quickly, it follows both the initial increase in the exchange rate and the subsequent decrease. In contrast, producer and consumer prices feature a much higher autocorrelation than import prices. They are much more persistent and therefore, they simply increase to a lower extent instead of first increasing and then decreasing again.

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<sup>23</sup>Appendix D contains a figure depicting the impulse response function of the short-term interest rate to a depreciation shock.



The comparison of the short-run ERPT to the three price indices yields the expected results. On impact, import prices react much more than producer and consumer prices. Moreover, the IPI increases more quickly in the subsequent quarters than the PPI and the CPI.

However, the comparison of the pass-through in the long-run yields a surprising result: The estimated long-run ERPT is somewhat higher for consumer than for import prices. However, the difference is not significant. If the large confidence intervals in the long-run are considered, it could very likely be the case that the long-run ERPT to import prices is higher than to consumer prices.

In addition to exchange rates, import, producer and consumer prices, the model includes GDP and interest rates as additional time series. A joint analysis of the responses of all these series to a depreciation shock fosters the comprehension of the economic processes that take place in the aftermath of this shock. The direct effect of a depreciation shock is a change in the relative price of domestic and foreign goods. As a consequence, there is upward pressure on domestic price indices. This is confirmed by the model estimates, which show that import, producer and consumer prices increase significantly after a depreciation shock. Import prices are directly linked to exchange rates: If the law of one price held for these goods, import prices would change one for one with the exchange rate. In contrast, producer and consumer prices depend on exchange rates only to the extent to which they rely on imported inputs and to which they compete with foreign products. Therefore, import prices should react more strongly to exchange rates than producer and consumer prices. This result is confirmed by the model estimates.

Besides the upward pressure on domestic prices, there is an additional consequence of the exchange rate induced change in the relative prices of domestic and foreign goods. Since domestic products become relatively cheaper, exports are likely to increase. Indeed, the model finds a significant positive response of GDP to a depreciation shock.<sup>24</sup> This demand induced increase in GDP puts further upward pressure on domestic prices. As a consequence, monetary authorities targeting inflation are likely to react and to counteract the inflationary pressure by restricting monetary policy. The results of the model are in line with this conjecture. The model indicates that the short-term interest rate increases significantly one quarter after a depreciation shock (see Appendix D).

While GDP increases in the short-run, the exchange rate shock has no effect on GDP in the long-run. Various factors contribute to the fact that GDP declines back to its initial level. The increase in interest rates exerts a dampening effect on domestic demand. Moreover, domestic prices increase and the partially re-appreciating exchange rates dampen exports. Similar to GDP, the increase in interest rates is also of temporary nature. Up to two years after a depreciation shock, interest rates are significantly higher. But in the long-run, the response is not significantly different from zero. Overall, the estimated

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<sup>24</sup>Appendix D contains a figure depicting the impulse response function of GDP to a depreciation shock.

impulse responses of all time series of the model to a depreciation shock are in line with economic theory and intuition.

### 6.3 Model (II): unit root tests, order of the model and cointegrating relations

Model (II) distinguishes between consumer prices for goods and for services. Unit root tests indicate that the seasonally adjusted log CPI of goods is an integrated process of order one: The hypothesis of a unit root cannot be rejected for the time series in levels, but it is clearly rejected for the first-differenced series by both the ADF and the PP test. In contrast, the seasonally adjusted log CPI of services is integrated of order two. Both the ADF and the PP test fail to reject the hypothesis of a unit root for the first-differenced series, but reject the hypothesis for the twice-differenced series. For these reasons, the VEC model includes the CPI of goods in levels whereas it contains the CPI of services in first-differences (i.e. the consumer price inflation of services).

A lag order of four is chosen for model (II). With a lag order of four, the residuals of the model are not significantly different from white noise processes whereas they would be for smaller orders. A lag exclusion test confirms that the coefficients from the fourth lag are jointly significantly different from zero. Moreover, the lag order four lies between the orders suggested by the information criteria BIC and AIC. Finally, the order is equal to that chosen for model (I), which enhances the comparability between the models.

Since model (II) contains the first-differenced series of the CPI of services, one period of observations is lost. Moreover, since the model includes four lags of the first-differenced endogenous variables, five observations are lost. Thus, the estimation of model (II) is based on 106 quarters of observations.

The Johansen test indicates a positive number of cointegrating relations for model (II). Both the trace and the max test find one cointegrating equation at the 5% level. However, the trace test almost rejects the hypothesis of at most one cointegrating relation with a p-value of 0.0518. For several reasons, model (II) is estimated with two cointegrating relations.<sup>25</sup> First of all, this increases the comparability with model (I), which includes two cointegrating equations as well. Secondly, an analysis of several sub-periods shows that both tests indicate at least two cointegrating relations in many subsamples. Finally, a model estimated with only one cointegrating relation is likely to miss an important aspect for the estimation of the ERPT since, in the first cointegrating equation, the coefficients of the exchange rate and the import price index are not significantly different from zero. In contrast, these coefficients are significantly different from zero in the second cointegrating relation for some subsamples. Therefore, the second cointegrating equation is included in

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<sup>25</sup>The model with one cointegrating relation and the resulting ERPT are also estimated as a robustness check. Section 7.4 contains the results of this analysis.

the model.

The estimated cointegrating equations are as follows:

$$GDP_t - 0.423IPI_t - 0.694CPIG_t + 1.800CPIS_t - 0.029IR_t - 0.004t \sim I(0),$$

$$ER_t + 6.722IPI_t + 20.822CPIG_t + 97.167CPIS_t - 0.042IR_t - 0.036t \sim I(0).$$

$CPIG_t$  and  $CPIS_t$  denote the CPI of goods and the consumer price inflation of services, respectively. Several likelihood ratio tests are used to test some restrictions on the cointegrating relations. This facilitates the understanding of these relations. In the first relation, the coefficients of the exchange rates and the IPI are not significantly different from zero. Thus, the first equation describes a relation between output, interest rates and consumer prices. The second cointegrating equation describes a relation between exchange rates, price indices and CPI inflation of services, because a likelihood ratio test is not able to reject the hypothesis that the coefficients of GDP and interest rates in this equation are jointly equal to zero. Thus, the cointegrating relations are qualitatively similar to those of model (I).

#### 6.4 Model (II): exchange rate pass-through to various price indices

There is a significant reaction of import prices to exchange rate shocks in the short-run (figure 5). On impact, a depreciation shock of one percent leads to an increase in import prices by 0.36%. The ERPT elasticity increases to 0.95 in the fifth quarter after the shock. Afterwards, pass-through to import prices decreases. In the long-run, the pass-through elasticity amounts to 0.37. The ERPT elasticity is significantly different from zero up to seven quarters after the initial shock. The 95% confidence interval is very large in the long-run. In particular, it includes both zero and one. Thus, neither the hypothesis of complete pass-through to import prices in the long-run nor that of zero pass-through can be rejected.

Import prices react quite quickly to exchange rate changes. After about one and a half year, the adjustment is mostly accomplished. From then on, the response of the IPI follows more or less in parallel the impulse response function of the exchange rates (see figure 8). The initial exchange rate shock leads to a long-run change in exchange rates of about 0.6%, while import prices increase by about 0.4%. Thus, in the long-run, about two thirds of the exchange rate movement are passed-through to import prices.

The impact of a one percent depreciation shock on the CPI of goods is depicted in figure 6. The pass-through is significantly positive in the short-run, but rather low. On impact, the ERPT elasticity amounts to 0.13. It increases to 0.32 after one year and

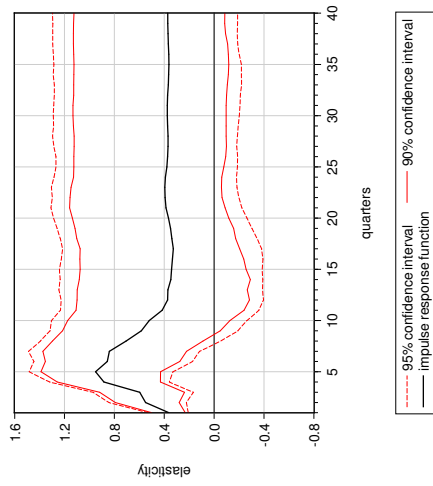


Figure 5: Estimated ERPT to import prices

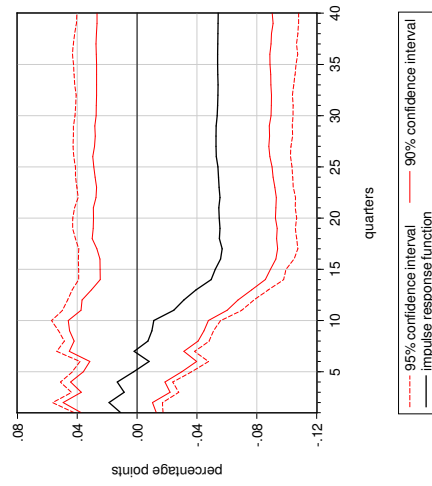


Figure 7: Estimated ERPT to consumer price inflation for services

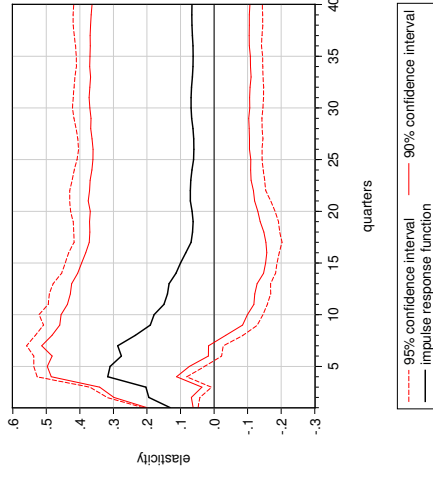


Figure 6: Estimated ERPT to consumer prices for goods

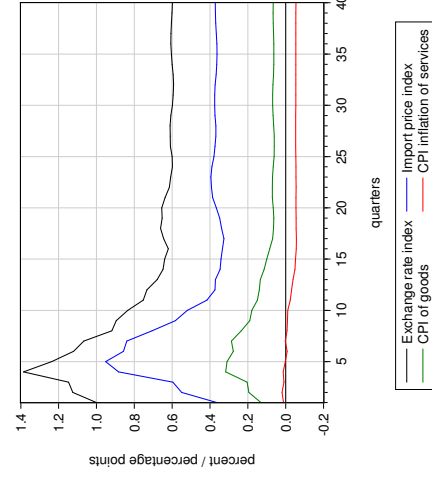


Figure 8: Response in percent of exchange rates, import prices and consumer prices for goods, and response in percentage points of consumer price inflation for services to a depreciation shock of 1%

decreases afterwards to 0.07 in the long-run. The long-run change in the CPI of goods relative to the long-run change in the exchange rate index amounts to 0.11, indicating a low pass-through to consumer prices of goods. Compared to import prices, consumer prices of goods need more time to complete the adjustment process. Only in the fourth year after the initial exchange rate shock, the CPI of goods stabilizes at its new long-run level. The pass-through elasticity is significantly different from zero at the 5% level up to five quarters after the shock. The long-run ERPT is not significantly different from zero, but it is significantly lower than one. Thus, the hypothesis of complete pass-through to consumer prices of goods is rejected at the 5% level.

Figure 7 shows the reaction of the CPI inflation of services in response to an exchange rate shock. The ERPT is not significantly different from zero, neither in the short- nor in the long-run. Thus, model (II) is not able to find evidence for an impact of exchange rate shocks on service price inflation.

Figure 8 plots a comparison of the ERPT to the price indices of model (II). Moreover, the response of the exchange rate index after the initial shock is depicted. The dynamics of the exchange rate impulse response function are hump-shaped. After the initial jump of one percent, exchange rates increase further during one year before decreasing during three years and stabilizing afterwards at about 0.6% above the initial level. As the graph shows, the dynamics of both import prices and consumer prices for goods feature a similar pattern. The ERPT to these indices is hump-shaped as well and peaks almost in the same quarter as the exchange rate index.

## 6.5 Model (III): unit root tests, order of the model and cointegrating relations

Model (III) splits the CPI by distinguishing between consumer prices for goods of foreign and of domestic origin. Both the ADF and the PP test indicate that the former series is integrated of order one while the latter is integrated of order two. As a consequence, the VEC model includes the CPI of foreign goods in levels whereas it contains the CPI of domestic goods in first-differences (i.e. the consumer price inflation for domestic goods).

As for models (I) and (II), a lag order of four is chosen. Besides comparability, there are several reasons for this choice. Firstly, the null hypothesis that the residuals of this model are white noise cannot be rejected. Secondly, the coefficients of the fourth lag are significantly different from zero. Finally, the lag order four lies between the orders suggested by the information criteria BIC and AIC.

The estimation of model (III) is based on 106 quarters of observations. One quarter is lost since the model contains the first-differenced series of the CPI for domestic goods. Five more observations are lost due to the inclusion of four lags of the first-differenced endogenous variables.

Both the trace and the max test indicate one cointegrating relation at the 5% level. However, both tests find a second cointegrating relation at the 10% level. Thus, the model could be estimated using either one or two cointegrating relations. For the following reasons, two cointegrating relations are included:<sup>26</sup> Firstly, this increases comparability with models (I) and (II). Secondly, the Johansen test indicates at least two cointegrating relations for many subsamples. Finally, the coefficient of the exchange rate index is not significantly different from zero in the first cointegrating relation. Therefore, it may be important to include the second relation in order to estimate the ERPT to prices properly.

The estimated cointegrating equations are as follows:

$$\begin{aligned} GDP_t - 2.04IPI_t + 9.36CPIF_t + 148.78CPID_t - 0.18IR_t - 0.02t &\sim I(0), \\ ER_t + 49.40IPI_t - 237.87CPIF_t - 3766.40CPID_t + 3.95IR_t + 0.43t &\sim I(0). \end{aligned}$$

$CPIF_t$  and  $CPID_t$  denote the CPI of foreign goods and the consumer price inflation of domestic goods, respectively. The cointegrating relations are qualitatively similar to those of model (I) and (II). A likelihood ratio test cannot reject the joint hypothesis that the coefficients of the exchange rate index and the IPI are zero in the first equation and that the coefficients of GDP and the interest rate are zero in the second equation. Thus, the test cannot reject that the first cointegrating equation describes a relation between GDP, interest rate and consumer prices while the second describes a relation between exchange rates, price indices and the CPI inflation of domestic goods.

## 6.6 Model (III): exchange rate pass-through to various price indices

Import prices react significantly to exchange rate shocks (figure 9). A depreciation shock of one percent leads to an increase in the IPI by 0.37% within the same quarter. Import prices increase further during one year. They stabilize one percent above the pre-shock value before they decrease quite quickly to their new long-run value, which lies 0.73% above the initial value. The ERPT elasticity is significantly different from zero at the 5% level up to two years after the shock. At the 10% level, the pass-through is significantly different from zero even in the long-run. However, it is not significantly different from one. Thus, the hypothesis of an ERPT elasticity of one cannot be rejected for import prices.

The adjustment process of import prices takes place quite quickly. After about one and a half year, the adjustment is mostly accomplished and the response of the IPI follows more or less in parallel the impulse response function of the exchange rates (see figure 12).

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<sup>26</sup>The model with one cointegrating relation and the resulting ERPT are also estimated as a robustness check. See section 7.6 for the results of this analysis.

The initial depreciation shock of one percent leads to a long-run change in the exchange rate index of 0.93%, while the IPI increases by 0.73%. Thus, in the long-run, almost four fifths of the exchange rate movement are passed-through to import prices.

Figure 10 depicts the estimated ERPT elasticity to the CPI of foreign goods. The estimated elasticity on impact amounts to 0.20 and is significantly different from zero at the 5% level. The ERPT increases to about 0.5 after one year. At this level, the CPI of foreign goods is more or less stable for one year, before it decreases to its new long-run level, which lies 0.33% above the initial level. Compared to the IPI, the CPI of foreign goods needs more time to complete the adjustment process. Two and a half years after the shock, the impulse response function of the CPI of foreign goods follows more or less in parallel the dynamic evolution of the exchange rate index (see figure 12). The ERPT to the CPI of foreign goods is significantly different from zero at the 5% level up to two years after the shock. At the 10% level, the pass-through is significantly different from zero even in the long-run. Moreover, the 95% confidence interval of the impulse response function lies below one. Thus, the initial exchange rate shock of one percent leads to a change in the CPI of foreign goods of less than one percent.

Figure 11 plots the response of consumer price inflation for goods of domestic origin to a depreciation shock of one percent. The ERPT is not significantly different from zero at the 10% level, neither in the short-run nor in the long-run.

For a comparison of the ERPT to the price indices of model (III), figure 12 shows the dynamics of the pass-through to these time series. Moreover, the response of the exchange rate index after its initial shock is plotted. The dynamics of the exchange rate impulse response function are hump-shaped. The initial jump of one percent is followed by a further increase. The exchange rate index peaks one year after the shock, before it decreases and finally stabilizes 0.93% above the pre-shock value. As the figure shows, the response of both the IPI and the CPI of foreign goods feature hump-shaped dynamics which are similar to the exchange rate index, except that there is some delay relative to the evolution of the exchange rates.

The comparison of the ERPT to the price time series in model (III) yields the expected results. Exchange rates exert the largest influence on import prices, followed by consumer prices for goods of foreign origin, whereas they have no significant impact on CPI inflation for domestic goods. This finding holds both in the short-run and in the long-run. Moreover, the IPI reacts somewhat more quickly than the CPI of foreign goods.

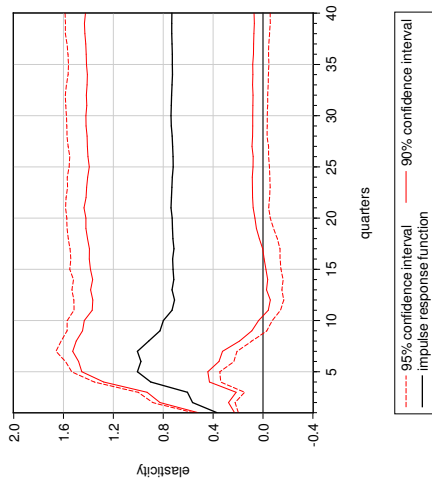


Figure 9: Estimated ERPT to import prices

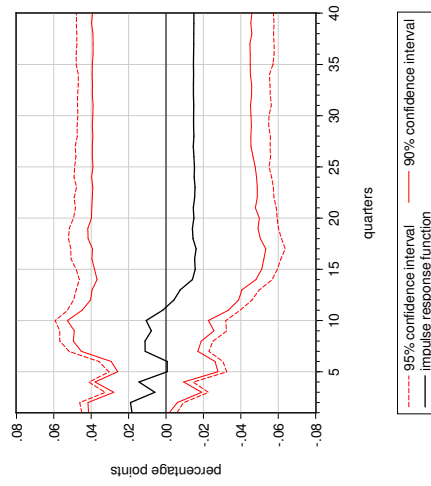


Figure 11: Estimated ERPT to consumer price inflation for goods of domestic origin

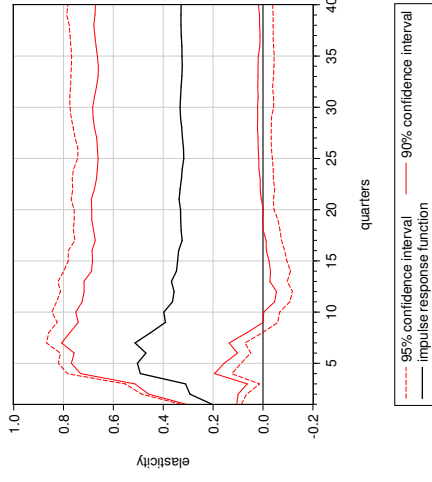


Figure 10: Estimated ERPT to consumer prices for goods of foreign origin

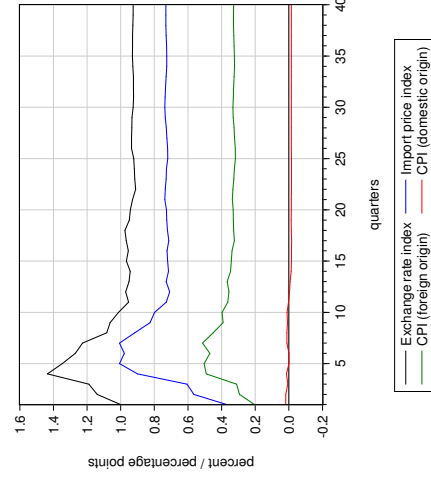


Figure 12: Response in percent of exchange rates, import prices and consumer prices for goods of foreign origin, and response in percentage points of consumer price inflation for goods of domestic origin to a depreciation shock of 1%



## 6.7 Summary and comparison of the results of the models (I), (II) and (III)

Table 2 contains an overview of the ERPT estimated using the models (I), (II) and (III). The pass-through to the CPI inflation for services and to the CPI inflation for goods of domestic origin is not listed since these estimates are not significantly different from zero in any quarter after the shock.

The comparison of the pass-through estimates of the models (I), (II) and (III) yields several results. First of all, the estimates of the ERPT to import prices are robust across the models, both with respect to the extent and the dynamics of pass-through. Estimates for the ERPT elasticity on impact range from 0.32 to 0.37 and are all significantly different from zero at the 5% level. The impulse response function is hump-shaped for all models, with a peak approximately five quarters after the initial shock. The long-run change in the IPI relative to the long-run change in the exchange rate index varies between 0.62 and 0.79. The models agree that import prices react more quickly than the other price indices to exchange rate shocks. This consistency of the findings indicates that the results for import prices are robust to the exclusion of producer prices from the model and to changes in the way how consumer prices are included in the model.

Secondly, there is a significant pass-through to consumer prices on impact. The estimated ERPT elasticity is highest for the CPI of foreign goods (0.20), followed by the CPI of goods (0.13) and the overall CPI (0.07). The same order holds for the speed of adjustment: Consumer prices for goods of foreign origin react more quickly than the CPI of goods, which in turn reacts more quickly than the overall CPI. The responses of consumer price inflation for services and for goods of domestic origin are not significantly different from zero.

Thirdly, there are large differences regarding the long-run ERPT to consumer prices. Model (III) estimates a ratio of the long-run percentage change in the CPI of foreign goods to the long-run percentage exchange rate change of 0.35. According to model (II), this ratio amounts to 0.11 for the CPI of goods. This result is reasonable since the CPI of goods contains both foreign and domestic goods and, hence, it is expected to feature a lower ERPT than the CPI of foreign goods. However, model (I) finds a long-run change of the overall CPI relative to the long-run change in the exchange rate index of 0.84. This is much higher than the findings of the other models. Moreover, it leads to an inconsistency. Since the CPI inflation for services and for goods of domestic origin does not react significantly to exchange rate shocks, the CPI of foreign goods and the CPI of goods are expected to react more than the overall CPI. However, according to the results of the models, the overall CPI reacts more strongly than each of its sub-indices, which is not possible. Thus, the estimates of the ERPT to consumer prices are not robust to changes in the way how consumer prices are incorporated in the model. However,

| <i>import prices</i> |           |            |             |
|----------------------|-----------|------------|-------------|
|                      | model (I) | model (II) | model (III) |
| ERPT on impact       | 0.32      | 0.36       | 0.37        |
| ERPT after 1 year    | 0.68      | 0.88       | 0.90        |
| ERPT after 10 years  | 0.42      | 0.37       | 0.73        |
| long-run ratio       | 0.76      | 0.62       | 0.79        |

| <i>producer prices</i> |           |
|------------------------|-----------|
|                        | model (I) |
| ERPT on impact         | 0.06      |
| ERPT after 1 year      | 0.19      |
| ERPT after 10 years    | 0.30      |
| long-run ratio         | 0.54      |

| <i>consumer prices</i> |                         |                             |                                      |
|------------------------|-------------------------|-----------------------------|--------------------------------------|
|                        | model (I):<br>total CPI | model (II):<br>CPI of goods | model (III): CPI<br>of foreign goods |
| ERPT on impact         | 0.07                    | 0.13                        | 0.20                                 |
| ERPT after 1 year      | 0.18                    | 0.32                        | 0.49                                 |
| ERPT after 10 years    | 0.47                    | 0.07                        | 0.33                                 |
| long-run ratio         | 0.84                    | 0.11                        | 0.35                                 |

The *ERPT* is the percentage change in the respective price index in response to an initial exchange rate shock of 1%. The *long-run ratio* is defined as the long-run percentage change of the price index relative to the long-run percentage exchange rate change estimated by the respective model.

Table 2: Summary of the pass-through estimates of the models (I), (II) and (III)

taking into account that there are huge confidence intervals for the long-run estimates, the inconsistency could simply be due to imprecise estimates. As a consequence, any conclusions based on the long-run estimates should be interpreted with caution.

In addition, there is a difference between model (I) on the one hand and models (II) and (III) on the other hand regarding the dynamics of the ERPT to consumer prices. The findings of model (I) indicate a slow and steady adjustment of the overall CPI to its new long-run level, whereas the results of models (II) and (III) find a hump-shaped pattern with a rather quick increase after the shock followed by a gradual decrease to the long-run level.

Finally, an important difference between the results of the models consists in the gap between the ERPT to import prices and to consumer prices in the long-run. Model (I) finds virtually no gap, which indicates that the presence of non-tradable goods and distribution costs do not play an important role in the long-run. In contrast, models (II) and (III) indicate a much higher long-run ERPT for the IPI than for consumer prices of goods and foreign goods. As a consequence, the importance of the presence of non-tradable goods and distribution costs in the long-run remains unclear.

In summary, the results for the ERPT to the IPI and for the short-run ERPT to consumer prices are robust and reasonable, whereas the results concerning the long-run ERPT to consumer prices differ across the models.

## 7 Comparisons and robustness checks

This section analyzes the robustness of the results discussed in the previous sections 6.2, 6.4 and 6.6. For each of the models, two alterations are examined. Firstly, several subsamples are used to estimate the ERPT, which allows assessing changes in the ERPT over time. Secondly, this section addresses the changes in the estimated ERPT when the number of cointegrating relations in the VEC model is altered and it compares the ERPT estimated using a VEC model with that obtained from a VAR model.

### 7.1 Model (I): analysis of subsamples

The whole sample period used for the estimation of model (I) ranges from 1980 to 2010. Out of this total sample, several subsamples are selected and the ERPT is estimated for these subsamples. In principle, there is a huge number of subsamples that could be chosen. This section presents results obtained from samples that are reduced either by five or by ten years of observations. In particular, the ERPT is presented for the subsamples from 1980 to 2005, 1985 to 2010, 1980 to 2000, 1985 to 2005 and 1990 to 2010.

Figure 13 depicts the estimated ERPT to the CPI for different subsamples. Albeit somewhat lower for both the periods 1980 to 2005 and 1985 to 2010, the estimated ERPT is similar to the estimate from the whole sample, both with respect to the extent and to the dynamics of pass-through. The differences between the subsamples are somewhat more pronounced for producer prices (figure 14). The dynamics of the pass-through are different in the medium term, but both the short-run and the long-run ERPT estimates are very similar across the subsamples. The variation between the subsamples is largest for import prices (figure 15). The point estimates indicate a considerably lower short-run and long-run ERPT to import prices in the more recent subsample. However, the differences are still minor if the large confidence intervals are taken into consideration. Thus, these estimates do not indicate that the ERPT has significantly increased or decreased over time.

The comparison of the even smaller subsamples ranging from 1980 to 2000, from 1985 to 2005 and from 1990 to 2010 points towards a reduction in the ERPT over time. While the short-run pass-through to the price indices is significantly positive in the period from 1980 to 2000 with point estimates indicating substantial pass-through, no ERPT estimate to any price index is significantly different from zero in the other two subsamples. Thus, there may be a considerable decline in the ERPT to all price indices over time. Yet, taking into consideration the huge confidence intervals, it is possible that no reduction in the ERPT has occurred. The point estimates and the significance of the estimates from these three subsamples are summarized in the tables 3 to 5.

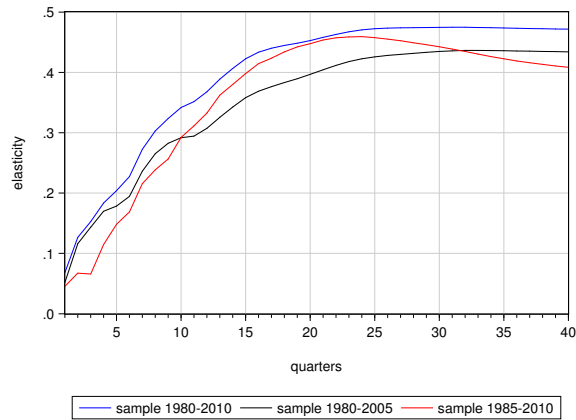


Figure 13: Estimated ERPT to consumer prices for different subsamples

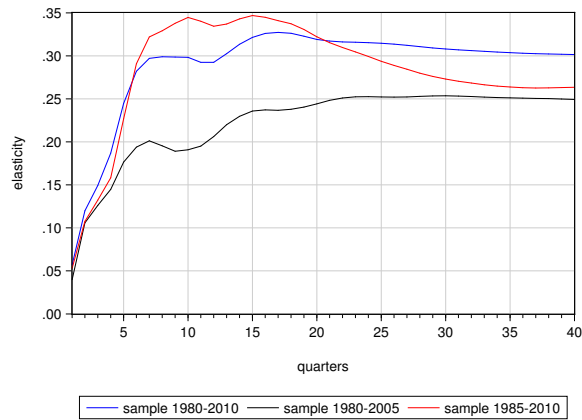


Figure 14: Estimated ERPT to producer prices for different subsamples

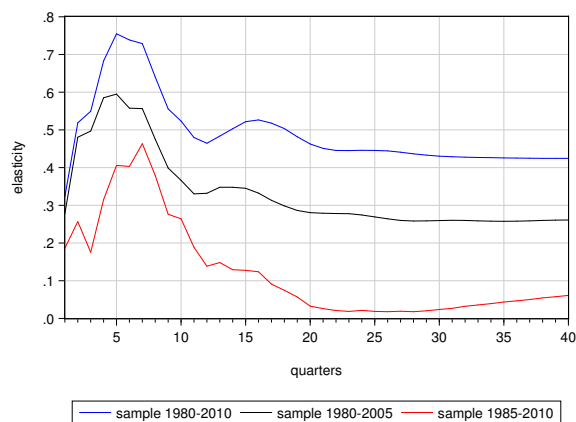


Figure 15: Estimated ERPT to import prices for different subsamples

| subsample    | years since the exchange rate shock |         |         |        |
|--------------|-------------------------------------|---------|---------|--------|
|              | 0                                   | 1       | 2       | 10     |
| 1980 to 2000 | 0.048*                              | 0.171** | 0.273** | 0.343  |
| 1985 to 2005 | 0.038                               | 0.104   | 0.177   | -0.070 |
| 1990 to 2010 | 0.035                               | 0.063   | 0.072   | 0.043  |

\* and \*\* indicate significance at the 10% and 5% level, respectively.

Table 3: Estimated ERPT to consumer prices and significance for different subsamples

| subsample    | years since the exchange rate shock |        |        |        |
|--------------|-------------------------------------|--------|--------|--------|
|              | 0                                   | 1      | 2      | 10     |
| 1980 to 2000 | 0.047*                              | 0.161* | 0.184  | 0.214  |
| 1985 to 2005 | 0.002                               | -0.008 | -0.040 | -0.172 |
| 1990 to 2010 | 0.008                               | 0.046  | 0.058  | 0.005  |

\* and \*\* indicate significance at the 10% and 5% level, respectively.

Table 4: Estimated ERPT to producer prices and significance for different subsamples

| subsample    | years since the exchange rate shock |         |        |        |
|--------------|-------------------------------------|---------|--------|--------|
|              | 0                                   | 1       | 2      | 10     |
| 1980 to 2000 | 0.309**                             | 0.702** | 0.577  | 0.416  |
| 1985 to 2005 | 0.152                               | 0.159   | -0.118 | -0.133 |
| 1990 to 2010 | 0.115                               | 0.216   | 0.000  | -0.016 |

\* and \*\* indicate significance at the 10% and 5% level, respectively.

Table 5: Estimated ERPT to import prices and significance for different subsamples

## 7.2 Model (I): alternative number of cointegrating relations

As discussed in section 6.1, the cointegration test does not conclusively indicate the number of cointegrating relations for model (I). Therefore, as a robustness check, this section analyzes and compares the ERPT which results if alternative numbers of cointegrating equations are used in the VEC model. Moreover, the pass-through estimates of the VEC models are compared to estimates from a VAR model. Since many previous studies presenting estimates for the ERPT have used VAR models, it is interesting to compare the results from this master thesis with the results of a VAR model that uses exactly the same data and sample period. The VAR model includes the same time series as the VEC models, but the series are differenced in order to be stationary. To increase comparability with the VEC model, the order of the VAR model is chosen identical to the number of lags of the endogenous variables in the VEC model.

Figures 16 to 18 show estimates of the ERPT to consumer, import and producer prices, respectively. For all price indices, the short-run pass-through is robust to variations in the number of cointegrating relations. Moreover, the dynamics of the pass-through change only slightly if a cointegrating relation is added or removed.

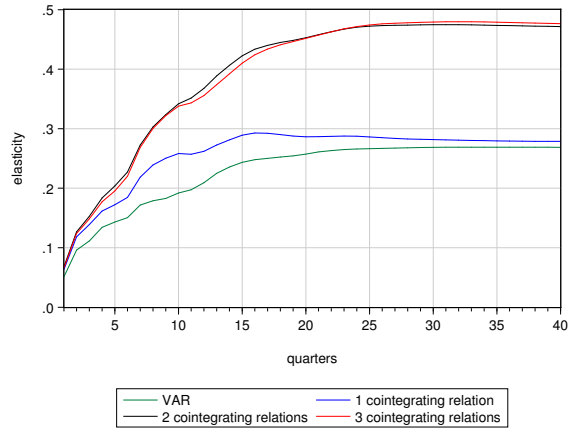


Figure 16: Comparison of the ERPT to consumer prices estimated using a VAR model and VEC models with different number of cointegrating relations

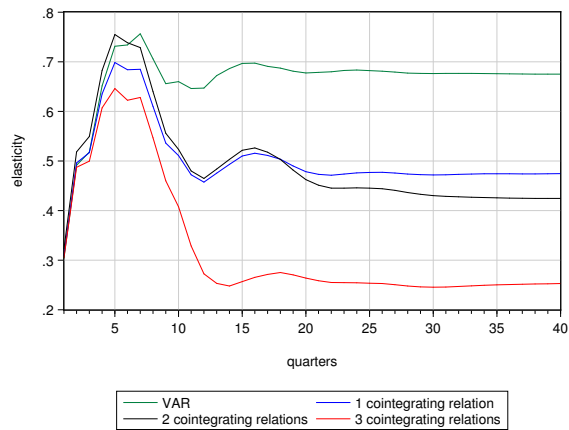


Figure 17: Comparison of the ERPT to import prices estimated using a VAR model and VEC models with different number of cointegrating relations

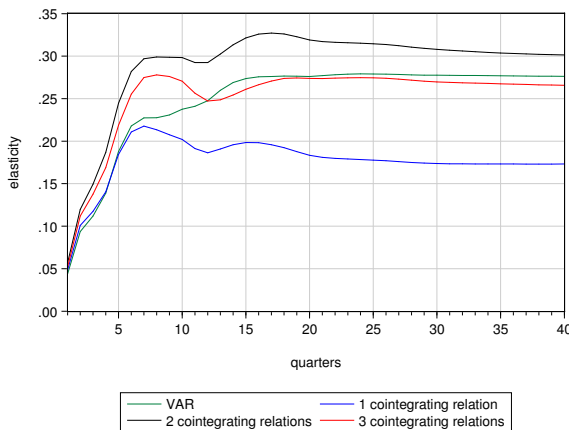


Figure 18: Comparison of the ERPT to producer prices estimated using a VAR model and VEC models with different number of cointegrating relations

The comparison of the long-run pass-through across the models is not based on the absolute ERPT elasticities. Instead, the long-run price change is related to the long-run exchange rate change in order to take into account differences in the long-run response of the exchange rate index to exchange rate shocks. These comparisons reveal some considerable differences in the long-run pass-through across the models.

For consumer prices, there is a substantial difference between the VEC model using one cointegrating relation and the VAR model on the one hand and the other VEC models on the other hand. The long-run pass-through is substantially lower if at most one cointegrating relation is considered: The ratio of the long-run price change to the long-run exchange rate change is below 0.3 for these models, while it exceeds 0.8 for the VEC models with two or three cointegrating relations.

The long-run change in import prices relative to the long-run exchange rate change is rather similar for all models (with ratios ranging from 0.44 to 0.53) except for the VEC model with two cointegrating relations (with a ratio of 0.76). Thus, the inclusion of the second cointegrating equation leads to a considerably higher long-run pass-through to import prices, but the inclusion of a third cointegrating relation reduces the ERPT again.

Similar to the ERPT to the CPI, the inclusion of the second cointegrating equation, which describes a long-run relation between exchange rates and price indices, makes a crucial difference for the estimated long-run ERPT to producer prices. The ratio of the long-run PPI change to the long-run exchange rate change is substantially lower for the VAR model and the VEC model with one cointegrating equation (with ratios below 0.25) compared to the VEC models with more cointegrating relations (with ratios exceeding 0.5).

The reason for the large difference between the VAR model and the VEC model with one cointegrating relation on the one hand and the VEC models with more cointegrating relations on the other hand is that the second cointegrating equation defines a long-run relation between exchange rates and price indices. Neglecting this long-run equilibrium relation makes a crucial difference for the estimation of the ERPT in the long-run. In contrast, since exchange rates have no significant impact in the first cointegrating equation, the differences between the VAR model and the VEC model with one cointegrating relation are small.

In summary, while the short-run ERPT estimates and the pass-through dynamics are robust both to alternative numbers of cointegrating relations and to the estimation of a VAR instead of a VEC model, there are some considerable differences regarding the long-run estimates. This finding is not surprising, since the cointegrating equations describe long-run equilibrium relations. While the results of the VAR model and the VEC model with one cointegrating equation are rather similar, including the second cointegrating relation substantially increases the long-run ERPT. Hence, the analysis shows that if cointegrating relations describe a relation between exchange rates and prices, they should

be included in the model for a proper estimation of the ERPT to prices.

### 7.3 Model (II): analysis of subsamples

Out of the entire sample ranging from 1983 to 2010, a huge number of subsamples could be selected for separate analysis. Similar to the procedure chosen for model (I), this section shows the results for subsamples that are reduced by five years of observations. In particular, the ERPT is presented for the subsamples ranging from 1983 to 2005 and from 1988 to 2010.

Figure 19 shows that the ERPT to import prices features a similar dynamic pattern in both subsamples and in the entire sample. Moreover, the estimated pass-through elasticities are almost identical in the first subsample and in the complete sample. However, the ERPT to import prices is substantially lower in the second subsample. It is still positive on impact, but it is already insignificant one year after the shock, while these estimates are still significantly positive for the first subsample and for the entire sample (table 6).

A similar conclusion can be drawn for the CPI of goods. The estimated ERPT is very similar in the period from 1983 to 2005 and in the entire sample, both with respect to the extent and to the dynamics of pass-through (figure 20). However, it is quite different for the subsample from 1988 to 2010. The dynamics are different; the distinct hump-shape has vanished. Moreover, the ERPT is not significantly different from zero at the 5% level in the second subsample, while it is significant both for the subsample from 1983 to 2005 and for the entire sample up to one year after the shock (table 7).

For the service price inflation at the consumer level, the point estimates indicate a reduction in the ERPT over time (figure 21). In the earlier subsample, a depreciation shock leads to a significantly higher service price inflation one year after the shock (table 8). In contrast, the exchange rate shock has no significant impact on consumer price inflation for services in the second subsample and in the total sample.

Overall, these results indicate a reduction of the ERPT over time. Of course, due to the large confidence intervals, this conclusion is not necessarily true. But evidence points in that direction since, for the second subsample, there are almost no ERPT estimates that are significantly positive while there are many significant estimates for the first subsample. This is in line with the findings from model (I) which also point towards a decline in ERPT over time. But as a consequence of the large confidence bounds, it is still possible that no reduction in the ERPT has occurred.

### 7.4 Model (II): alternative number of cointegrating relations

The cointegration test for model (II) (section 6.3) has shown that there are either one or two cointegrating relations. For reasons discussed in section 6.3, model (II) was estimated with two cointegrating relations. As a robustness check, this section presents the pass-



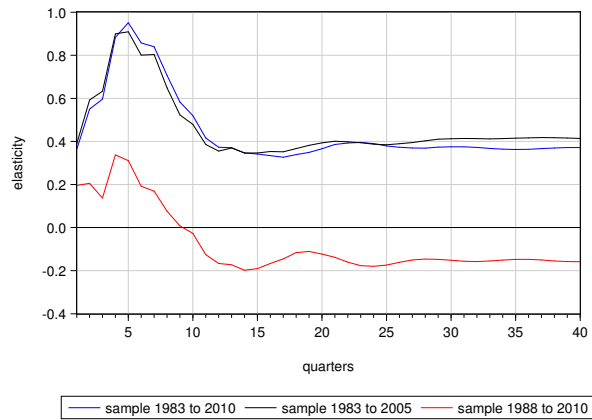


Figure 19: Estimated ERPT to import prices for different subsamples

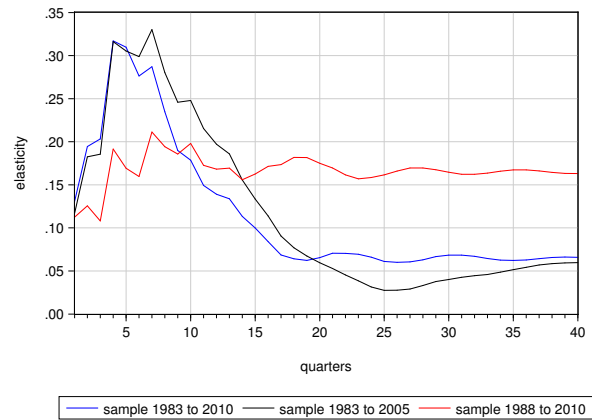


Figure 20: Estimated ERPT to consumer prices of goods for different subsamples

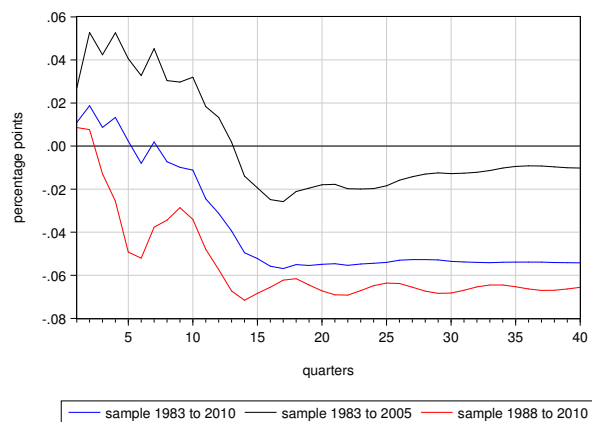


Figure 21: Estimated ERPT to consumer price inflation of services for different subsamples

| subsample    | years since the exchange rate shock |         |        |        |
|--------------|-------------------------------------|---------|--------|--------|
|              | 0                                   | 1       | 2      | 10     |
| 1983 to 2010 | 0.364**                             | 0.883** | 0.707* | 0.372  |
| 1983 to 2005 | 0.390**                             | 0.899** | 0.649  | 0.414  |
| 1988 to 2010 | 0.196*                              | 0.338   | 0.076  | -0.158 |

\* and \*\* indicate significance at the 10% and 5% level, respectively.

Table 6: Estimated ERPT to import prices and significance for different subsamples

| subsample    | years since the exchange rate shock |         |       |       |
|--------------|-------------------------------------|---------|-------|-------|
|              | 0                                   | 1       | 2     | 10    |
| 1983 to 2010 | 0.131**                             | 0.317** | 0.235 | 0.066 |
| 1983 to 2005 | 0.117**                             | 0.316** | 0.280 | 0.060 |
| 1988 to 2010 | 0.112*                              | 0.192   | 0.194 | 0.163 |

\* and \*\* indicate significance at the 10% and 5% level, respectively.

Table 7: Estimated ERPT to consumer prices of goods and significance for different subsamples

| subsample    | years since the exchange rate shock |         |        |        |
|--------------|-------------------------------------|---------|--------|--------|
|              | 0                                   | 1       | 2      | 10     |
| 1983 to 2010 | 0.011                               | 0.013   | -0.007 | -0.054 |
| 1983 to 2005 | 0.027                               | 0.053** | 0.030  | -0.010 |
| 1988 to 2010 | 0.009                               | -0.026  | -0.034 | -0.066 |

\* and \*\* indicate significance at the 10% and 5% level, respectively.

Table 8: Estimated ERPT to consumer price inflation of services and significance for different subsamples

through estimates of the model which includes only one cointegrating relation. In addition, it compares the ERPT estimates from a VAR model and VEC models with one, two and three cointegrating relations.

For the model with one cointegrating relation, figure 22 depicts the impulse responses of exchange rates, import prices, consumer prices for goods and the consumer price inflation of services in response to a depreciation shock of one percent. In the short-run, the ERPT is very similar to the estimates presented in section 6.4. However, there are some differences with respect to the dynamics and the long-run pass-through. The distinct hump-shaped pattern is not present any more for the impulse response functions of exchange rates, import prices and consumer prices for goods and the adjustment occurs more quickly than in the original model (II). Moreover, the long-run ERPT estimates are higher for all prices. As a consequence, more estimates are significantly different from zero. The ERPT to the IPI is significantly positive in the long-run at the 5% level. For the CPI of goods, this holds at the 10% level. Only the response of the CPI inflation of services is still not significantly different from zero at all.

Table 9 summarizes the ERPT estimates of the VEC models with one and two cointegrating relations and of the VAR model. It reports for the IPI and for the CPI of goods

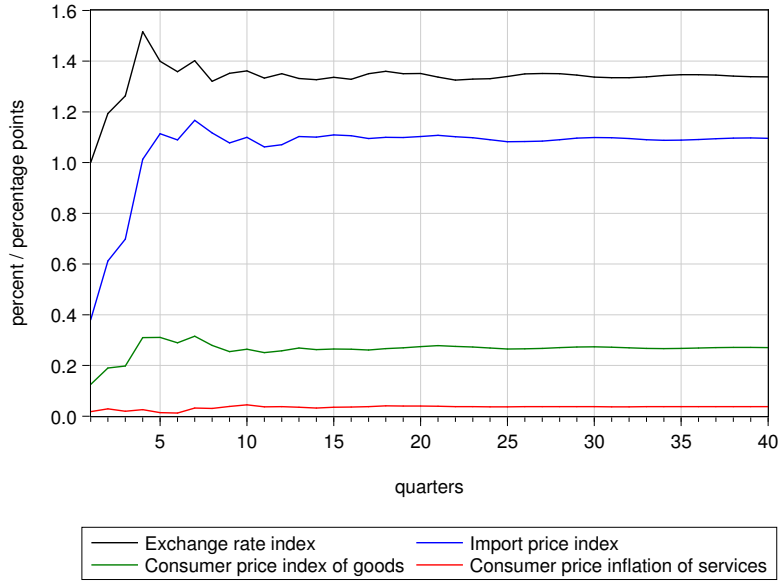


Figure 22: Response in percent of exchange rates, import prices and consumer prices for goods, and response in percentage points of consumer price inflation for services to an exchange rate shock according to the VEC model incorporating one cointegrating relation

both the ratio of the price change on impact to the initial exchange rate change and the ratio of the long-run price change to the long-run exchange rate change. The VAR model finds a somewhat smaller short-run impact of exchange rate shocks on import prices and on consumer prices for goods, but the long-run pass-through is similar to the VEC models.

|                          | ratio of price index change to exchange rate change |                  |              |                  |                 |             |
|--------------------------|---|------------------|--------------|------------------|-----------------|-------------|
|                          | short-run   |                  |              | long-run         |                 |             |
|                          | (I)<br>1 point.                                     | (II)<br>2 point. | (III)<br>VAR | (IV)<br>1 point. | (V)<br>2 point. | (VI)<br>VAR |
| import prices            | 0.380   | 0.364            | 0.315        | 0.819            | 0.621           | 0.635       |
| consumer prices of goods | 0.125   | 0.131            | 0.086        | 0.202            | 0.110           | 0.192       |

*Short-run* refers to the quarter when the shock occurs.  
*Long-run* is defined as ten years after the initial shock.

Table 9: Comparison of the ratio of price change to exchange rate change of the VAR model and the VEC models with 1 and 2 cointegrating relations

Figures 23 and 24 plot the estimated ERPT to import prices and to the CPI of goods, respectively. The results for the short-run pass-through are robust across the VEC models. The dynamic evolution of the pass-through seems to differ across the VAR and VEC models, but these differences can largely be attributed to the distinct impulse response of exchange rates to a depreciation shock. This response is much more hump-shaped in the VEC models with two or three cointegrating relations, which translates into the reaction of prices. Thus, the comparison indicates that the impulse response function of the exchange rate index rather than the response of the IPI or the CPI of goods tends to lack robustness with respect to the dynamics.

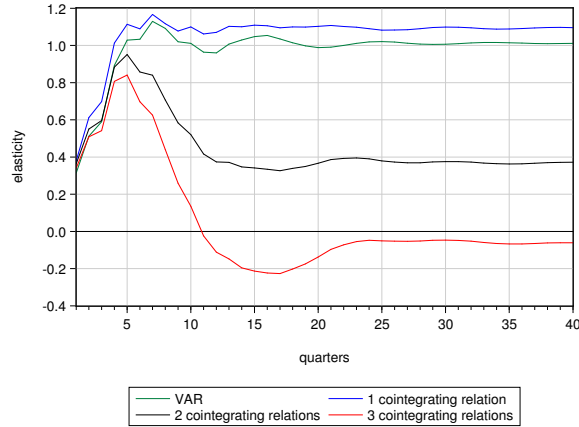


Figure 23: Comparison of the ERPT to import prices estimated using a VAR model and VEC models with different number of cointegrating relations

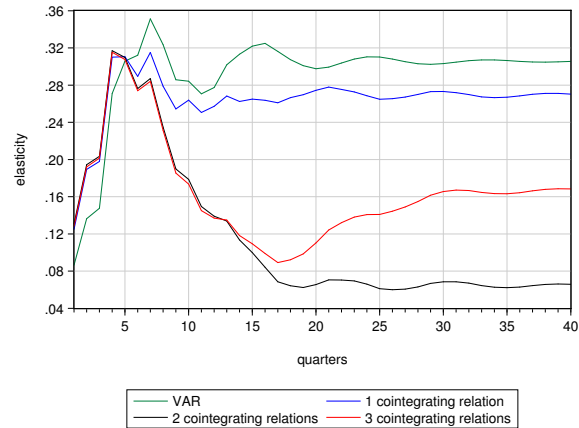


Figure 24: Comparison of the ERPT to consumer prices for goods estimated using a VAR model and VEC models with different number of cointegrating relations

The comparison of the long-run price changes relative to the long-run exchange rate changes in the aftermath of a depreciation shock indicates that the long-run pass-through results are mostly robust to alternative numbers of cointegrating relations. The estimates from the VAR model and the VEC models are relatively close compared to the large confidence intervals, except for the model with three cointegrating relations, which indicates a substantially lower and even slightly negative pass-through to the IPI in the long-run. But this is no major problem since the cointegration test for model (II) (section 6.3) does not indicate three cointegrating relations, but either one or two, and for these two models, the results are quite robust.

The estimated impact of exchange rate shocks on the consumer price inflation of services is not significantly different from zero both for the VAR model and for all VEC models. Thus, the findings of the models regarding the pass-through to the CPI inflation

of services are qualitatively consistent.

Overall, the results of model (II) are quite robust to the addition or the removal of a cointegrating relation. Moreover, the comparison of the VAR model and the VEC models reveals only relatively small differences.

## 7.5 Model (III): analysis of subsamples

This section shows pass-through estimates of model (III) for the same subsamples for which model (II) is analyzed in section 7.3. That is, the ERPT is presented for the subsamples ranging from 1983 to 2005 and from 1988 to 2010.

The estimates of the ERPT to import prices of the entire sample resemble the estimates of the period from 1983 to 2005 (figure 25). In the short-run, the ERPT is almost identical. Moreover, the dynamic evolution is similar. The only noteworthy difference consists in the long-run pass-through, for which the estimates are lower in the subsample from 1983 to 2005. The ERPT to the IPI differs much more in the subsample from 1988 to 2010. It is substantially lower than in the first subsample and in the entire sample. Except for the pass-through on impact, which is significantly different from zero at the 10% level, exchange rate shocks have no significant impact on import prices in the second subsample (table 10). In contrast, there are significantly positive estimates for the first subsample and the total sample.

The analysis of the ERPT to the CPI of foreign goods shows that there are almost no differences between the first subsample and the total sample (figure 26). However, the point estimates for the more recent subsample are again substantially lower. As a consequence, the estimates for these subsamples are only significantly different from zero on impact at the 10% level (table 11). In contrast, the ERPT is significantly positive at the 5% level for more than one year in both the subsample from 1983 to 2005 and the total sample. However, since the confidence intervals are large, the difference between the ERPT estimates is too small to allow the conclusion that the pass-through to consumer prices for goods of foreign origin has declined.

The comparison of the subsamples regarding the consumer price inflation of domestic goods indicates a decline in pass-through over time. Both the short-run and the long-run estimates are lower in the subsample from 1988 to 2010 (figure 27). In the earlier subsample, a depreciation shock leads to a significant increase in consumer price inflation for goods of domestic origin one year after the shock (table 12). For the total sample and the second subsample, no estimates are significantly different from zero.

Overall, the analysis in this section indicates that the impact of exchange rate shocks on the price indices of model (III) has declined over time. As the confidence intervals are large, this conclusion might be only due to imprecise estimates. Nevertheless, the finding that all point estimates are lower for the more recent subsample and hardly significantly

different from zero provides evidence for a decline in the ERPT.

| subsample    | years since the exchange rate shock |         |         |        |
|--------------|-------------------------------------|---------|---------|--------|
|              | 0                                   | 1       | 2       | 10     |
| 1983 to 2010 | 0.370**                             | 0.900** | 0.917** | 0.731* |
| 1983 to 2005 | 0.351**                             | 0.887** | 0.741   | 0.505  |
| 1988 to 2010 | 0.181*                              | 0.243   | 0.016   | -0.128 |

\* and \*\* indicate significance at the 10% and 5% level, respectively.

Table 10: Estimated ERPT to import prices and significance for different subsamples

| subsample    | years since the exchange rate shock |         |         |        |
|--------------|-------------------------------------|---------|---------|--------|
|              | 0                                   | 1       | 2       | 10     |
| 1983 to 2010 | 0.204**                             | 0.492** | 0.450** | 0.328* |
| 1983 to 2005 | 0.192**                             | 0.550** | 0.543*  | 0.316  |
| 1988 to 2010 | 0.168*                              | 0.268   | 0.300   | 0.198  |

\* and \*\* indicate significance at the 10% and 5% level, respectively.

Table 11: Estimated ERPT to consumer prices for goods of foreign origin and significance for different subsamples

| subsample    | years since the exchange rate shock |         |        |        |
|--------------|-------------------------------------|---------|--------|--------|
|              | 0                                   | 1       | 2      | 10     |
| 1983 to 2010 | 0.018                               | 0.014   | 0.011  | -0.015 |
| 1983 to 2005 | 0.031                               | 0.045** | 0.031  | -0.003 |
| 1988 to 2010 | 0.005                               | -0.014  | -0.019 | -0.049 |

\* and \*\* indicate significance at the 10% and 5% level, respectively.

Table 12: Estimated ERPT to consumer price inflation for goods of domestic origin and significance for different subsamples

## 7.6 Model (III): alternative number of cointegrating relations

The Johansen test for model (III) indicates two cointegrating relations at the 10% level, but only one at the 5% level (section 6.5). Section 6.6 has presented the ERPT estimated using a model with two cointegrating relations. This section shows the pass-through estimates of the model with only one cointegrating equation. Moreover, it provides a comparison of the ERPT estimated using a VAR model and VEC models with one, two and three cointegrating relations.

For the model estimated with one cointegrating relation, figure 28 depicts the impulse response functions of exchange rates, import prices, consumer prices for goods of foreign origin and consumer price inflation for goods of domestic origin in response to a depreciation shock of one percent. The ERPT on impact is very similar to the results of section 6.6. The same holds for the dynamics and for the long-run changes in the IPI and in the CPI of foreign goods, provided that the ratio of the long-run price change to

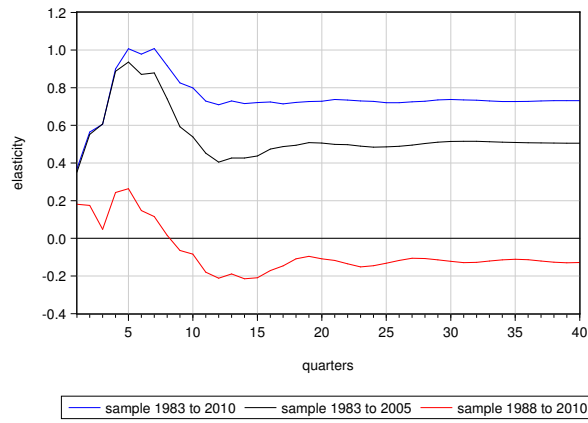


Figure 25: Estimated ERPT to import prices for different subsamples

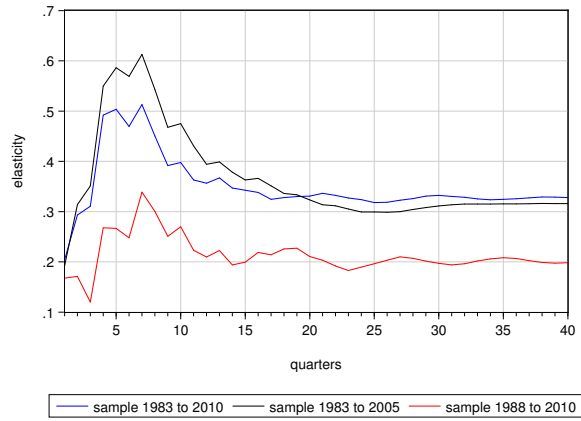


Figure 26: Estimated ERPT to consumer prices for goods of foreign origin for different subsamples

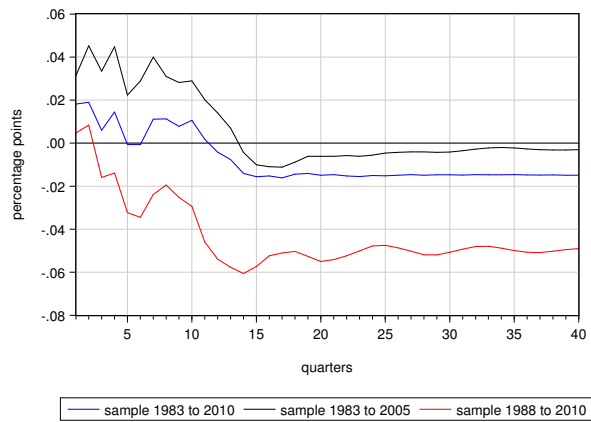


Figure 27: Estimated ERPT to consumer price inflation for goods of domestic origin for different subsamples

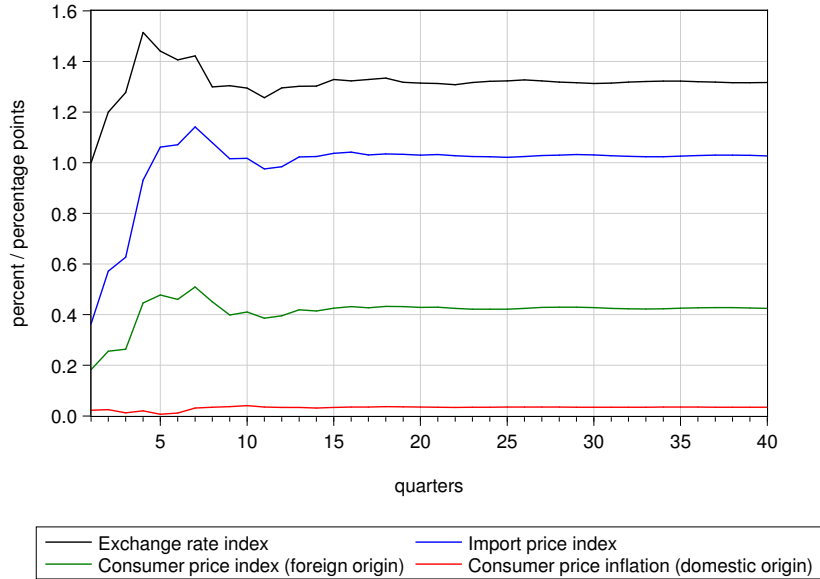


Figure 28: Response in percent of exchange rates, import prices and consumer prices for goods of foreign origin, and response in percentage points of consumer price inflation for goods of domestic origin in response to an exchange rate shock according to the VEC model incorporating one cointegrating relation

the long-run exchange rate change is considered. The models differ with respect to the significance of several ERPT estimates. According to the model with one cointegrating relation, the long-run pass-through to the IPI and to the CPI for goods of foreign origin are significantly different from zero at the 5% level, instead of the 10% level as in section 6.6. Moreover, the model incorporating one cointegrating relation finds a significantly positive impact on the CPI inflation of domestic goods in the quarter when the depreciation shock occurs, whereas the original model fails to find a significant response.

Table 13 summarizes the pass-through estimates of the VEC models with one and two cointegrating relations and of the VAR model. For both the IPI and the CPI of foreign goods, the table reports the ratio of the price change on impact to the initial exchange rate change and the ratio of the long-run price change to the long-run exchange rate change. Compared to the two VEC models, the VAR model tends to indicate somewhat lower pass-through both for the short-run and the long-run. However, the differences are small compared to the large confidence intervals.

Figure 29 compares the ERPT to the IPI estimated using a VAR model and VEC models with one, two and three cointegrating relations. The short-run pass-through estimates are robust across the models, albeit the point estimates are somewhat lower for the VAR model and the VEC model with three cointegrating relations. The dynamics of the ERPT to import prices are qualitatively similar, but there are quantitative differences. The long-run pass-through, measured as long-run change in the IPI relative to the long-run exchange rate change, almost coincides for the VEC models with one and two



|                                  | ratio of price index change to exchange rate change |          |       |          |          |       |
|----------------------------------|---|----------|-------|----------|----------|-------|
|                                  | short-run   |          |       | long-run |          |       |
|                                  | (I)   | (II)     | (III) | (IV)     | (V)      | (VI)  |
|                                  | 1 coint.  | 2 coint. | VAR   | 1 coint. | 2 coint. | VAR   |
| import prices                    | 0.364   | 0.370    | 0.318 | 0.780    | 0.790    | 0.633 |
| consumer prices (foreign origin) | 0.183   | 0.204    | 0.141 | 0.322    | 0.354    | 0.303 |

*Short-run* refers to the quarter when the shock occurs.  
*Long-run* is defined as ten years after the initial shock.

Table 13: Comparison of the ratio of price change to exchange rate change of the VAR model and the VEC models with 1 and 2 cointegrating relations

cointegrating relations, but it is somewhat lower for the VAR model and substantially lower for the VEC model with three cointegrating relations.

The comparison of the ERPT to consumer prices for goods of foreign origin shows that the results for the short-run are very robust across the VEC models, while the VAR model indicates a lower pass-through in the first few quarters after the exchange rate shock (figure 30). The ratio of the long-run change in the CPI of foreign goods to the long-run exchange rate change is similar for all four models. The price dynamics relative to the impulse response function of the exchange rate index are robust as well, except for the model with three cointegrating relations.

The findings of the VAR model and the VEC models are robust with respect to the impact of exchange rate shocks on the consumer price inflation for goods of domestic origin. No model finds a significant impact, except for the VEC model with one cointegrating relation, which indicates that a depreciation shock leads to a significantly higher CPI inflation of domestic goods in the quarter when the shock occurs.

In summary, the results of model (III) are almost identical to the findings of the VEC model with one cointegrating relation. This is very important, since the cointegration test for model (III) (section 6.5) indicates either one or two cointegrating relations. The results are also similar to the estimates from a VAR model, although the VAR model indicates somewhat lower pass-through. However, the findings are only partially robust to the inclusion of a third cointegrating relation.

## 8 Conclusion

In recent years, many studies have investigated the ERPT to various price indices. Theoretical considerations reveal that the pass-through from exchange rate shocks to prices is a complex transmission mechanism depending on many country-specific factors. As a consequence, separate estimations of the ERPT have to be conducted for different countries. Previous studies have mostly relied on single equation or VAR models to estimate the ERPT to prices. This master thesis contributes to the existing evidence on the ERPT in two respects: Firstly, it uses an alternative estimation method, namely a VEC model.

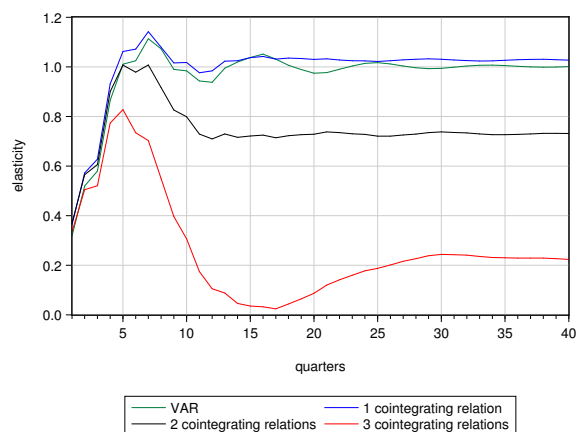


Figure 29: Comparison of the ERPT to import prices estimated using a VAR model and VEC models with different number of cointegrating relations

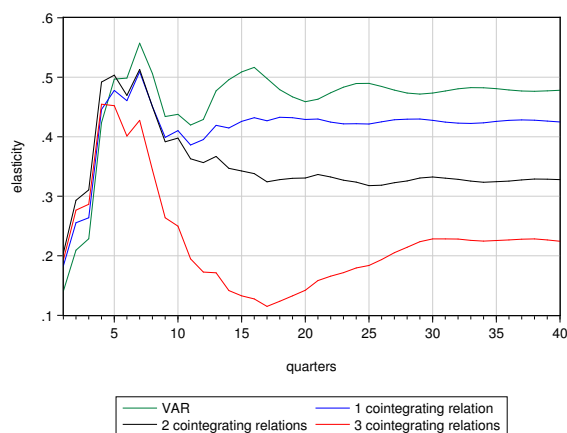


Figure 30: Comparison of the ERPT to consumer prices for goods of foreign origin estimated using a VAR model and VEC models with different number of cointegrating relations

VEC models feature the advantage of incorporating both short-run dynamic interactions between the variables and long-run equilibrium relations contained in the variable levels. For Switzerland, the ERPT has not yet been analyzed in the framework of a VEC model. Moreover, evidence on the ERPT based on VEC models is in general scarce. Secondly, this master thesis contributes to the evidence on the ERPT by analyzing the pass-through to various sub-indices of the CPI.

The results of this master thesis reveal a significant impact of exchange rate shocks on various price indices. In the short-run, the ERPT elasticity is highest for import prices (estimates range from 0.32 to 0.37 within the quarter when the shock occurs), followed by consumer prices for goods of foreign origin (ERPT elasticity on impact of 0.20), consumer prices for goods (0.13), the aggregate CPI (0.07) and producer prices (0.06). The CPI inflation for services and for goods of domestic origin show no significant response to

exchange rate shocks.

The duration of the adjustment process increases along the distribution chain. Import prices adjust relatively quickly to exchange rate shocks. Still, they need more than a year to complete a large part of the adjustment. The adjustment dynamics follow, with a small lag, the evolution of the exchange rates. Producer prices complete their adjustment within two years after the shock. The aggregate CPI adjusts slowly and steadily to exchange rate shocks. It needs more than four years in order to complete the adjustment. Consumer prices for goods and, in particular, for goods of foreign origin react more quickly than the overall CPI, but slower than producer and import prices.

For the long-run estimates, confidence intervals are large. Nevertheless, ERPT to some prices indices is significant even in the long-run. Model (I) finds that exchange rate shocks have a long-run impact on the aggregate CPI which is significant at the 10% level. Model (III) indicates that the long-run ERPT is significantly different from zero both for import prices and for the CPI of foreign goods. For import prices, none of the models can reject the hypothesis of a long-run ERPT of one. Point estimates indicate that the long-run ERPT is substantial for import, producer and consumer prices. The ratio of the long-run price change relative to the long-run exchange rate change ranges from 0.62 to 0.79 for import prices and amounts to 0.54 and 0.84 for the PPI and the CPI, respectively. There is an inconsistency regarding the results of the different models with respect to consumer prices since the long-run ERPT to all CPI sub-indices is substantially lower than the long-run pass-through to the aggregate CPI. However, taking into account that there are huge confidence intervals for the long-run estimates, the inconsistency could simply be due to imprecise estimates.

The analysis of several subsamples indicates that the ERPT has declined over time for all price (sub-)indices. Because of the large confidence intervals, this conclusion has to be made with caution. Yet, the fact that there is hardly any significant ERPT estimate in the more recent subsamples while there are many significant estimates in the earlier subsamples points towards a reduction in pass-through.

A comparison of the results from the VEC models with estimates from VAR models shows that a large part of the results is qualitatively similar. However, the VAR models tend to find somewhat lower pass-through estimates for many price indices. For some prices, the long-run ERPT estimates of the VAR are considerably lower.

The findings of this master thesis have important implications. The results shed light on the ERPT transmission mechanism and its determinants. First of all, assuming that import prices are sticky within a quarter, the ERPT on impact is high if most import prices are set in foreign currency (PCP) and low if most prices are set in local currency (LCP). Since a one percent depreciation shock leads to an increase in import prices of less than 0.4%, the results suggest that a majority of import prices is set in local currency. This is in line with the theoretical considerations of Devereux and Engel (2001) who find

that countries with a stable monetary policy are likely to have their import prices set in their own currency and, as a consequence, face a low ERPT. Thus, sticky prices combined with LCP provide a possible explanation for the incomplete ERPT to Swiss import prices in the short-run.

Secondly, the gap between the short-run ERPT elasticity of import prices and consumer prices highlights the importance of transportation and distribution costs as well as the presence of non-tradable goods. In addition, consumer prices adjust much slower to exchange rate shocks than import prices. Moreover, the short-run ERPT is lower for the aggregate CPI than for the CPI of goods, which is in turn lower than for the CPI of foreign goods. Thus, price indices which include non-tradable goods or which depend to a larger amount on transportation and distribution costs react to a lower extent to exchange rate shocks.

Thirdly, the finding of incomplete ERPT to import prices in the long-run may emphasize the importance of imperfect competition and international price discrimination. However, since the confidence intervals grow large, the long-run pass-through to import prices is not significantly different from one.

Beyond providing a better understanding of the ERPT mechanism and its determinants, the findings of this master thesis have also important implications for policy. The results show that exchange rate shocks have significant, substantial and long-lasting effects on various price indices, which is important to know for any institution that forecasts inflation. In particular, central banks which target price stability should incorporate the inflationary effects of exchange rate movements when deciding on their policy.

Finally, the results of this master thesis have methodological implications. For the long-run pass-through estimates, the differences between the VAR and the VEC models can be substantial. Thus, the findings of this master thesis show that it is reasonable to test for cointegrating relations and, if there are some, to include them in the model, in particular if there is a cointegrating relation between exchange rates and prices.

There are several limitations of this study. First of all, the estimated models lack theoretical foundation. They are not general equilibrium models that are derived from the optimizing behavior of economic agents. Hence, the Lucas critique (Lucas, 1976) applies. This study is a purely data-based examination of the ERPT based on models which are rather ad hoc and using aggregated data. However, this is an appropriate approach for the purpose of this thesis and it can be seen as complementary to the evidence from general equilibrium models. An additional limitation is given by the identifying assumptions, which are open to dispute. However, solving the identification problem requires some assumptions and the assumptions chosen in this thesis are frequently used in the empirical literature on the ERPT and are based on empirical evidence. An additional problem of the analysis in this master thesis is given by the lack of robustness of some results. In particular, the Johansen test does not unambiguously indicate the number of cointegrating

relations. Moreover, the analysis of subsamples reveals that the number of cointegrating relations fluctuates over time. This may be problematic since the number of cointegrating relations has a substantial impact on some long-run results. Thus, the long-run findings of this master thesis can only be interpreted with caution.

The results and limitations of this master thesis reveal several directions for future research. First of all, the decline in the ERPT over time indicated by the results of this thesis requires a detailed analysis with respect to its causes. Potential reasons for a decrease in the long-run pass-through are a decline in competition or a lower share of imports. However, the share of imports to GDP has increased for Switzerland, which should increase the ERPT. Thus, other reasons should be analyzed. A possible reason for the decline in the short-run pass-through is an increase in the stability of monetary policy. Structural break tests could be used to check whether policy changes, for example the change in the monetary policy concept of the Swiss National Bank in 2000, have had an impact on the ERPT. Structural breaks may also be a reason for changes in the number of cointegrating relations. Secondly, the ERPT to Swiss prices could be estimated by setting up a dynamic stochastic general equilibrium (DSGE) model. According to the Lucas critique (Lucas, 1976), policy changes can systematically alter the structure of econometric models. There are many possible policy changes which may affect the ERPT. Moreover, the ERPT depends on factors which change over time, such as the import share or the degree of competition. As a consequence, the ERPT is likely to vary over time. Therefore, it might be very interesting to set up a DSGE model which provides results that are robust to policy changes and which allows simulating the effect of changes in import share or competition on the ERPT. Thirdly, since this master thesis is one of the first studies estimating the ERPT in the framework of a VEC model, further research on the pass-through using this method is desirable, for example by repeating the analysis with data from other countries. Finally, a further direction for future research consists in the estimation of the ERPT to more disaggregated prices. An analysis of prices on the sectoral level may shed further light on the importance of various influencing factors for the complex transmission mechanism from exchange rate shocks to price adjustments.

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# Appendices

## Appendix A: Derivation of equations of the theoretical model of international strategic pricing

### Expenditure minimization problem

Utility of the representative household in period  $t$  is a function of a composite consumption good  $C_t$ , which is a Dixit-Stiglitz aggregate of  $C_{j,t}$ , the consumption of good  $j$  in period  $t$ . Utility does not directly depend on the consumption of each good  $j$ ,  $C_{j,t}$ . As a consequence, independent of the amount of  $C_t$  that the household wants to consume, it chooses  $C_{j,t}$  such as to minimize expenditure for the desired amount of  $C_t$ . Thus, the household wants to minimize

$$\sum_{j=1}^N C_{j,t} P_{j,t} \quad (27)$$

by choosing  $C_{j,t}$ , subject to

$$\left( \sum_{j=1}^N C_{j,t}^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}} = \bar{C}, \quad (28)$$

i.e. the composite consumption good  $C_t$  is equal to the desired amount  $\bar{C}$ .  $P_{j,t}$  denotes the price of good  $j$  in period  $t$ .  $N$  denotes the number of different goods in the economy. The Lagrangian of this minimization problem reads as follows:

$$\mathcal{L} = \sum_{j=1}^N C_{j,t} P_{j,t} - \lambda \left[ \left( \sum_{j=1}^N C_{j,t}^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}} - \bar{C} \right]. \quad (29)$$

The first order condition with respect to  $C_{j,t}$  is given by:

$$P_{j,t} = \lambda C_t^{\frac{1}{\theta}} C_{j,t}^{-\frac{1}{\theta}}, \quad (30)$$

in which  $C_t$  is the Dixit-Stiglitz aggregate of  $C_{j,t}$ :

$$C_t = \left[ \sum_{j=1}^N C_{j,t}^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}}. \quad (31)$$

Let  $Z_t$  denote the total expenditure for consumption goods in period  $t$  at the optimum of the household. Using the first order condition (equation (30)),  $Z_t$  is characterized by the following equation:

$$Z_t = \sum_{j=1}^N C_{j,t} P_{j,t} = \sum_{j=1}^N \lambda C_t^{\frac{1}{\theta}} C_{j,t}^{\frac{\theta-1}{\theta}} = \lambda C_t^{\frac{1}{\theta}} C_t^{\frac{\theta-1}{\theta}} = \lambda C_t. \quad (32)$$

The price index of the economy,  $P_t$ , is defined as the minimum expenditure needed to buy one unit of  $C_t$ . Thus, by equation (32),  $P_t = \lambda$  holds. Plugging this relation into equation (30) yields

$$P_{j,t} = P_t C_t^{\frac{1}{\theta}} C_{j,t}^{-\frac{1}{\theta}}. \quad (33)$$

Rearranging leads to

$$C_{j,t} = \left( \frac{P_{j,t}}{P_t} \right)^{-\theta} C_t. \quad (34)$$

This equation shows that the demand for good  $j$  in period  $t$  depends on the relative price  $\frac{P_{j,t}}{P_t}$ , total (aggregate) consumption  $C_t$  and on  $\theta$ , the elasticity of substitution across goods. Given some simplifying assumptions, namely that demand for good  $j$  is given by the demand of private households (i.e. there is no government demand) and that aggregate demand  $Y_t$  is equal to aggregate consumption  $C_t$ , equation (34) can be rewritten as follows:

$$C_{j,t} = \left( \frac{P_{j,t}}{P_t} \right)^{-\theta} C_t = \left( \frac{P_{j,t}}{P_t} \right)^{-\theta} Y_t = Y_{j,t}, \quad (35)$$

which is the demand function for a generic good  $j$  used in the theoretical analysis of this master thesis (equation (3)).

### Aggregate price index

The formula for the overall price index (equation (4) in the theoretical analysis section) can be derived by plugging equation (34) into equation (31) and by rearranging:

$$\begin{aligned} C_t &= \left[ \sum_{j=1}^N C_{j,t}^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}} = \left[ \sum_{j=1}^N \left[ \left( \frac{P_{j,t}}{P_t} \right)^{-\theta} C_t \right]^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}} \\ 1 &= \left[ \sum_{j=1}^N \left( \frac{P_{j,t}}{P_t} \right)^{1-\theta} \right]^{\frac{\theta}{\theta-1}} = P_t^\theta \left[ \sum_{j=1}^N P_{j,t}^{1-\theta} \right]^{\frac{\theta}{\theta-1}} \\ P_t &= \left( \sum_{j=1}^N P_{j,t}^{1-\theta} \right)^{\frac{1}{1-\theta}}. \end{aligned} \quad (36)$$

### Profit maximization of domestic firms

The profit function of a domestic firm  $i$  in period  $t$  is characterized by the following equation:

$$\Pi_{i,t} = \left( P_{i,t} - \frac{W_t^h}{A_t^h} \right) \left( \frac{P_{i,t}}{P_t} \right)^{-\theta} Y_t. \quad (37)$$

Maximizing profits with respect to  $P_{i,t}$  yields the following first order condition:

$$\left(\frac{P_{i,t}}{P_t}\right)^{-\theta} Y_t - \theta \left(P_{i,t} - \frac{W_t^h}{A_t^h}\right) Y_t \left(\frac{P_{i,t}}{P_t}\right)^{-\theta-1} \left(\frac{P_t - P_{i,t} \frac{\partial P_t}{\partial P_{i,t}}}{P_t^2}\right) = 0. \quad (38)$$

Rearranging leads to

$$P_{i,t} = \theta \left(P_{i,t} - \frac{W_t^h}{A_t^h}\right) \left(1 - \frac{\partial P_t}{\partial P_{i,t}} \frac{P_{i,t}}{P_t}\right). \quad (39)$$

The elasticity of the price index,  $P_t$ , with respect to the price of a domestic firm  $i$ ,  $P_{i,t}$ , is denoted as  $\psi_{i,t}$ . Then, solving for  $P_{i,t}$  yields the equation

$$P_{i,t} = \frac{\theta(1 - \psi_{i,t})}{\theta(1 - \psi_{i,t}) - 1} \frac{W_t^h}{A_t^h}, \quad (40)$$

which is exactly equation (10) in section 3.1.

### Profit maximization of foreign firms

Assuming that foreign firms set their prices in the currency of the country in which the products are sold, profits in foreign currency of a foreign firm  $j$  in period  $t$  are characterized by the following equation:

$$\Pi_{j,t}^* = \left(\frac{P_{j,t}}{S_t} - \frac{W_t^{f*}}{A_t^f}\right) \left(\frac{P_{j,t}}{P_t}\right)^{-\theta} Y_t. \quad (41)$$

Variables denoted with a \* are denominated in foreign currency. Maximization with respect to  $P_{j,t}$  yields the following first order condition:

$$\frac{1}{S_t} \left(\frac{P_{j,t}}{P_t}\right)^{-\theta} Y_t - \theta \left(\frac{P_{j,t}}{S_t} - \frac{W_t^{f*}}{A_t^f}\right) Y_t \left(\frac{P_{j,t}}{P_t}\right)^{-\theta-1} \left(\frac{P_t - P_{j,t} \frac{\partial P_t}{\partial P_{j,t}}}{P_t^2}\right) = 0. \quad (42)$$

Rearranging leads to

$$\frac{P_{j,t}}{S_t} = \theta \left(\frac{P_{j,t}}{S_t} - \frac{W_t^{f*}}{A_t^f}\right) \left(1 - \frac{\partial P_t}{\partial P_{j,t}} \frac{P_{j,t}}{P_t}\right). \quad (43)$$

The elasticity of the price index,  $P_t$ , with respect to the price of a foreign firm  $j$ ,  $P_{j,t}$ , is denoted as  $\psi_{j,t}$ . Then, solving for  $P_{j,t}$  yields equation

$$P_{j,t} = \frac{\theta(1 - \psi_{j,t})}{\theta(1 - \psi_{j,t}) - 1} \frac{W_t^{f*}}{A_t^f} S_t, \quad (44)$$

which is exactly equation (11) in section 3.1.

### Market share of a generic firm

The following steps show that the elasticity of the price index,  $P_t$ , with respect to the price of a generic firm  $i$ ,  $P_{i,t}$ , is exactly equal to the market share of firm  $i$ . This elasticity is denoted as  $\psi_{i,t}$ .

$$\psi_{i,t} \equiv \frac{\partial P_t}{\partial P_{i,t}} \frac{P_{i,t}}{P_t} = P_t^\theta P_{i,t}^{-\theta} \frac{P_{i,t}}{P_t} = \left( \frac{P_{i,t}}{P_t} \right)^{1-\theta}. \quad (45)$$

In the above equation, the derivative of  $P_t$  with respect to  $P_{i,t}$  is computed using the formula for the overall price index (equation (36)).

The market share of firm  $i$  is given by the ratio of its revenue to the total revenue in the economy:

$$\frac{P_{i,t} Y_{i,t}}{\sum_{k=1}^N P_{k,t} Y_{k,t}} = \frac{P_{i,t} Y_{i,t}}{P_t Y_t} = \frac{P_{i,t} \left( \frac{P_{i,t}}{P_t} \right)^{-\theta} Y_t}{P_t Y_t} = \left( \frac{P_{i,t}}{P_t} \right)^{1-\theta}. \quad (46)$$

The comparison of equations (45) and (46) proves that the market share of firm  $i$  is exactly equal to  $\psi_{i,t}$ .

## Appendix B: Definitions of price indices

### Laspeyres index

The Laspeyres index is a weighted average of prices in a certain period relative to a base period. The Laspeyres price index in period  $t$  with base period 0,  $L(0, t)$ , is computed according to the formula

$$L(0, t) = \sum_i w_{i,t} \frac{p_{i,t}}{p_{i,0}} = \frac{\sum_i p_{i,t} q_{i,0}}{\sum_i p_{i,0} q_{i,0}},$$

in which  $w_{i,t}$ ,  $p_{i,t}$  and  $q_{i,t}$  denote the weight, the price and the quantity of good  $i$  in period  $t$ , respectively. The second equality is obtained by applying the particular weights  $w_{i,t}$  of the Laspeyres index, which are based on the share of nominal expenditures on good  $i$  in the base period 0 and which are given as follows:

$$w_{i,t} = \frac{p_{i,0} q_{i,0}}{\sum_i p_{i,0} q_{i,0}}.$$

### Paasche index

The Paasche index is a weighted average of prices in a certain period relative to a base period. The Paasche price index in period  $t$  with base period 0,  $P(0, t)$ , is computed according to the formula

$$P(0, t) = \sum_i w_{i,t} \frac{p_{i,t}}{p_{i,0}} = \frac{\sum_i p_{i,t} q_{i,t}}{\sum_i p_{i,0} q_{i,t}},$$

in which  $w_{i,t}$ ,  $p_{i,t}$  and  $q_{i,t}$  denote the weight, the price and the quantity of good  $i$  in period  $t$ , respectively. The second equality is obtained by applying the particular weights  $w_{i,t}$  of the Paasche index, which are based on the current quantities of the goods and are given as follows:

$$w_{i,t} = \frac{p_{i,0} q_{i,t}}{\sum_i p_{i,0} q_{i,t}}.$$

In the context of the import-weighted exchange rate index constructed for this master thesis,  $p_{i,0} = 100$  for all  $i$  since the exchange rates have been indexed to 100 in the base period. Thus, the weights  $w_{i,t}$  are given by the ratio of Swiss imports from country  $i$  in period  $t$ ,  $q_{i,t}$ , to the sum of Swiss imports in period  $t$  from all countries which are included in the calculation of the exchange rate index.

## Appendix C: Import-weighted exchange rate index

The import-weighted exchange rate index is computed using exchange rate data from the 28 countries listed in table 14 below. The second column shows the sample average share of Swiss imports originating from the respective country. The third column indicates the earliest period in which exchange rate data are available and, hence, the period from which onward the respective country is included in the index. The data on the shares of nominal imports are provided by the Swiss Federal Customs Administration.

| country                   | average import share in percent | first quarter of data availability |
|---------------------------|---------------------------------|------------------------------------|
| Euro area                 | 68.87                           |                                    |
| <i>Germany</i>            | 31.58                           | 1980Q1                             |
| <i>France</i>             | 10.80                           | 1980Q1                             |
| <i>Italy</i>              | 10.12                           | 1980Q1                             |
| <i>Netherlands</i>        | 4.59                            | 1980Q1                             |
| <i>Austria</i>            | 3.94                            | 1980Q1                             |
| <i>Belgium</i>            | 3.44                            | 1980Q1                             |
| <i>Spain</i>              | 1.65                            | 1980Q1                             |
| <i>Ireland</i>            | 1.61                            | 1980Q1                             |
| <i>Finland</i>            | 0.63                            | 1990Q1                             |
| <i>Portugal</i>           | 0.37                            | 1980Q1                             |
| United States             | 6.32                            | 1980Q1                             |
| United Kingdom            | 5.57                            | 1980Q1                             |
| Japan                     | 3.19                            | 1980Q1                             |
| Sweden                    | 1.51                            | 1980Q1                             |
| China                     | 1.25                            | 1980Q1                             |
| Russian Federation / USSR | 1.17                            | 1999Q1                             |
| Denmark                   | 0.88                            | 1980Q1                             |
| Hong Kong                 | 0.84                            | 1980Q1                             |
| Libya                     | 0.62                            | 1995Q3                             |
| Taiwan                    | 0.49                            | 1980Q1                             |
| South Africa              | 0.47                            | 1980Q1                             |
| Canada                    | 0.44                            | 1980Q1                             |
| Czech Republic            | 0.43                            | 1993Q1                             |
| Brazil                    | 0.42                            | 1995Q4                             |
| Thailand                  | 0.40                            | 1990Q1                             |
| South Korea               | 0.39                            | 1980Q1                             |
| Hungary                   | 0.38                            | 1995Q4                             |
| India                     | 0.35                            | 1990Q1                             |

Table 14: Import shares and availability of exchange rate data for the countries included in the import-weighted exchange rate index

Figure 31 plots the import-weighted exchange rate index over the sample period from 1980 to 2010 in quarterly frequency. Moreover, it depicts two export-weighted exchange rate indices provided by the Swiss National Bank.<sup>27</sup> These indices are based on 24 and 40 countries, respectively. The latter index is only available from 1999 on. In the graph, the indices are normalized to 100 index points in 1999. The graph shows that the dynamic evolution is very similar for all three indices. They consistently indicate an appreciation of the Swiss franc over the sample period. Nevertheless, there is a difference between the import-weighted and the export-weighted indices. Thus, it might be more appropriate to use the constructed import-weighted index than to use the existing export-weighted indices for estimating the ERPT to prices, in particular to import prices.

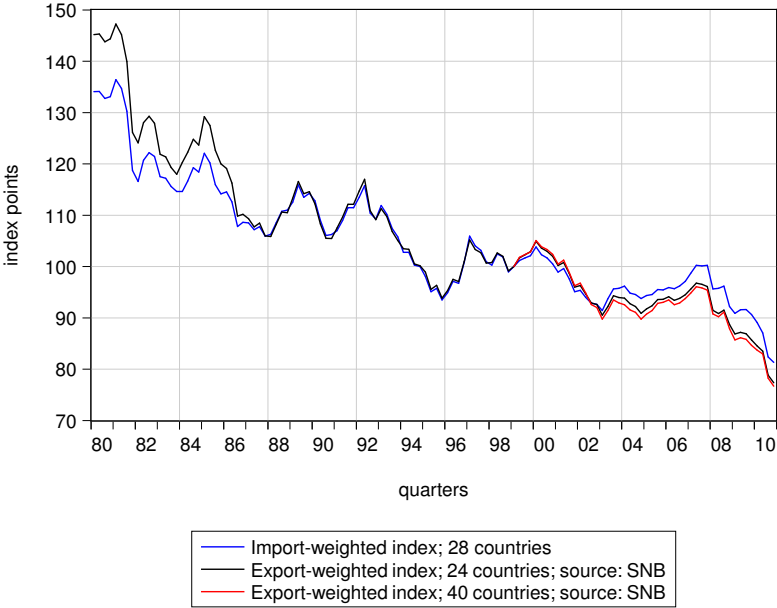


Figure 31: Import-weighted exchange rate index in comparison to two export-weighted exchange rate indices published by the Swiss National Bank (SNB).

<sup>27</sup>These indices are publicly available on <http://www.snb.ch/de/iabout/stat/statpub/statmon/stats/statmon>. However, they are based on an inverse definition of the exchange rates: An increase in the export-weighted indices represents an appreciation of the Swiss franc. Thus, these indices are transformed in order to be comparable with the import-weighted index constructed for this master thesis, for which an increase represents a depreciation of the Swiss franc.

# Appendix D: Impulse response functions to an exchange rate shock according to model (I)

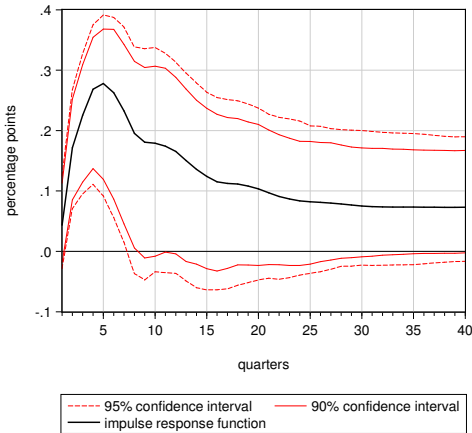


Figure 32: Response of the short-term interest rate (in percentage points) to a depreciation shock of one percent

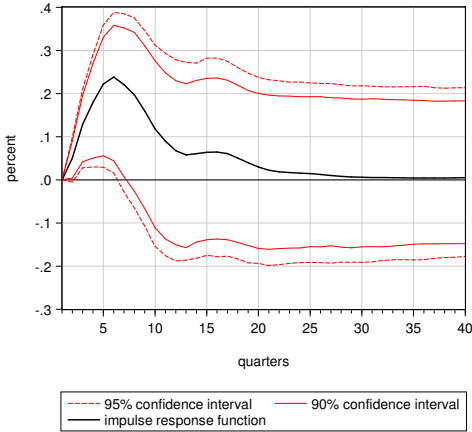


Figure 33: Response of real GDP (in percent) to a depreciation shock of one percent