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Spillovers of uncertainty shocks: Evidence from GVAR model

Master's Thesis

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Declaration of Authorship

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Prague, August 1, 2023

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Abstract

This thesis aims to supplement extensive literature on uncertainty impact in the real world and much scarcer literature on its spillover properties. Recently, numerous events induced high economic policy uncertainty such as the Great Financial Crisis, the COVID-19 pandemic, the Brexit referendum, tariff disputes, etc. have highlighted how relevant are the spillover properties.

To investigate them across a global panel of countries, we propose a GVAR model that incorporates the Economic Policy Uncertainty Index as a measure of uncertainty. We model effect of an uncertainty shock to the US economy on quarterly and monthly data.

Our model reveals two key findings. First, uncertainty spillover occurs immediately without lags and causes spikes in local uncertainty. Secondly, it negatively impacts output, interest rates, inflation and equity prices, but share of impact taken by each variable varies country by country. This is supportive of "real options" hypothesis and indicates, that majority of impact occurs via investment.

Overall, this paper sheds new light on the intricate relationship between uncertainty and economic conditions, emphasizing the need for policymakers to carefully consider the impact of policy uncertainty on both domestic and international economic conditions.

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Keywords	uncertainty, spillovers, VAR, GVAR, monetary restriction hypothesis
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Abstrakt

Cílem této práce je doplnit rozsáhlou literaturu o dopadu nejistoty v reálném světě a mnohem méně literatury o jejích přelévacích vlastnostech. V poslední době četné události vyvolané vysokou nejistotou v hospodářské politice, jako byla velká finanční krize, pandemie COVID-19, referendum o brexitu, celní spory atd., zdůraznily, jak důležité jsou vlastnosti spilloveru.

K jejich zkoumání na globálním panelu zemí předkládáme model GVAR, který zahrnuje index nejistoty hospodářské politiky jako ukazatel nejistoty. Na čtvrtletních a měsíčních datech modelujeme vliv šoku nejistoty na ekonomiku USA.

Náš model přináší dvě klíčová zjištění. Zaprvé, k přelévání nejistoty dochází okamžitě bez zpoždění a způsobuje skokové zvýšení místní nejistoty. Za druhé, má negativní dopad na produkci, úrokové sazby, inflaci a ceny akcií, ale podíl dopadu do jednotlivých proměnných se v jednotlivých zemích liší. To podporuje hypotézu "reálných možností" a naznačuje, že většina efektu se odehrává přes investice.

Celkově tento článek vrhá nové světlo na složitý vztah mezi nejistotou a ekonomickými podmínkami a zdůrazňuje potřebu, aby tvůrci politik pečlivě zvažovali dopad nejistoty politiky na domácí i mezinárodní ekonomické podmínky.

Klasifikace JEL	F42, F02, F62, E47, D80
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Acronyms

EBP Excess bond premium

ECB European Central Bank

EDF Expected default frequency

EMV Equity market volatility index

EPU Economic policy uncertainty index

ER Exchange Rate

FTSE Financial Times Stock Exchange

GDP Gross Domestic Product

GFC Great financial crisis

GVAR Global vector autoregression

IMF International Monetary Fund

IR Interest Rate

IVAR Infinite-dimensional VAR

VAR Vector autoregression

VECM Vector error correction model

ZLB Zero lower bound

Chapter 1

Introduction

Uncertainty is a powerful concept that has been affecting economic theory since the beginning of the 20th century when the seminal paper of Knight (1921) came out. Since then, it has been found that uncertainty can have a profound impact on economic conditions in the real world. Effects of uncertainty shock are not limited to local economic impacts. Just like shocks to other variables, uncertainty shock can have spillover effects, but contrary to majority of economic shocks, uncertainty shock can spread immediately via media channels and have impact throughout the world.

The Great Financial Crisis provided an undeniable example of such uncertainty spillover effects. Since then, number of major events increasing economic policy uncertainty occurred, with most of them having a profound effect abroad. Events like regular debates about the US debt ceiling, Trump's trade disputes of the US with China and pther countries can certainly impact decisions of economic agents abroad. Also more locally focused events beyond the US had demonstrable impact on policy uncertainty abroad, like UK Brexit negotiations, Chinese political power shifts, local elections, Arab Spring, etc. Finally, there are events, that are shocking and their impact abroad is apparent e.g. Covid crisis, war in Ukraine and subequnt energy price dynamics, inflation crisis, and many others.

Comovement of international policy uncertainty is easily demonstrable using the Economic Policy Uncertainty Index, and we take this opportunity to use this data to investigate how economic policy uncertainty origination abroad affects uncertainty and economy in other parts of the world.

We examine the relationship using a global vector autoregressive model (GVAR) from Pesaran *et al.* (2004) and Dees *et al.* (2007b), which enables to model multiple agents' interaction in a single autoregressive framework. In this kind of multi-agent VAR number of coefficients grows exponentially with number of agents (countries), which is solved by exposing each country only to two types of shocks: local and foreign, which are constructed as weighted averages of values of other countries.

We will then use the orthogonalized impulse response functions from uncertainty shock to major economies (USA, Eurozone, India, China) to estime the effects of local uncertainty shock on other countries of the panel.

There is extensive literature available of effects of uncertainty in economy, with some conflicting ideas and a number of theories on mechanism of action. Among the most prevalent are the "real options" theory, which claims that value of waiting and not investing increases during time of uncertainty in contrast to value of potential an investment leading to decrease in investment throughout the economy. Supporting this theory, empirically, investment is the first of all major economic aggregates to shrink faced with uncertainty. Another theory projecting output decline due to uncertainty shock states, that agents demand compensation for additional risk they are taking, therefore the risk praemia increase, which hinders output. Our model provides evidence for the "real options" theory. There are also theories implying positive impact of uncertainty: "growth options" - higher potential return of investment during uncertainty should induce investment, and "Oi-Hartman-Abel" theory suggesting that firms will leverage their flexibility to use opportunities coming with uncertainty and increase production and prices of goods in demand while decreasing those for which demand declined. Recent literature using EPU index, is rather consistent on the negative impact of the EPU shock on output and economy in generally, which our results confirm.

Literature on spillover effects is much scarcer. Negative effects from uncertainty spillovers were confirmed for US spillover to UK, to eurozone and to a representative sample of world economy. Negative impact of uncertainty modelled by VIX and EPU was found for panels of over 40 countries. Other papers looked for a "common part" of uncertainty or impact of "global macroeconomic uncertainty" on individual countries finding negative impact.

While literature uses a number of definitions to describe and quantify uncertainty, which range from a financial index to very broad measures, our analysis is limited to economic policy uncertainty. However, our conclusion do not differ vastly from the findings in literature presented above.

Our contribution in this thesis is twofold. Firstly, we apply another panel data methodology to mutli-country setting to analyze uncertainty spillovers. Secondly, while number of papers limit themselves to analysing quarterly data, we extract the most possible value out of the EPU by using GDP interpolation in the latter part achieving more precise and significant results.

We have two main findings: spillover of the economic policy uncertainty occur immediately and has a negative impact on output, interest rates, inflation and prices. Our results indicate possible trade-offs between impacts on these variables making the finding highly policy-relevant.

The thesis continues in the following way: Section 2 provides an overview of the current literature on uncertainty, its measurement, types properties as well as its impact on economy, transmission channels and possible policy implications. Section 3 describes the GVAR methodology in detail, discusses specifications, and introduces the data used in the model. Section 4 presents the results of the paper and discusses the IRFs from the model. Section 5 concludes.

Chapter 2

Literature review

This section consists of two parts: first we review available literature on uncertainty, its origin, effects and properties, in the second, methodological part, we describe uncertainty research methodology and an overview of GVAR literature.

2.1 Uncertainty

Uncertainty was of profound interest for about a century with modern economics often referring to Knight (1921) for definition of uncertainty and risk. There, he distinguishes risk, which has a distribution, which is known and therefore can be hedged, and uncertainty, where the distribution is unknown. This distincion does not correspond very well with what relevant literature describes as uncertainty. It is a rather nonspecific, hard to quantify and general term (Bloom 2014), which encompasses both policy uncertainty as well as the volatility of prices or second moment of consumer confidence (Perić & Sorić 2018), directly rejecting the notion of Knightian uncertainty).

2.1.1 Measurement

The broad definition of uncertainty or even lack thereof allowed the literature to split into strands specializing on different aspects of it. The focus on a specific "type" of uncertainty is often determined by the metric used to quantify uncertainty. Papers in Finance often tend to use derivatives of financial variables to construct uncertainty measure such as implied volatility indices (VIX index (also known as CBOE volatility index) (Bloom 2009; Rey 2015; 2016), FTSE option, Sterling option (Haddow *et al.* 2013)), difference between

expected and realized values of indicators (e.g. here a square root of weighted averages with weights determined by a factor model) (Scotti 2016), dispersion of growth forecasts (Bachmann *et al.* 2013) or dispersion of company earnings forecasts as in Jurado *et al.* (2015).
A large part of the literature uses indices based on variance in surveys of professional forecasters or perceived confidence of forecasters themselves. Alternatively, surveys of population are used for gathering data on unemployment or their own impression of the economic situation.

Finally, there are news-based indicators, which usually look for a set of words or phrases related to uncertainty in media outputs. The EPU index is probably the best known, but there are also other, e.g. EMV (Equity market volatility index) (Baker *et al.* 2019). There is evidence suggesting that they are not inferior to indices based on market data (Zhu *et al.* 2019).

Each of these has its own advantages and disadvantages, tends to focus on slightly different aspects of uncertainty and can be affected by specific factors, e.g. assumptions made in the models for implied volatility, questions in surveys used, which may not guide participants to answer on the second moment, but also induce responses, which include the first moment (confidence), etc. Media-based indices may be subject to structural changes (Haddow *et al.* 2013) but overall they tend to provide a similar picture to each other (Bloom 2014).

2.1.2 Causes

Economic uncertainty causes are not a direct concern of this thesis, however, they provide valuable background for final analysis, so we allowed ourselves to address them briefly. Probably the most important conclusion of the available literature is the countercyclicality of uncertainty. It has been confirmed for most measuring methods and for all major recessions (Bloom 2014; Baker *et al.* 2012). This is partially due to the nature of the indicators themselves, e.g. increased indebtedness and therefore higher risk increases the prices of options or more imprecise projections during recession due to fast development, but these effects do not explain all the changes in the indices or even their majority (Bekaert *et al.* 2013). Consequently, there is a number of values getting more volatile during recessions like economic performance of companies or prices (Bloom *et al.* 2018; Vavra 2014), which naturally translates into higher volatility of wages (Storesletten *et al.* 2004; Heathcote *et al.* 2010).

The literature has discerned 4 distinct impacts of the economic cycle on uncertainty (Bloom 2014):

- Good business conditions help spread information
- In normal conditions, individuals can predict the future more easily
- Changes in public policy, which cause uncertainty, occur mainly during recessions
- Trying new ideas and research during periods of bad business conditions

Finally, uncertainty is higher in emerging market economies (Bank 2013; Bhattarai *et al.* 2020) e.g. via higher sensitivity to trade policy uncertainty (Borojo *et al.* 2022).

Obviously, uncertainty and especially economic policy uncertainty is often caused by exogenous uncertainty shocks from political decisions like those mentioned in the introduction.

2.1.3 Impacts and transmission

Among the components of aggregate demand, the investment reacts most strongly to policy uncertainty, followed by consumption. Government spending generally does not respond to shocks in policy uncertainty (Bloom 2017). Since investment is greater in larger firms, which are governed by boards of highly-qualified managers it tends to be based on data and forward looking predictions. Consumption on the other hand can either not be adjusted for low-income population and high earners also do not tend to plan the consumption so far forward as investment. This has been used in explanation for the muted consumer response to Brexit contrasting with pronounced response of firms (Bloom 2017). Channels of impact have multiple similar classifications in literature. For consistency, we used again Bloom (2014).

Real options

This concept is being described in the literature for many years (Bernanke 1983; Brennan & Schwartz 1985; McDonald & Siegel 1986; Dixit & Pindyck 1994). When a firm makes an investment decision, there are essentially 2 possible outcomes to it: to invest or not to invest (how poetic :D). The value of the "NO" option increases with higher uncertainty as there is chance that "YES" might lead to wasting money on a bad investment project. "NO" option value also increases with reversibility costs, i.e. whether it would be hard to adjust to new conditions or not. Some firms may therefore prefer to wait (if it is not costly). Similar logic can be applied to households yielding a decrease in consumption, investment, and hiring. This tendency to wait and not to make decisions can also result in lower responsiveness to policy (which is also suggested by other authors in other contexts (Vavra 2014; Foote *et al.* 2000; Bertola *et al.* 2005)).

Precautionary savings hypothesis offers slightly different motivation, but very similar outcomes. Faced with uncertainty agents may choose to hold higher amounts of cash, causing interest rates to fall. Consequent increase in investment, which is implied by theory does not occur due to the openness of economies allowing funds to flow out (Fernández-Villaverde *et al.* 2011) or due to price stickiness, which does not allow markets to clear especially close to the zero lower bound, where the changes in interest rates can not materialize (Fernández-Villaverde *et al.* 2015).

Monetary contraction

Uncertainty increases the risks and probability of default resulting in higher risk praemia during periods of uncertainty to compensate for this. This will have an effect equivalent to monetary tightening in many models and will slow down growth (Bai *et al.* 2011; Christiano *et al.* 2014; Gilchrist *et al.* 2014). Similarly for models assessing Knightian uncertainty, agents unable to assess the risk hedge for the worst case, which worsens with higher uncertainty, therefore, leading to a similar contraction.

Positive effects

Bloom (2014) also mentions the positive impacts of uncertainty, which tend to have rather long-term effects, both of which, however, do not seem to match in size the negative factors. The "growth options" theory is based on a unilateral increase of potential benefits from risk-taking behavior, especially in research. It is claims precisely the opposite to the "real options" hypothesis from above. Uncertainty widens the distribution of potential effect, which is constrained by 0 from the bottom side (i.e. no profits and the investment is lost) but unconstrained from the upper side, therefore the expected value of an investment

grows (Paddock *et al.* 1988).
The other is known as Oi–Hartman–Abel effect (Oi 1961; Hartman 1972; Abel 1983) and assumes firms may be risk-loving so they could exploit changes in prices and demand by adjusting production and pricing. In the short-term it may be a very restrictive assumption, however, in the long term, it may not be as far-fetched and may provide an additional transmission channel of uncertainty to growth.

In conclusion, it can be inferred from the literature presented, that there is an asymmetric effect of uncertainty on growth. It is certainly damaging in the short run. In the longer term, the effects are much less pronounced, and it is very hard to produce consistent results on impact in the longer term. Especially in the GFC period, we could notice a high spike in uncertainty affecting the short-term development followed by growth, which makes a compelling argument for neither positive nor negative long-term impact of uncertainty. Despite policymakers attributing big impact to the uncertainty in post-GFC period, the econometric evidence to support that is scarce (Bloom 2014; Baker *et al.* 2012). It appears, that long-term positive effects go via investment and research, whereas negative effects primarily affect spending and consumption (which is consistent with the channels presented). This effect structure is highly relevant with respect to the specification of the GVAR model.

2.1.4 Spillovers

Many shocks apparently originate abroad, which is a trivial observation to make and many authors confirm it (Bloom 2017). As anecdotal evidence, he presents 2 graphs: of the US EPU 2.1, where he claims 4 out of 12 big shocks originated abroad, which is already an impact worth investigating, given the impact on economic reality and Australian EPU 2.2, where 9 out of 10 shock came from abroad. This illustrates, how smaller economies are predominantly shocked by foreign policy uncertainly shocks and therefore knowledge of spillover mechanisms is crucial for policymaking.

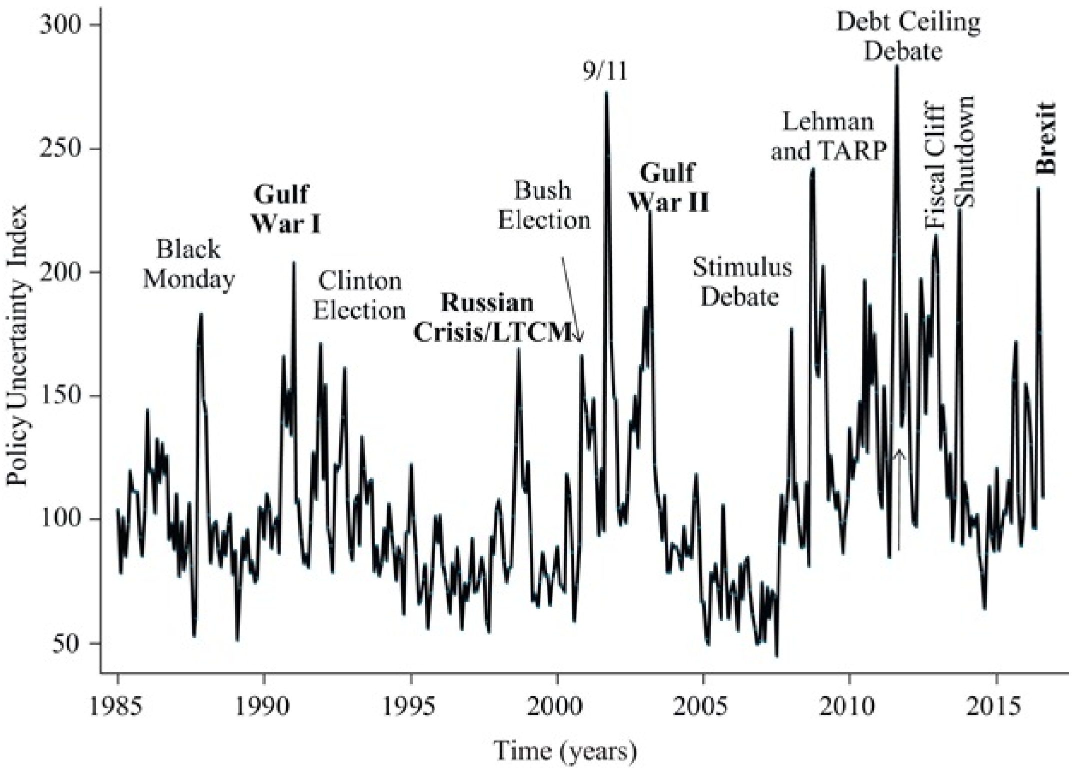

Figure 2.1: US EPU shocks

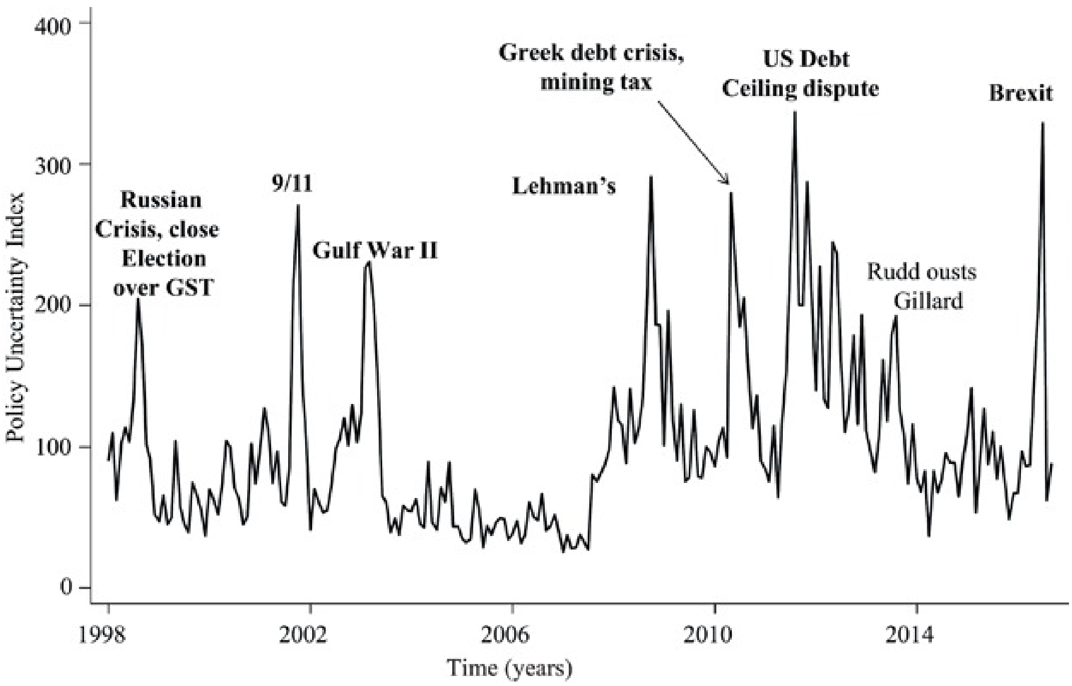

Figure 2.2: Australia EPU shocks

The shock spillovers from abroad will be correspondingly more significant for small open economies due to their high dependency on foreign markets and their relative size. The effects are also more pronounced for emerging market economies, which are dependent of financial flows from developed world (Bhattarai *et al.* 2020).

Biljanovska *et al.* (2021) claims up to two-thirds of the negative effects of uncertainty can be attributed to spillovers and provides another visualisation 2.3 of high interconnectedness of the current world, where periods of both idiosyncratic policy uncertainty shocks before the GFC and global shocks with spillovers after the GFC and during the European debt crisis:

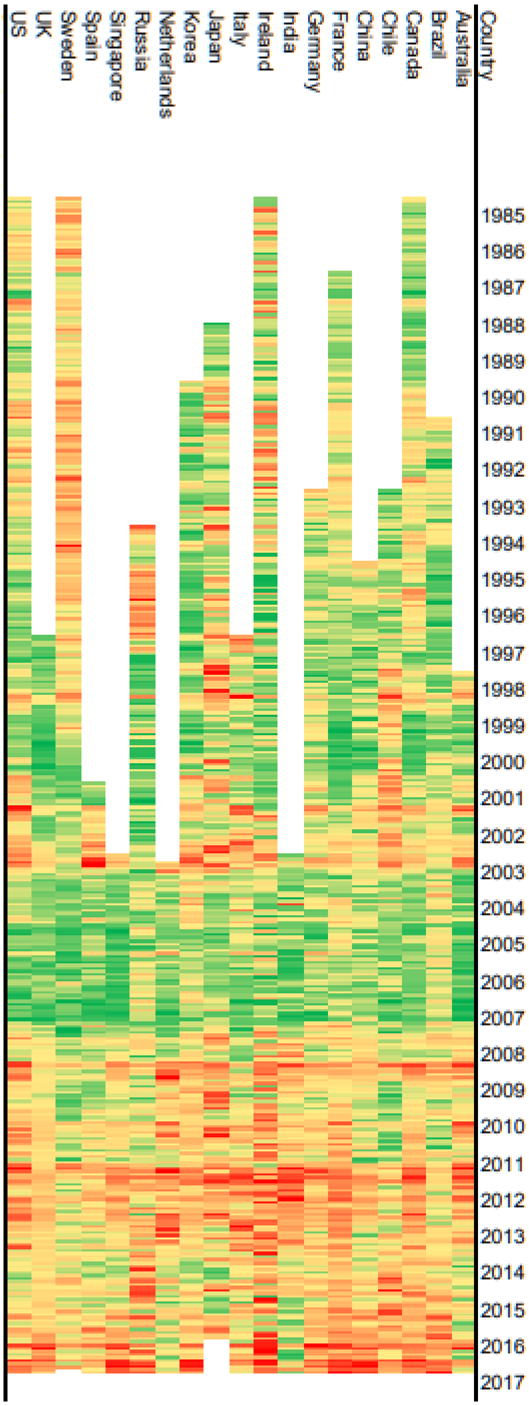

Figure 2.3: Heatmap of EPU, Source: Biljanovska *et al.* (2021)

The paper also provides evidence for real impact of foreign (here US) uncertainty on real variables abroad and demonstrates the association of economic integration with spillover and therefore impact intensity **??**:

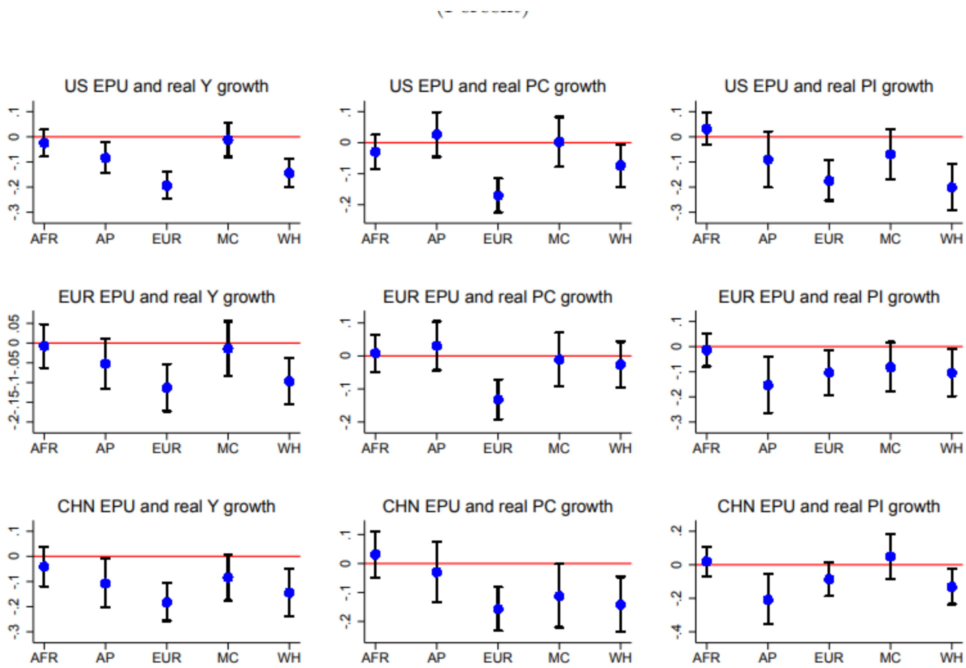

Figure 2.4: Impact intensities of EPU, Source: Biljanovska *et al.* (2021)

2.2 Methodologies used for research

The main issue of any method analyzing uncertainty is distilling the causal relationship between uncertainty and any real effect as there is a high chance of omitting a variable or missing reverse causation with variables affecting and affected by a wide range of factors. In literature, there are three main research streams dealing with these issues.

Causal separation by timing approaches

This literature strand builds on the assumption that uncertainty is a leading indicator and focuses on time windows where uncertainty shocks can be distinguished from the noise. Despite being a popular and certainly an intuitive approach separating short-term and long-term effects of uncertainty has been repeatedly rejected by papers analyzing the long-term effects of high uncertainty. There is some evidence, that consistently high uncertainty is negatively linked to GDP in the long run e.g., which will never reclaim the growth lost by decreased investment (Ramey & Ramey 1994; Engle & Rangel 2008; Bloom 2009; Barrero *et al.* 2017).

An extensive body of literature applies the shock analysis in micro (Bloom *et al.* 2007) and macro setting (Romer 1990; Novy & Taylor 2020). All of them agree on a slowdown in reaction to shocks mainly via decrease in investment due to attractive wait-and-see option. This category also includes all autoregressive models such as Baker *et al.* (2012; 2016a); Bhattarai *et al.* (2020); Biljanovska *et al.* (2021); Antonakakis *et al.* (2018), which were used extensively primarily during the last few years to measure spillovers.

Structural models

Structural models are a very popular tool, however, for uncertainty impact modeling they show high sensitivity to specification. Bloom (2014) uses his own model in Bloom *et al.* (2012), which confirms the above-mentioned contraction caused by uncertainty via "pause in hiring and investment, cutting aggregate capital and labor through depreciation and attrition" and claims a rebound of GDP in the second year after the shock. This contrasts with models from similar time using heterogeneous agents in Bachmann & Bayer (2013; 2014) which suggest smaller impacts of uncertainty. They place more emphasis on micro than macro uncertainty and have less volatile uncertainty, they exclude some costs and include others (e.g. exclude labor adjustment cost). However it is non-obvious which assumption set is superior, which highlights the need for additional research within this field.

Natural experiments and causation direction

The causal relationship between the real variables and the uncertainty is a tricky hypothesis for testing as most of the shocks happen simultaneously. Generally this is being addressed by using VARs and assuming the direction of causation or using timing for identification, which is complex due to contemporaneous movement of variables and forward-looking properties of consumption and investment. There is a plenty of VAR literature claiming uncertainty drives macro variables (Bloom 2009; Fernández-Villaverde *et al.* 2011; Christiano *et al.* 2010) or vice versa causality reported in Bachmann & Bayer (2011); Bachmann *et al.* (2013), where author claims that "negative first-moment shocks to a firm's profitability, whether idiosyncratic or aggregate, lead the firm to review its modus operandi and to change its strategy to survive. If our view is correct, then the root cause of aggregate fluctuations are first moment shocks, and rising uncertainty is an amplification device". This is not a unique result. There is literature supporting this idea, e.g. Bloom *et al.* (2018), where he claims recessions are best modelled by as if they were driven by shocks with a negative first moment and a positive second moment".

To solve this issue Baker & Bloom (2013) uses exogenous shocks as instruments to separate the causal effects. Assuming that some shock are primarily first-moment shocks (ë.g. a natural disasters) and other affect mainly the second moment, although not exclusively (e.g. coups). He concludes, that first and second moments effects have significant impact, with that of second moment being equal or higher.

2.3 GVAR literature

The study of global economy is a complex task, especially given the growing interconnectedness and interdependence of national economies. In order to effectively model these interactions, scholars have developed various large-scale macroeconomic models. One such model is the Global Vector Autoregression (GVAR) approach, which was introduced by Pesaran *et al.* (2004). Its methodological contribution lays a unique solution to the curse of dimensionality that plagues other models, allowing for more coherent and consistent simulation analysis. While other large models are available, they often lack the completeness and closed system required for effective analysis. This section aims to explore the GVAR approach in detail, highlighting its theoretical and methodological contributions to the study of the global economy.

Global Vector Autoregression - GVAR was developed in the aftermath of the Asian financial crisis (Gupton 1997) as a response to the demand for models of regional systemic risk factors impact on the credit risk of banks. At the time, global models existed but were large and of little use in forecasting (Di Mauro & Pesaran 2013). Therefore in Pesaran *et al.* (2004), a GVAR model was outlined, which went beyond credit risk and was useful for analysis of shock transmissions and modelling long-term macroeconomic relationships. The framework was used for the first time on a sample of 33 countries, where 8 Euro area countries were modelled together as a block. The framework was further developed in Dees *et al.* (2007b) (often mentioned in the literature under the acronym "DdPS" compiled of authors' names) by providing a theoretical framework for GVAR model as an approximation of an unobserved global common factor model and has shown efficiency of GVAR approach in these situations. He also developed a procedure for construction of bootstrap confidence intervals using sieve bootstrap, which also serves as a robustness check. Finally, they have shown that the GVAR impulse response functions can be used for structural analysis.

Global VAR is particularly well suited for applications with multiple weakly dependent (here in a sense, that neither should exert a disproportionately large influence over other units) units. These are typically national economies but can also be state, regional or other units, as apparent in the following review.

Over the last decade, there have been numerous applications of the GVAR model in academic literature. Additionally, the GVAR approach has been adopted by policy institutions such as the International Monetary Fund (IMF) and European Central Bank (ECB), where it was very popular as a technique to comprehend the linkages between individual countries.

This section groups the GVAR literature into two strands: international transmission and forecasting and applications in finance

2.3.1 International transmission and forecasting

Although the initial Pesaran *et al.* (2004) paper was focused on global risk scenarios' impact on bank portfolios, a significant amount of literature investigating international economic relationships appeared. First of these was already mentioned Dees *et al.* (2007b), which used GVAR for analysis of US monetary policy shocks (although the main contribution of the paper is clearly the development of the method, not the policy recommendations). The authors then investigated the GVAR modelling further in other papers (Pesaran *et al.* 2009a;b). Other papers generally follow the methodology or at least build on it to a certain extent.

Since then, the GVAR framework has been used to extend numerous papers with various hypotheses, which were often based on VAR estimation. One interesting example of this is the application of the framework of VAR forecasts of the probability of recessions, output gaps and other variables based on expectations and Bayesian model averaging from Garratt *et al.* (2003; 2009); Garratt & Lee (2010) and other work in Garratt *et al.* (2016), where they "stack" VAR models on top of each other to form a GVAR and capture the international linkages between G7 countries. The sample includes both before and after 2008 Great Financial Crisis; therefore, the GVAR model was well tested on capturing international relations. The GVAR model produced similar forecasts as the benchmark model (in their case distinct VARs) but with "clearly more accurate" timings. The contribution from the GVAR model was "extremely useful for investigating the dynamic cross-country interactions". GVAR performance was also found superior to other autoregressive techniques in De Waal *et al.* (2015); De Waal & Van Eyden (2016), where they compared 6 methodologies: large GVAR (33 countries as in Dees *et al.* (2007b)), small GVAR, VECM model, AR model and a random walk model. They concluded that the large GVAR performed better than other models, second best was the small GVAR. Although small GVARs were proven to be efficient for some economies, e.g. the Swiss one in Assenmacher (2013), the bigger models are more appropriate for a small economy with intensive international trade relationships, which is South Africa in that specific paper.

Papers that do not necessarily further GVAR methodology but are worth mentioning in this section investigate a number of issues. One such paper is Bussière *et al.* (2009), where the authors analyze the impact of exchange rates on foreign trade flow and compare it with the impact of demand changes in different geographies. Interestingly, they found the impact of exchange rates to be much less pronounced than that of the local demand shocks. The same authors later on in Bussiere *et al.* (2013) analyze the response of real effective exchange rates to global shocks before and after the European Monetary Union's (EMU) creation. Their findings are highly relevant for a number of European policymakers. The researchers have found compelling evidence that the pattern of responses is highly dependent on the nature of global shocks. Specifically, they found that after EMU, the responses of euro area countries to global US dollar shocks have become comparable to the pre-EMU response of Germany, which was known for having Europe's most credible legacy currency. In contrast, the responses of euro area countries to global risk aversion shocks have become similar to the pre-EMU response of peripheral economies such as Italy, Portugal, or Spain. Additionally, the study suggests that the divergence in external competitiveness among euro area countries over the past decade, which is a central issue in the ongoing debate on the future of the euro area, is more likely due to country-specific shocks rather than global shocks.

A number of papers use sign restrictions for identification, albeit the most popular is either Cholesky decomposition or direct interpretation from GIRFs, which avoids the identification problem altogether. Chudik *et al.* (2012) and Cashin *et al.* (2014) use sign restriction in their GVAR focusing on commodity prices. The first paper finds a significant negative output impact of a supply-induced positive shock to oil prices on importing countries with a stronger effect for emerging economies. The real effective exchange rates of importers decrease (and vice versa) with a simultaneous increase in the REER of the USD. The second comparison compares the impacts of supply- and demand-induced shock and finds the effects to be strongly asymmetrical. The demand shock is related to long-term inflationary pressures, a surge in real output, a hike in interest rates, and a decline in equity prices in most of the countries included in the sample. Georgiadis (2015; 2016) investigate the cross-country effects of monetary policy shocks, focussing on the spillovers from US monetary policy shocks and the transmission of euro area monetary policy across member states. Shocks to monetary policy are identified using sign restrictions. The results show that the effects of U.S. monetary policy shocks on aggregate output vary across countries, with foreign output effects being larger than domestic effects for many economies. The transmission of euro area monetary policy shocks also varies significantly, with countries having more wage and fewer unemployment rigidities exhibiting stronger output effects. Eickmeier & Ng (2011) investigate the role of credit in international business cycles using a GVAR approach. The paper focuses on the transmission of credit supply shocks in the United States, the euro area and Japan. Using sign restrictions on the short-run impulse responses to financial shocks that have the effect of reducing credit supply to the private sector, the authors find that negative US credit supply shocks have stronger negative effects on domestic and foreign GDP, compared to credit supply shocks from the euro area and Japan. Domestic and foreign credit and equity markets also respond to credit supply shocks, and exchange rate responses are consistent with a flight to quality to the U.S. dollar.

In Dees *et al.* (2009), Dees *et al.* (2010) and Dees *et al.* (2014), GVAR was used not as a sole model but as a part of something else. It was used as a baseline for stacking country models onto each other in a multi-country New Keynesian DSGE model and for estimating steady-state values of using its error-correction properties. Both these techniques combined, adding international linkages in the same way as GVAR does and using GVAR deviations, gave "much more sensible" (Di Mauro & Pesaran 2013) results than those obtained using deviations from Hodrick-Prescott filter or without using these international linkages. A significant contribution of this literature strand is solving a number of theoretical issues of the GVAR/DSGE interaction, contributing to the foundation of a promising research area.

A series of works Chudik & Pesaran (2011); Chudik *et al.* (2013); Chudik & Pesaran (2013) analyzing impact of the US economy on the world and adjusted GVAR model for a "dominant unit", in this case the USA. However, they found only limited evidence for its superiority. In the series they also develop another model - the IVAR (Infinite-dimensional VAR).

There were a few papers (Cesa-Bianchi *et al.* 2012; Feldkircher & Korhonen 2014; De Waal & Van Eyden 2016) analysing the regional importance of or concluding the recent increase in international impacts from China in the past year. They used all time-varying trade weights in calculating the international variables. They find that most, if not all, of the increase can be attributed to the increase in relevant trade weights and a higher impact on GVAR outputs. Regional analysis in the form of impact decomposition was also performed for Korea (Greenwood-Nimmo *et al.* 2012), Japan (Boschi & Girardi 2011) emerging Europe (Feldkircher 2015) or for internal links between the EU (Sun *et al.* 2013).

Following work in Pesaran *et al.* (2004) and Dees *et al.* (2007b), Galesi & Lombardi (2009) applied GVAR to a context similar to that of the famous paper of Clarida *et al.* (2000), where he estimates the impact of a shock to oil prices and food prices on the US and other economies. He concludes that while oil price shock mainly impacts developed countries, a shock to food prices does the opposite - impacts developing nations. He also uses generalised forecast error variance decomposition to determine that most of headline inflation in regions is attributed to foreign sources. He uses a sample of 33 countries with one block for the eurozone and a sample of monthly data from 1999-2007. Similar conclusions are made by Anderton *et al.* (2009). They use a number of methods to determine the international interaction of structural variables and find the significant influence of foreign development on local inflation in developed countries. GVAR was specifically used to determine the influence of oil prices on the US and the eurozone and was not found significant.

Eickmeier & Ng (2015) in her paper studies international propagation of US credit shocks. They first outline differences between Factor augmented VAR (FAVAR) and GVAR. While both reduce the number of parameters by creating "foreign" variables, GVAR uses external information (typically trade flows) for weighing. In contrast, FAVAR uses the only the country data without any additions like trade weights. The main contribution of this paper is the use of sign restrictions in a GVAR to achieve a "structural" interpretation of the results, an infrequently used method used, e.g., in Chudik & Fratzscher (2011). The complexity of achieving a structural interpretation has also been mentioned as one of the drawbacks of the GVAR method as a whole in Kilian & Lütkepohl (2017). Chudik & Fratzscher (2011) also used the FDI (foreign direct investment) weighing in combination with trade weights as a validation step in the GVAR estimation, which is rarely performed in other papers.

Dees *et al.* (2007a) and Greenwood-Nimmo & Shin (2012) provide examples of error-correcting properties of the GVAR. They estimate the local VAR estimates as VECMs (Vector Error Correction Model), which enables them to capture the long-run relationship between variables (they use strongly related ones: real short- and long-term interest rate, real exports and imports, real equity prices, inflation, output, etc.), which is a strong asset of GVAR framework used quite frequently. The cointegration is then used for forecasting and scenario modelling.

Finally, the last substrand of literature worth mentioning in the context of the international macroeconomic application of GVAR would be Smith (2013). The author presents pooling techniques to improve the short- and medium-term forecasting capabilities of GVAR models. She mentions several drawbacks of the GVAR modelling, which are often omitted in the relevant literature due to publication bias. One of the shortfalls of big models such as GVARs is structural stability due to susceptibility to structural breaks, which are a critical factor in determining forecasting performance (Clements & Hendry 2006) even in smaller models. Moreover, the global model can become unstable even if all partial VAR models are internally stable. These issues can be mitigated by, e.g. choosing an appropriate time window, rolling windows or incorporating the break into the model, but each method brings its own caveats (Pesaran & Timmermann 2007). One option to avoid it is pooling the results (forecasts, estimates, ...) over the time windows (AveW) with the same model, over different specifications of the same model(AveM), over different models and/or Bayesian averaging of the previously mentioned options and their combinations (Elliott & Timmermann 2013). And indeed in Pesaran *et al.* (2009a) comes to the conclusion, that averaging over multiple specification and estimation windows bring a significant improvement in model performance.

Few papers also use GVAR to investigate the international impacts of uncertainty. Cesa-Bianchi *et al.* (2014; 2020) uses global uncertainty measured by a set of volatility indicators, including the VIX index, in a VECM model by developing with an additional block forming a GVAR-VOL model. There, the volatility does not directly interact with local variables but only via correlation with the reduced-form residuals of the GVAR model and can therefore affect the macroeconomic variables only with a lag. They find volatility to be persistent, countercyclical and strongly negatively associated with future GDP growth. The effect occurs only via the common component, i.e. a global uncertainty shock has no effect on GDP once conditioned on other local and global factors. Han *et al.* (2016) offers on the other hand a typical GVAR with EPU included and focuses on impacts of foreign EPU on China, where he finds the highest effects of the US EPU with a certain impact of EPU of the EU to the RMB exchange rate.

2.3.2 Applications in finance

Compared to literature in international macroeconomics, finance applications of GVAR are scarcer but the usecase of the GVAR to model is the same - modelling the international relationship between variables.

One of these applications can be found in stress testing. The GFC has convincingly shown, how important international linkages are for financial stability and GVAR is a way to capture them. Castrén *et al.* (2010) therefore employ the GVAR model from Dees *et al.* (2007b) and combine it with EDF (expected default frequency) model from Merton (1974). The EDF is incorporated into the GVAR system of equations by just adding the relevant equations to the system for estimation and adding another equation associating EDF with GVAR variables. EDF data enter the GVAR estimation as exogenous. A similar problem is solved in another way by Oura *et al.* (2010); Pesaran *et al.* (2006), where EDF variables are incorporated directly into the GVAR regression as endogenous, therefore the model can capture both two-way relationships between the two types of data, which was not possible in the first setting due to exogeneity of the EDF data in the GVAR model. On the other hand, this approach allows work with different sample lengths for EDF and GVAR data.

This section on GVAR literature aimed to capture possible applications of GVAR literature and the methodological alterations/extensions used in the model to demonstrate its flexibility in detail. Therefore the section does not mention a number of applications, especially in finance, where the methodology included GVAR, but was similar one of the presented cases. For additional examples of a wide variety of GVAR applications, Chudik & Pesaran (2016) offers an extensive review of GVAR literature focusing on findings and topics of relevant papers rather than on methods used. Apart from that, the paper mentions two directions of potential theoretical development of the method:

- Development of theoretical understanding of GVAR behaviour with $N, T \to \infty$, specifically cointegrating relationships with large N and long sample, the impact of shrinkage for rest-of-the-world countries and or linking the GVAR to spatial literature

- Integration of GVAR into DSGE modelling. Although first steps were made in the above-mentioned papers (Dees *et al.* 2009; 2010; 2014), there is still plenty of unanswered questions. "Full integration of the GVAR and the DSGE approaches would require the development of N-country open economy DSGE models capable of modelling long-run as well as short-run business cycle movements" (Chudik & Pesaran 2016).

2.4 Other approaches to VAR in data-rich environments

As mentioned above, the crucial asset of the GVAR model is the ability to tackle highly dimensional data, which it achieves using the approach in 3.1. Three other important approaches have been developed for modelling data sets with a large number of variables, each solving the dimensionality differently: common factor models, large Bayesian VARs, and Panel VARs. Factor models shrink a large set of variables into a small set of factors, which can be used with the vector of domestic variables to form a small-scale model. This is then used in a FAVAR model famously applied to e.g. monetary policy in Bernanke *et al.* (2005), when they need to shrink the number of macroeconomic indicators.

Large-scale Bayesian VARs shrink the parameter space by imposing tight priors on all or a subset of parameters. Several researchers have explored this approach, e.g. Carriero *et al.* (2009) for ER forecasting.

Large Bayesian VARs are similar to Panel VARs. Still, the latter considers the variables' structure, namely the division of the variables into different cross-section groups and variable types. Parameter space is shrunk in the Panel VAR literature by assuming that the unknown coefficients can decompose into components (common, lag-specific, country-specific, etc.). A review of the Panel VAR approach can be seen, e.g. in Canova & Ciccarelli (2013). Further it compares panel VAR models with other approaches commonly used in the literature for estimating dynamic models involving diverse units. Lastly, the article provides insight on addressing structural time variation in panel VAR models.

Chapter 3

Methodology and data

3.1 GVAR

The model is based on dividing the analysis into sub-problems for specific units, typically countries as most data are gathered at that level, but it can be anything from a municipality to a multinational union. GVAR overcomes the curse of dimensionality by reducing the number of variable sets to two per each sub-model, local and foreign, constructed as a weighted average of foreign variables. This move imposes the assumption of weak exogeneity. It is usually satisfied given the size of most world economies compared to the global one. These local models are then solved simultaneously.

We begin with a set of local variables k_i for each of N countries over the estimation window $t = 1, 2, \dots, T$. Then we denote x_{it} a $k_i \times 1$ vector of local variables of country i at time t, and let $x_t = (x'_{1t}, x'_{2t}, \dots, x'_{Nt})'$ denote a $k \times 1$ vector of all the variables in the panel, where $k = \sum_{i=1}^{N} k_i$. Foreign (rest-of-the-world) country-specific cross-section averages of foreign variables are in the $k^* \times 1$ vector

$$x^*_{it} = \tilde{\mathbf{W}}'_i \mathbf{x}_t \tag{3.1}$$

for $i = 1, 2, \dots, N$. $\tilde{\mathbf{W}}_i$ is then $k \times k^*$ weighting matrix. The most popular weighing method in constructing foreign variables is using trade volumes, capital flows (for equity prices), geographical distance (Vansteenkiste 2007) or input-output table-based weights (Hiebert & Vansteenkiste 2010). For our application, the trade weights will be the most appropriate as trade is a relatively good proxy for policy relationship (policy change in a country with an intensive trade relationship will affect me more than in a country without it, although this, in theory, might lead to underestimation of the US policy spillovers, as in this case policy also makes direct impact abroad via financial markets, etc., which are only partially represented in the trade weights. However, this treatment was already used in GVAR setting for investigation of impacts on China (Han *et al.* 2016). k_i and k^* are small as in standard VARs. Theoretically, more variables could be used with some shrinkage method used for the country-level submodels.

The country-level submodel is typically specified in the following way:

$$\begin{aligned} \mathbf{x}_{it} &= \mathbf{a}_{i0} + \Phi_i \mathbf{x}_{i,t-1} + \Lambda_{i0}\mathbf{x}^*_{it} + \Lambda_{i1}\mathbf{x}^*_{i,t-1} + \varepsilon_{it} \\ t &= 1, 2, \ldots, T; i = 0, 1, 2, \ldots, N \end{aligned} \tag{3.2}$$

where $\mathbf{x}_{it}$ is a $k_i \times 1$ vector of local (country-specific) variables, Φ_i is a $k_i \times k_i$ matrix of coefficients relevant to a specific lag of the local variables, x^*_{it} is the $k^*_i \times 1$ vector of foreign variables relevant for the country of the specific submodel i. Λ_{in} and Λ_{i1} are $k_i \times k^*_i$ matrices of fixed coefficients. Remaining ε_{it} is a $k_i \times 1$ vector of country-specific shocks. These shocks are assumed to be serially uncorrelated of zero mean and a regular variance-covariance matrix such, that

$$E_{it} \sim i.i.d\,(0, \Sigma_{ii}) \tag{3.3}$$

A crucial feature of the GVAR is allowing for cross-regional correlation. This is reflected in the assumptions that

$$\begin{aligned} E\left(\varepsilon_{it}\varepsilon'_{jt'}\right) &= \Sigma_{ij} \text{ for } t = t'; \\ 0 &= \Sigma_{ij} \text{ for } t \neq t. \end{aligned} \tag{3.4}$$

The classic macroeconomic setting of GVAR includes six variables for each country: "real output (y_{it}), price index (p_{it}) or its rate of change, a real equity price index (q_{it}), the exchange rate ε_{it} (measured in terms of a reference currency, say US dollar), an short-term interest rate (r_{it}), and real money balances (m_{it})." (Pesaran *et al.* 2004). This gives $\mathrm{x}_{it} = (y_{it}, p_{it}, q_{it}, \epsilon_{it}, \rho_{it}, m_{it})^T$, with $k_i = 6$. We will, however replace equity prices for the Economic Policy Uncertainty Index (EPU). A set of endogenous variables for country $i (i \neq 0)$, therefore typically looks like this:

$$\left.\begin{aligned} ep_{it} &= (EP_{it}/CPI_{it}) \\ rer_{it} &= (E_{it}/CPI_{it}) \\ p_{it} &= \ln(CPI_{it}) \\ r_{it} &= 0.25 * \ln(1 + R_{it}/100) \\ m_{it} &= \ln(M_{it}/CPI_{it}) \\ y_{it} &= \ln(GDP_{it}/CPI_{it}) \end{aligned}\right\}$$

where

GDP_{it} = Gross Domestic Product of country, seasonally adjusted,i during period t in domestic currency,

CPI_{it} =Consumer Price Index in country i at time t, at a reference value),

M_{it} = Nominal Money Supply in domestic currency,

EP_{it} =local index of equity prices

E_{it} = Exchange rate of country i at time t in terms of US dollars,

R_{it} = Nominal rate of interest per annum, in per cent.

As a consequence we can see there are multiple linkages of domestic and foreign variables.

- Domestic variables directly depend on lags of foreign variables from 3.2
- Common factors for all variables - global commodities prices, global events (not present in our model)
- Cross-regional shock term correlation as described in 3.4. Note that there is only contemporaneous impact; lagged impact is not transmitted via this channel. This reduces the dimensionality of the model significantly as opposed to other models.

These models are solved simultaneously for all country-specific VARX * models due to the interdependence of $\mathbf{x}_{it}$ and $\mathbf{x}^*_{it}$ between countries. We will start by rewriting 3.2 in matrix form. For this we define $(k_i+ k^*_i) \times 1$ vector analysis) and for ex ante forecasting. For this purpose we first define the $(k_i+ k^*_i) \times 1$ vector

$$\mathbf{z}_{it} = \begin{pmatrix} \mathbf{x}_{it} \\ \mathbf{x}^*_{it} \end{pmatrix}, \tag{3.5}$$

and rewrite 3.2 as

$$\mathbf{A}_i \mathbf{z}_{it} = \mathbf{a}_{i0} + \mathbf{B}_i \mathbf{z}_{i,t-1} + \varepsilon_{it} \tag{3.6}$$

where

$$\mathbf{A}_i = \left(\mathbf{I}_{k_i}, -\mathbf{\Lambda}_{i0}\right), \quad \mathbf{B}_i = \left(\mathbf{\Phi}_i, \mathbf{\Lambda}_{i1}\right). \tag{3.7}$$

The matrices $\mathbf{A}_i$ and $\mathbf{B}_i$ have dimensions $k_i \times (k_i + k_i^*)$. Additionally, $\mathbf{A}_i$ has a full column rank, namely $\text{Rank}\left(\mathbf{A}_i\right) = k_i$. (Pesaran *et al.* 2004; Dees *et al.* 2007b;a) If we now gather all the weights into a weights matrix we can expand 3.6 into

$$\mathbf{A}_i \mathbf{W}_i \mathbf{Z}_t = \mathbf{a}_{i0} + \mathbf{B}_i \mathbf{W}_i \mathbf{Z}_{t-1} + \varepsilon_{it}, \tag{3.8}$$

where $\mathbf{W}_i$ is a $(k_i + k_i^*) \times k$ matrix of weights.
If we combine the models over countries, i.e. we incorporate the iteration over i we get the following form:

$$\mathbf{G}_t = \mathbf{a}_0 + \mathbf{H}\mathbf{z}_{t-1} + \varepsilon_t \tag{3.9}$$

with

$$\mathbf{a}_0 = \begin{pmatrix} \mathbf{a}_{00} \\ \mathbf{a}_{10} \\ \vdots \\ \mathbf{a}_{N0} \end{pmatrix}, \varepsilon_t = \begin{pmatrix} \varepsilon_{0t} \\ \varepsilon_{1t} \\ \vdots \\ \varepsilon_{Nt} \end{pmatrix} \tag{3.10}$$

$$\mathbf{G} = \begin{pmatrix} \mathbf{A}_0 \mathbf{W}_0 \\ \mathbf{A}_1 \mathbf{W}_1 \\ \vdots \\ \mathbf{A}_N \mathbf{W}_N \end{pmatrix}, \mathbf{H} = \begin{pmatrix} \mathbf{B}_0 \mathbf{W}_0 \\ \mathbf{B}_1 \mathbf{W}_1 \\ \vdots \\ \mathbf{B}_N \mathbf{W}_N \end{pmatrix} \tag{3.11}$$

here $\mathbf{G}$ is a $k \times k$ generally regular matrix. By rearranging we get the final Vector Autoregressive model.

$$\mathbf{z}_t = \mathbf{G}^{-1}\mathbf{a}_0 + \mathbf{G}^{-1}\mathbf{H}\mathbf{z}_{t-1} + \mathbf{G}^{-1}\varepsilon_t, \tag{3.12}$$

which can be directly estimated.

The coefficients estimated are consequently time-invariant in the estimation sample, which necessitates testing for structural breaks in the underlying data. We tried to keep the notation and structure of the section above consistent with Pesaran *et al.* (2004).

3.2 Relevant indices

The analysis focuses on the Economic Policy Uncertainty index, enabling us to model responses to shocks to economic policy. However, part of the literature indicates that EPU may not give the full picture.

Perić & Sorić (2018) mentions that economic uncertainty as perceived by the index and research - as the Knightian uncertainty (Knight 1921) - a situation where decision-makers can not evaluate probability distributions of possible future events, is only the second moment of societal sentiment. First moment of this would then be the sentiment itself, which authors suggest is captured by the consumer conditions index (CCI) provided by the OECD. Moreover, it has been repeatedly proven that the CCI Granger-causes overall economic activity (Matsusaka & Sbordone 1995; Batchelor & Dua 1998; Golinelli & Parigi 2004). On the other hand, EPU was not found to possess such a property (Perić & Sorić 2018); therefore, as an extension of this work a similar analysis could be performed with the CCI.

3.2.1 EPU

The index was developed by Baker *et al.* (2016a) in the aftermath of the 2008 financial crisis. The index consists of 3 components in the USA.

- Word frequency - Occurrence frequency of following words: ‘uncertainty’, ‘uncertain’, ‘economic’, ‘economy’, ‘congress’, ‘deficit’, ‘federal reserve’, ‘legislation’, ‘regulation’ or ‘white house’ in 10 major US newspapers (USA Today, the Miami Herald, the Chicago Tribune, the Washington Post, the Los Angeles Times, the Boston Globe, the San Francisco Chronicle, the Dallas Morning News, the New York Times, and the Wall Street Journal)

- Federal tax code provision, which should expire during the following 10 years

- Disagreement in the Survey of Professional Forecasters on future CPI and public purchases of goods and services.

These are weighted at 1/2, 1/6, 1/6 and 1/6, respectively.

One of the well-known issues of the EPU is inconsistency in the method of construction. Resources available are not the same for each country; therefore, for other countries, different methodologies were used, which makes the international comparison more complex. This, however, does not affect the regression significantly. We will try to alleviate this problem by normalizing the local EPU values for to mean of 100. Different methodologies are consistent over time, which is highly desirable for any model and enables us to use them in this thesis. Detailed description with initial papers available here.

Chapter 4

Regression

For the regression there were obviously multiple possible specifications, different treatment of cointegration, using dominant unit model or not, variable selection, lags, estimation window, weight matrix composition and many others. We applied the model to quarterly and monthly data. Robustness of the model on monthly data was very good, the implications did not change with changes in lag order or integration order of variables or other changes. The quarterly model was much more sensitive to any changes, which we attribute to smaller dataset available for the analysis, where patterns were not as discernible.

4.1 Data

The main data limitation was availability of the EPU index in numerous countries. As the index became available for most of them in 1997, this also determined the estimation window for the model of 1997Q1-2019Q4 for quarterly and 1997M1-2019M4 for monthly data (some countries do not have interest rate data available). The EPU data were assembled in the following papers: Arbatli *et al.* (2019); Armelius *et al.* (2017); Baker *et al.* (2013; 2016b); Cerda *et al.* (2016); Davis (2016); Davis *et al.* (2019); Ghirelli *et al.* (2019); Gil & Silva (2018); Hardouvelis *et al.* (2018); Kroese *et al.* (2015); Zalla (2016).

The set of countries used is following:

Australia (only for quarterly analysis)	**Eurozone:**	Germany
Brazil		Italy
Canada		Netherlands
China		Spain
Chile		France
India		
Japan		
Korea		
Mexico (only for monthly analysis)		
Sweden		
United Kingdom		
USA		

Table 4.1: Countries used in the model

The other time series were sourced from IFS in a manner consistent with Mohaddes & Raissi (2020). Interest rates are money market rates, where those were available, otherwise we used short-term corporat bond rates. Trade weights were sourced from the database available online created for Mohaddes & Raissi (2018) as well as PPP of each of the countries. AS equity prices were used quotes for MSCI national indices and a robustness check was performed on the most well know local index for each country like S&P500 for the US, DAX for Germany, CAC 40 for France, etc.

4.1.1 Regions

Regional aggregation is very an option in GVAR to aggregate major economic areas into one block, that then acts as a country, in our case we attempt to do this with the Eurozone. It is also an option to simplify the model and achieve more lags if needed - a trade-off between cross-sectional complexity and time complexity. It has been used in multiple applications of GVAR on macroeconomic relationships, most notably in both seminal papers: Pesaran *et al.* (2004); Dees *et al.* (2007b).

The Eurozone aggregation in our sample stems both from close economic ties, but mainly from common exchange rates and interest rates.

4.2 Specification

Our models use the following specification with inclusion of equity prices only for the last models presented

$$\left.\begin{array}{c} epu_{it} = \left(EPU_{it}/\sum_{t=1}^{t=T} EPU_{it} * T * 100\right) \\ ep_{it} = (EQ_{it}/CPI_{it}) \\ rer_{it} = (ER_{it} * CPI_{USDt}/CPI_{it}) \\ \pi_{it} = \ln\left((CPI_{it}) - \ln(CPI_{it-1})\right) \\ r_{it} = 0.25 * \ln\left(1 + R_{it}/100\right) \\ y_{it} = \ln\left(GDP_{it}/CPI_{it}\right) \end{array}\right\}$$

where

GDP_{it} =Real Gross Domestic Product of country i during period t in domestic currency,

CPI_{it} =Consumer Price Index in country i at time t,

EPU_{it} = Economic Policy Uncertainty Index, normalized

E_{it} = Exchange rate of country i at time t in terms of US dollars,

EQ_{it} = local equity price index i at time t in terms of US dollars,

R_{it} = Short term interest rate per annum, in per cent.

We avoided using any global variables in the final model as their impact on results for the EPU shocks was negligible, but they increased instability of the model. All data used were of monthly and quarterly frequency. EPU has usually monthly data, so the we use averaging for quarterly aggregation.

We used fixed weighting matrix, number of lags based on AIC but limited to 4 in 5-variable monthly model and 2 in other models due to dimensionality restrictions and model stability concerns.

4.3 Variable integration

The GVAR model does not require all the variables used to be I(0). It allows us to capture the longer-term relationships and possible cointegration between variables due to the error correcting properties of the individual model. For this, however, it is necessary, that all variables are either I(1), in which case we would try to use the VECM and capture the potential cointegration, or I(0), in which case the cointegration would not occur. It is crucial not to mix I(0) and I(1) variables since the model could pick up spurious cointegration as mentioned e.g. in (Cesa-Bianchi *et al.* 2020; Dees *et al.* 2007b). In our case the model is run in the VECM specification, therefore we will be looking for a unit root in the variables. As in the Dees *et al.* (2007b) we found the GDP, inflation and interest rates to be integrated of order 1 (which implies integration of prices of order 2). EPU time series also was found to have unit or close to unit root. Although literature often perceives volatility measures as I(0) (Harvey & Jaeger 1993; Cesa-Bianchi *et al.* 2020) Although our serial integration testing is does not fully support the I(1) integration of inflation (some test statistics do not exceed the critical value) we are confident, that this is not an issue. Firstly, literature tends to consider typical macroeconomic variables such as inflation or GDP I(1) (Harvey & Jaeger 1993), but the property was also proven in similar papers, notably the Dees *et al.* (2007b). To be absolutely certainty, we also estimated the model with CPI instead of inflation and conclusions did not change.

Similarly, for monthly EPU the test did reject the unit root hypothesis for some of the series. However, we still proceed with the analysis for a few reasons: integrated alternative for the EPU does not make sense, like in case of inflation and CPI, EPU was used in a number of papers using VAR methodologies, e.g. in Istrefi & Piloiu (2014); Biljanovska *et al.* (2021); Istrefi & Mouabbi (2018). Quarterly variants of both inflation and EPU were closer to I(1), than their monthly equivalents.

We performed two versions of serial correlation testing. The ADF test and weighted symmetric estimation of the ADF test as took place in Park & Fuller (1995). The modified ADF test outperforms the ADF test by exploiting the reversibility of stationary AR processes(Pantula *et al.* 1994; Smith *et al.* 2004).

Below 4.2 we present results of the quarterly aggregated EPU unit root testing, there ADF denoted Augmented Dickey-Fuller test and WS denotes weighted symmetric ADF estimation from Park & Fuller (1995).

Domestic Variables	EPU (tr)	EPU (tr)	EPU	EPU	D__EPU	D__EPU
Statistic	ADF	WS	ADF	WS	ADF	WS
Critical Value	-3.45	-3.24	-2.89	-2.55	-2.89	-2.55
AUSTRALIA	-2.32	-2.58	-2.19	-2.45	-7.92	-8.21
BRAZIL	-3.18	-3.39	-2.53	-2.47	-7.10	-7.32
CANADA	-4.14	-4.17	-0.99	-1.15	-8.12	-8.35
CHINA	-2.31	-2.47	-2.32	-2.45	-10.53	-10.76
CHILE	-3.89	-3.89	-1.90	-1.99	-7.34	-7.57
EURO	-3.03	-3.24	-2.73	-2.48	-5.60	-5.71
INDIA	-4.06	-3.60	-3.80	-3.58	-8.98	-8.69
JAPAN	-5.32	-5.48	-3.12	-3.04	-6.64	-6.91
KOREA	-3.25	-3.45	-3.26	-3.46	-7.50	-7.71
SWEDEN	-3.13	-3.28	-2.75	-2.59	-10.19	-10.39
UNITED KINGDOM	-0.40	-0.81	0.20	-0.12	-6.49	-6.66
USA	-3.31	-3.16	-3.21	-3.14	-8.16	-8.26

Table 4.2: EPU unit root test statistics, (tr) denotes testing with trend included in the test regression

4.4 Country specific models

In the next step we determined the lag order of VECMX* models as we do not need to include all lags in every model if it is not beneficial for the model. For the selection we used logLikelihood, AIC and SBC, the information criteria converged on all suggested numbers of lags, logLikelihood sometimes suggested different lag.

Country	# of lags
AUSTRALIA	2
BRAZIL	1
CANADA	2
CHINA	1
CHILE	2
EURO	1
INDIA	2
JAPAN	2
KOREA	2
SWEDEN	2
UNITED KINGDOM	1
USA	2

Table 4.3: VECMX* Order of country models in on quarterly data

Country	# of lags
BRAZIL	2
CANADA	4
CHINA	4
CHILE	2
FRANCE	4
GERMANY	2
INDIA	3
ITALY	3
JAPAN	4
KOREA	4
MEXICO	2
NETHERLANDS	2
SPAIN	2
SWEDEN	3
UNITED KINGDOM	3
USA	2

Table 4.4: VECMX* Order of 5-variable country models in on monthly data

4.5 Testing for weak exogeneity

Weak exogeneity, as mentioned in the methodology description is one of the crucial assumptions of a GVAR model. Although common sense would indicate, that given the size of the economies in the model relative to the "rest of the world" blocks is small enough to provide weak exogeneity we empirically test the assumption on the sample used in the model. The result is relevant mainly for the big economies such as USA and the EURO area, which are big enough to potentially affect the "world" data enough to violate the weak exogeneity assumption. In the table below it is apparent, that the assumption is not violated as Canada can not potentially affect the world interest rates sufficiently to justify this result of test.

Country	**Fcrit_0.05**	**GDP**	**inflation**	**IRs**	**EPU**	
AUSTRALIA	F(1,77)	3.97	0.65	0.03	0.05	0.13
BRAZIL	3.97	0.69	1.70	2.04	0.86	
CANADA	3.14	0.07	3.82	7.03	0.97	
CHINA	3.13	1.25	0.48	0.67	0.13	
CHILE	2.74	2.90	0.46	0.30	2.92	
FRANCE	2.73	0.45	0.98	0.83	0.94	
GERMANY	2.73	1.33	0.23	0.50	0.61	
INDIA	3.13	3.22	0.62	0.56	3.39	
ITALY	3.12	2.93	2.56	0.46	3.10	
JAPAN	3.13	2.42	0.54	0.36	0.43	
KOREA	3.97	1.06	0.50	0.86	1.72	
NETHERLANDS	3.12	1.56	1.05	0.51	2.28	
SPAIN	2.50	1.14	1.27	1.36	0.08	
SWEDEN	3.12	1.48	0.89	1.30	2.82	
UNITED KINGDOM	3.97	0.18	0.07	0.21	0.88	
USA	3.12	0.37	0.87	2.89	0.76	

Table 4.5: Test for Weak Exogeneity at the 5% Significance Level for "rest of the world" variables for quarterly data

Country	**Fcrit_0.05**	**GDP**	**inflation**	**IRs**	**EPU**	**EPs**
BRAZIL	3.88	0.00	0.29	0.89	2.04	0.71
CANADA	3.88	0.29	2.86	1.97	0.18	1.83
CHINA	3.04	2.68	0.08	2.72	2.27	0.53
CHILE	3.04	1.04	1.91	0.61	0.86	1.45
FRANCE	3.88	0.13	0.08	0.02	0.49	0.00
GERMANY	3.88	1.08	3.13	0.01	0.09	0.10
INDIA	2.64	1.60	0.31	0.91	0.79	1.03
ITALY	3.04	1.89	1.49	0.90	0.63	5.44
JAPAN	3.88	1.55	0.01	5.62	0.00	7.39
KOREA	2.41	1.78	2.83	3.79	5.38	0.57
MEXICO	2.64	0.73	1.22	0.81	1.18	3.50
NETHERLANDS	3.04	1.04	0.15	0.44	0.07	0.83
SPAIN	2.64	0.78	0.85	0.32	1.55	1.40
SWEDEN	3.04	1.64	0.88	1.76	1.37	2.45
UNITED KINGDOM	3.88	0.00	3.81	0.19	1.71	0.77
USA	3.04	1.55	1.63	0.19	2.55	2.83

Table 4.6: Test for weak exogeneity at the 5% Significance Level for "rest of the world" variables for monthly data

4.6 Testing for structural breaks

Structural breaks can be detrimental to a VAR model. Especially in a case of unstable model and volatile IRF like in our case investigation of structural breaks is highly relevant. Although there is some evidence suggesting GVAR models are able to accommodate structural breaks better than normal smaller models, since the structural break remains confined in the local model due to concept of co-breaking (Hendry & Mizon 1998) and estimation dependent on the data where the shock occurred (Dees *et al.* 2007b). There is a battery of tests available for testing the time breaks. These include the Ploberger & Krämer (1992) CUSUM statistic (PK sup) and its mean square variant (PK msq); the Nyblom (1989) test statistic (Nyblom); the Quandt (1960) likelihood ratio statistic (QLR) in its Wald form; the mean Wald statistic (MW) of Hansen (1992) and the Andrews & Ploberger (1994) Wald statistic based on the exponential average (APW).

For APW, MW and QLR we tested both standard and heteroskedasticity robust versions. All three testing procedures sequentially perform a Wald-type test at random places of one-time structural change. The standard version of them result in above 20% (for both quarterly and monthly data) of rejected alternatives, however the heteroskedasticity-robust version result in much lower rejections rate at below half of those reported by non-robust versions. Nyblom test works in a slightly different way - it takes a hypothesis of parameter constancy and tests it against a non-stationary alternative. This reported slightly lower rejection rate, around 20%, which again dropped significantly in the heteroskedasticity-robust test. These results indicate, that most of the detected structural breaks is due to heteroskedasticity, not necessarily being actual breaks. Finally both PK tests report less than 5 breaks for each frequency, which however do not appear in other tests. Finally, there is no time series, that would be found to have a structural break by multiple test types, and the shares of rejections are low enough according to the similar literature (Dees *et al.* 2007b), so that we do not have to worry about this issue.

Chapter 5

Results

The main tool of assessing results and their implications in VAR models are impulse response functions, since estimated coefficients are hard to interpret directly. This is also true for GVAR model, we therefore resort to analysis of IRFs to determine relationship of variables. Here, we will use orthogonalized IRFs as their shocks allow for structural interpretation as opposed to GIRFs.

For the following analysis we will be using bootstrapped IRFs. This is a popular choice made also in Dees *et al.* (2007b) due to very high volatility of their individual IRFs. Although our IRFs are much less volatile, that those in the paper mentioned (we reestimated the paper using authors' data) we still opt to use the bootstrapped IRFs for easy construction of confidence intervals and practically no cost except for more demanding computation.

5.1 Expected outcomes

Below we outline outcomes expected from literature review. After that we go through results of our models and analyze their IRFs with regard to our expectations.

5.1.1 Inflation

Literature does not provide a clear answer to uncertainty-inflation relationship question. The non-contradictory evidence mostly focuses on ideas how these impact each other's reactions, e.g. Vavra (2014) mentions "During times of high volatility, firms have greater desired price changes, which in turn lead the aggregate price level to become more responsive (and output less responsive) to nominal stimulus. This means that achieving a given increase in real output requires a greater increase in inflation during times of high volatility". Evidence of direct impact of uncertainty shock into inflation is conflicting. There is both evidence of positive impact of various types of uncertainty on inflation (Berument *et al.* 2009; Born & Pfeifer 2014; Fernández-Villaverde *et al.* 2015; Bonciani & Van Roye 2016) or expectations (Istrefi & Mouabbi 2018) as well as negative impact (Bloom 2009; Leduc & Liu 2016; Basu & Bundick 2017) as a result of output contraction or directly find the impact unclear Fountas & Karanasos (2007). We would argue, that the conclusion on the impulse response is dependent on the model assumption used, often those on frictions. In a similar manner Fasani & Rossi (2018) argues, that direction of inflation response to uncertainty shock is dependent on the Taylor rule used.

5.1.2 Interest rates

There is again mixed evidence. Given, that we use market short-term rates (mostly money market rates), increase in IRs could indicate increased risk praemia during time of increased uncertainty. This has indeed been found in Favara *et al.* (2016) or in Gilchrist & Zakrajšek (2012) where they use excess bond premium (EBP), a component of corporate bond spread and it is the part unaccounted for by fundamental risk of the individual bond. They show, that orthogonal shock to EBP causes protracted and significant economic downturn and a decline in inflation. This could indicate rising interest rates at the time of uncertainty, but the result is rather indicative of a channel how uncertainty can affect economy (monetary contraction hypothesis referred to in literature review).

On the contrary, in literature linking interest rates directly to uncertainty we find the opposite - a decline following the uncertainty shock. These papers support hypothesis of increased saving during uncertainty. These two conclusion might not be entirely contradictory as EBP is just a part of the total, that interest rates are. Despite EBP increase total IR might decrease due to other reasons, like change in underlying fundamentals, less risky projects being undertaken (indeed consistent with the higher value of option to wait), etc. Another factor is the data frequency. They used daily credit spreads to construct their metrics, we use monthly IR data. EBP can certainly react immediately, they might have captured an effect, that will not be visible in our data at all (although the impacts on real variables would be certainly discernible from monthly data).

We use total interest rates in the model, therefore we expect them to fall. Recent papers conclude Hartzmark (2016); Amisano & Tristani (2019), that high uncertainty is associated with low interest rates. He analyzes association of risk-free rate and inflation on more than 100 years of yearly and over 50 year of quarterly data and finds close and very robust ties between them in favour of precautionary savings hypothesis. This results corresponds to a strand of literature (Hansen & Singleton 1983; Harvey 1988; Campbell & Cochrane 1999; Bansal & Yaron 2004), which analyzes the following equation using various models:

$$r_t = \beta_0 + \beta_1 E_t\left[g_{t+1}\right] + \beta_2 \operatorname{Var}_t\left[g_{t+1}\right]$$

with r_t being risk-free rate between t and $t+1$ and g being lag of consumption growth. Despite they are not consistent in size of the coefficients, they all converge on positive β_1 and negative β_2.

Finally, central banks react strongly to uncertainty shocks from abroad (Istrefi & Piloiu 2014), which only supports the negative response of the interest rates. Unfortunately, we could not test this hypothesis in our framework as the data on policy rates were not available for all necessary countries and times (but this alone would not prevent us from the analysis) and those that were available were unfortunately multicollinear, which renders many matrix operations in the model impossible as they require full rank.

5.1.3 Output

One of the most comprehensive treatments of effects of uncertainty on GDP growth is available in Bloom (2009). He uses a model with time-varying second moments calibrated on firm-level data and simulates uncertainty shocks to economy. He simulates uncertainty shocks together with random set of macro and micro shocks and averages over responses to achieve his results. In his work he decomposes the total effect of uncertainty shock into "volatility" and "uncertainty" effect 5.1. The "volatility" effect stems from his asymmetric treatment of hiring and firing, where higher volatility of other real variables causes more hiring (more companies reaching hiring threshold), but not not more firing. Generally this can be interpreted as effects of volatility of real variables. This is an effect, that we can not identify in the model. Whether we capture it or not depends on whether our definition of uncertainty includes this volatility. The "uncertainty" effect stems from changes in expectations of real variables, which is much closer to what we believe EPU index captures, judging by how it is constructed (news-based indicator) and what type of uncertainty it targets (policy uncertainty) and therefore we would expect our results to be similar in shape to the "uncertainty" effect in the graph below. That effect corresponds to the real options hypothesis outlined in the literature review.

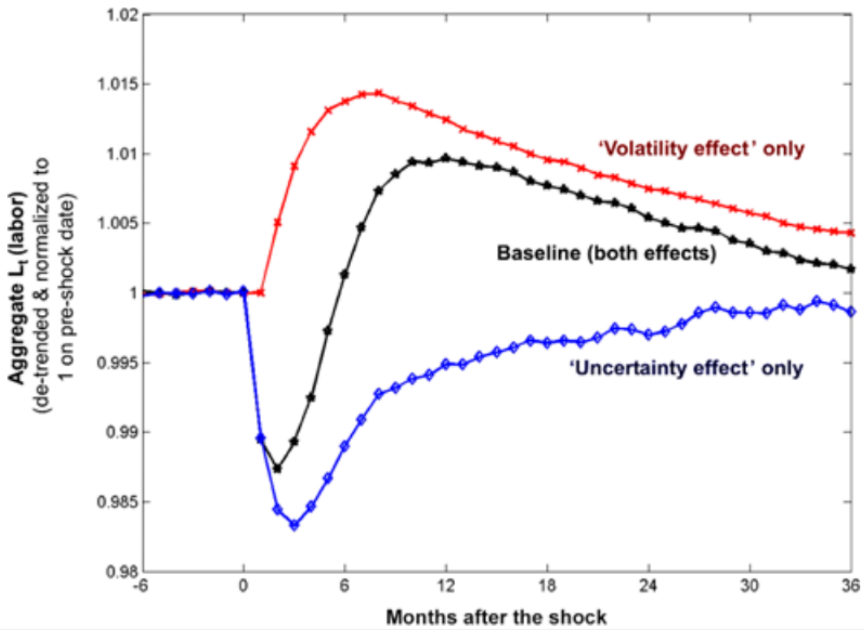

Figure 5.1: Response of GDP to uncertainty shock from Bloom (2009)

Please note, that we use GDP in levels, the graph displays GDP growth. However, it still illustrates decrease in total GDP.

There are many other authors confirming this result using different methodologies, e.g. VAR (Jurado *et al.* 2015; Baker *et al.* 2016a), linear regression with FE Baker *et al.* (2016a), Bayesian estimation of an AR process (Fernández-Villaverde *et al.* 2011), SVAR (Istrefi & Mouabbi 2018) or NK model (Amisano & Tristani 2019). Finally, given most of the effects mentioned in the literature review section lead to decrease in output, seeing positive output would be surprising.

5.1.4 EPU persistnce

Bloom (2009) provides answer to this question as well in 5.2, where simulation of a shock gives an exponential curve with a half-life of 2 months.

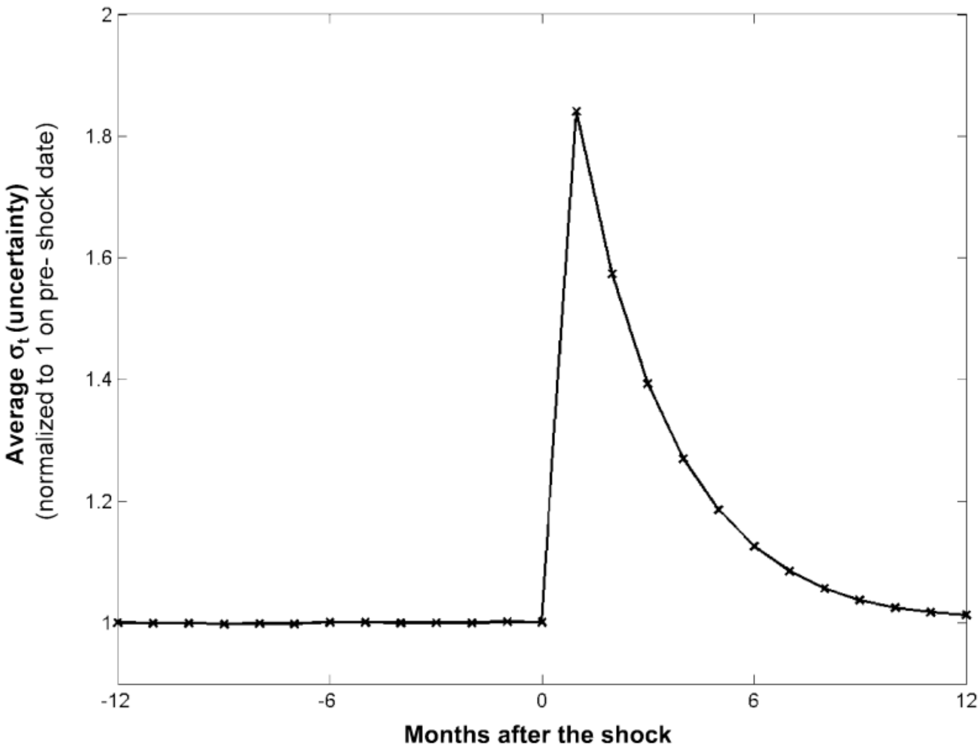

Figure 5.2: EPU persistence from Bloom (2009), half life of 2 months

Supporting this result, in a recent paper (Solarin & Gil-Alana 2021) integration of the EPU series was analyzed for each country with most of them being integrated $I(d)$, with d usually between 0.5 and 0.6, therefore authors find most series non-stationary but still mean reverting, consistently with Bloom (2009).

5.1.5 Exchange rates

Increased uncertainty was linked to exchange rate volatility (Krol 2014), consequently leading to effects on output (Braun & Larrain 2005; Aghion *et al.* 2009), unemployment (Feldmann 2011) and international trade (Auboin & Ruta 2013).

Beckmann & Czudaj (2017) investigates exchange rate expectations and policy uncertainty. Generally, he notes positive impact of policy uncertainty on forecast errors, among the reactions of currency pairs USD-XXX he finds Yen appreciating in response to a shock, while similar currency movement was not found for other investigated currencies (EUR, GBP, RMB). It therefore claims Yen has reputation of a safe haven currency, which is not a unique finding (Ranaldo & Söderlind 2010). Surprisingly, other major currencies had rather tendency to depreciate than appreciate, but all of these moves were insignificant. In our models we try to investigate the safe haven status of JPY and analyze how other currencies react to a shock elsewhere.

5.1.6 Equity prices

Theory would suggest that uncertainty has a negative effect on equity prices, but the literature on uncertainty and equity prices is surprisingly scarce. Finance papers tend to focus on returns rather than prices. Pástor & Veronesi (2013); Brogaard & Detzel (2015) report increased return or higher risk praemia in the aftermath of EPU increase, which is not in conflict with price decrease enabling future higher returns. However, there are not many recent papers explaining how equity prices react to uncertainty. Other papers by a similar group of authors (Pastor & Veronesi 2012; Kelly *et al.* 2016) indeed find, that prices decrease with policy uncertainty. However, they mostly focus on other effects on asset prices, e.g. report higher correlation within markets in high uncertainty environment. Still, we found no literature supporting positive response of equity prices to uncertainty, therefore, we expect them to decrease in the model.

Finally, using a Bayesian panel VAR Bhattarai *et al.* (2020) finds a negative impact of US uncertainty shock into equity prices and spillover of this effect to other countries.

5.2 5-variable quarterly model

We decided to present results from this model first. Although they do not fully support our final findings, they do not contradict them and they use variables directly, without adjustments, as we will do later to get monthly GDP.

In our first attempt of this GVAR we tried to specify a minimalist model with only GDP, inflation, interest rates and EPU. It did not match any of our expectations. We believe it was because there was no variable, that could react immediately to EPU shock and spillover. GDP and inflation are obviously incapable of immediate reaction, short-term interest rates might be, but their levels are partially tied to policy rates. This is obviously an issue as the uncertainty spreads instantly via media and internet. Therefore, our variables cannot possibly react to the EPU spillover in a way that would restore equilibrium in the economy in a similar time range. Adding exchange rates to the model opens a channel, which can react immediately (as they do, e.g. in case of

CB announcements) and intermediate the effect of uncertainty into other variables. And indeed, there is abundant literature on interaction of the exchange rates with all of our 4 key variables: effects on output and inflation via exports and imports and on interest rates via interest parity and capital movements.

We therefore employ the following specification:

$$\left.\begin{array}{c} epu_{it} = \left(EPU_{it}/\sum_{t=1}^{t=T} EPU_{it} * T * 100\right) \\ er_{it} = ER_{it} * CPI_{USDt}/CPI_{it} \\ \pi_{it} = \ln(CPI_{it}) - \ln(CPI_{it-1}) \\ r_{it} = 0.25 * \ln\left(1 + R_{it}/100\right) \\ y_{it} = \ln\left(GDP_{it}/CPI_{it}\right) \end{array}\right\}$$

where

ER_{it} = Nominal exchange rate of country i at time t in terms of US dollars

all other variables are the same as outlined above Please note, that since the ERs are set relative to the US dollar, decrease in ER implies appreciation. Also, unlike with other variables, there is no "foreign" and "local" ER for each country; there is only one treated as "local".
We aggregate the eurozone to reflect the reality of single exchange rate in multiple countries, which would otherwise be modelled separately and for better model stability. This measure was used very often in the GVAR literature (Chudik & Pesaran 2016), although not for EPU.

5.2.1 EPU spillovers

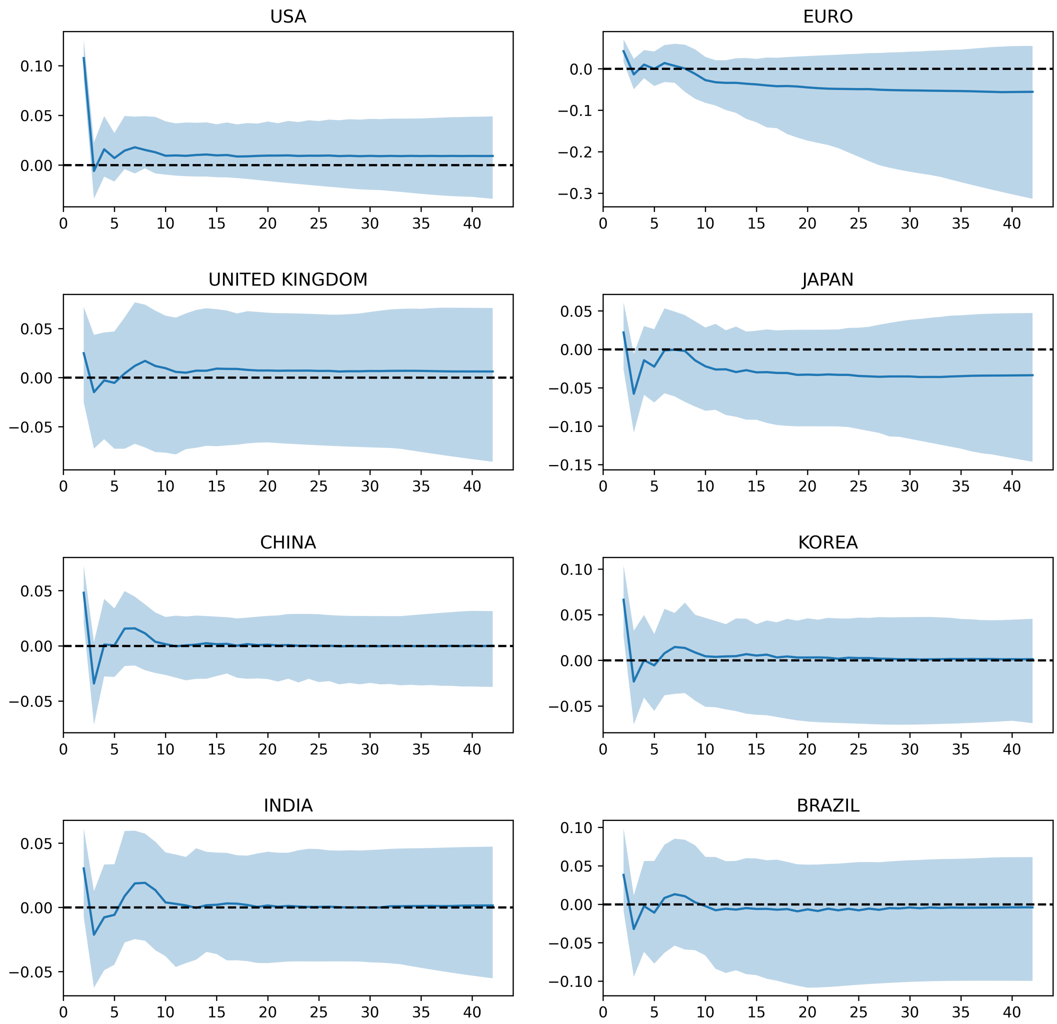

Figure 5.3: IRFs of EPU to +1SE shock to US uncertainty

The IRFs 5.18 above lead us to 2 findings: firstly, the spillover is immediate and the shock is smaller than the size of the initial US shock (it is not surprising, the model would not converge otherwise). Secondly, the responses fade away after 2 quarters, which is entirely consistent with the expectations mentioned above. There is no contemporaneous effect from exchange rates to uncertainty due to variable ordering, still we believe the persistent part of the IRF from the model above is absent here precisely due to fast reaction of exchange rates (i.e. the effect on other variables is now exercised by exchange rates).

5.2.2 Responses of exchange rates

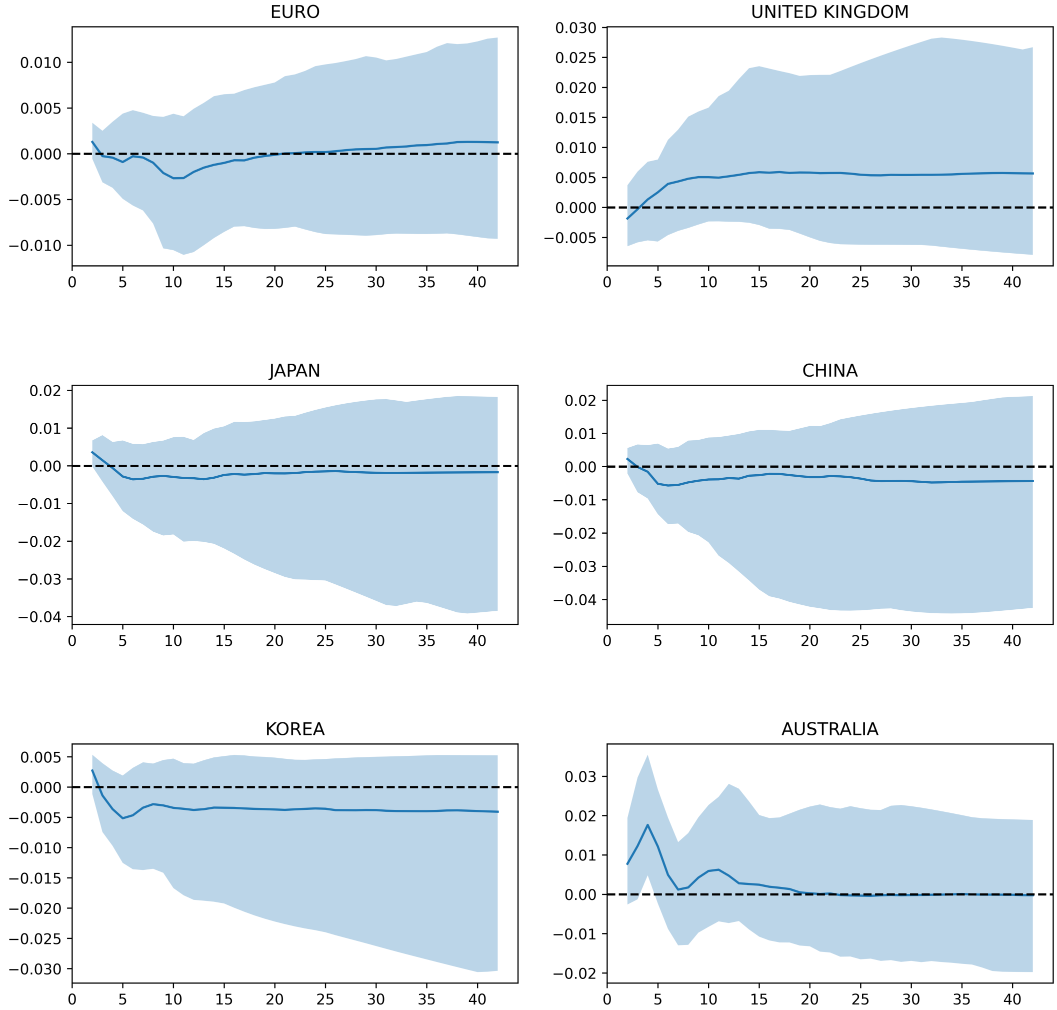

Figure 5.4: IRFs of exchange rates to +1SE shock to US uncertainty

The reaction of the exchange rates to the US uncertainty shock is insignificant; however, in line with expectations. As we have other currencies quoted in terms of the USD we can not see the movement directly, but all the response functions indicate appreciation of other currencies, which is equivalent to USD depreciation in this case. The effects are still negligible, which we attribute to the position of the USD in the financial markets (detail below). Only currencies experiencing depreciation are those of commonwealth countries: the UK, Australia and Canada (not displayed). We attribute this not just to economic ties of these countries, but also to institutional and cultural relationship (language, legal systems, politics, common history, cultural similarity, etc.), which could play a role in the transmission of the uncertainty shock. Still, these responses are so insignificant, that they just as well might have been just the opposite, so we do not attribute much significance to these results.

5.2.3 Response of GDP and inflation

In **??** local (US) response of GDP to uncertainty is negative, consistently with literature. Significant spillover effects to GDP are absent in this model, but direction is consistently negative. Given the shape of the EPU IRFs, instant spillover and subsequent fade-out, we believe that the size of the spillover is too small and short-lived to cause effects this model could capture.

For inflation **??** there is very little happening, only a slight uptick in the EU inflation. This could indicate uncertainty might cause supply shocks due to restricted US output, its biggest trading partner and consequent import restriction, despite EU exports about twice as much as it imports from the US. With UK, which has roughly balanced US imports and exports the same but more pronounced response is visible. Although this is not a dominant idea, uncertainty is indeed rather compared to a demand shock (Leduc & Liu 2016) based on the concurrent effects on output, there is some evidence supporting this idea (Fasani & Rossi 2018).

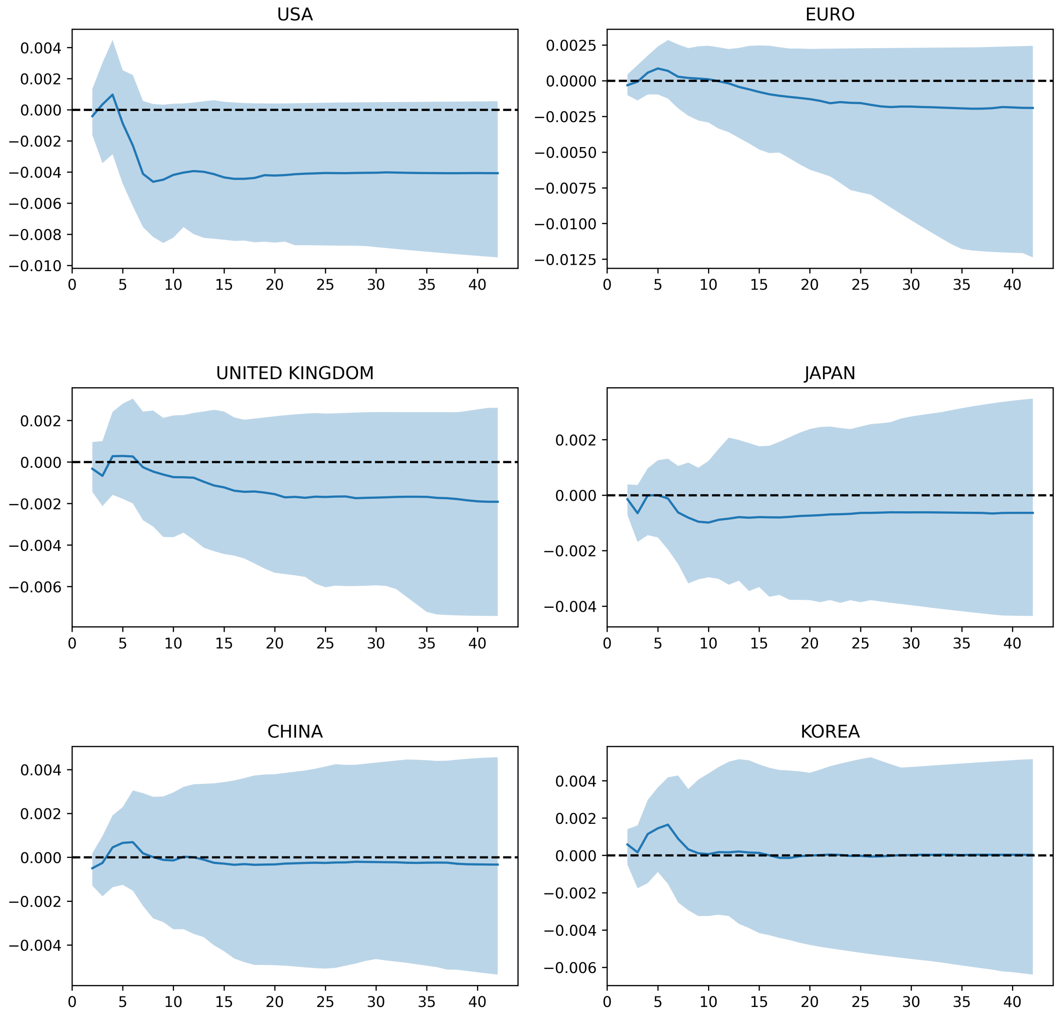

Figure 5.5: IRF of GDP to a positive US EPU shock of 1 SE

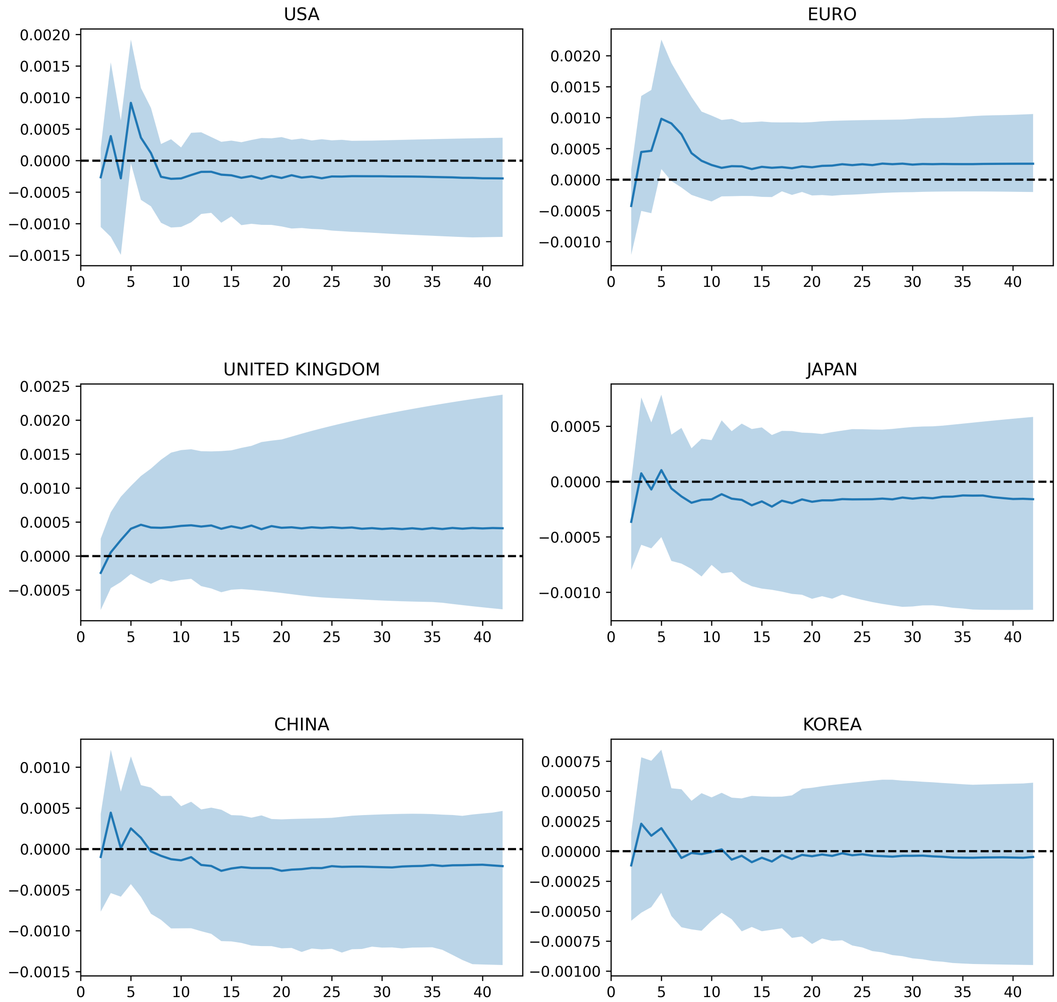

Figure 5.6: IRF of inflation to a positive US EPU shock of 1 SE

5.2.4 EPU impact into interest rates

A relatively unexpected is the response of interest rates to US positive uncertainty shock. The reaction for the US is significant as depicted below **??**, any other reaction to the shock is far from achieving significance. Since these are not policy rates but market short term interest rates (mostly money market rates), which reflect the current market conditions, positive response would speak for increased risk praemia as in Gilchrist & Zakrajšek (2012).

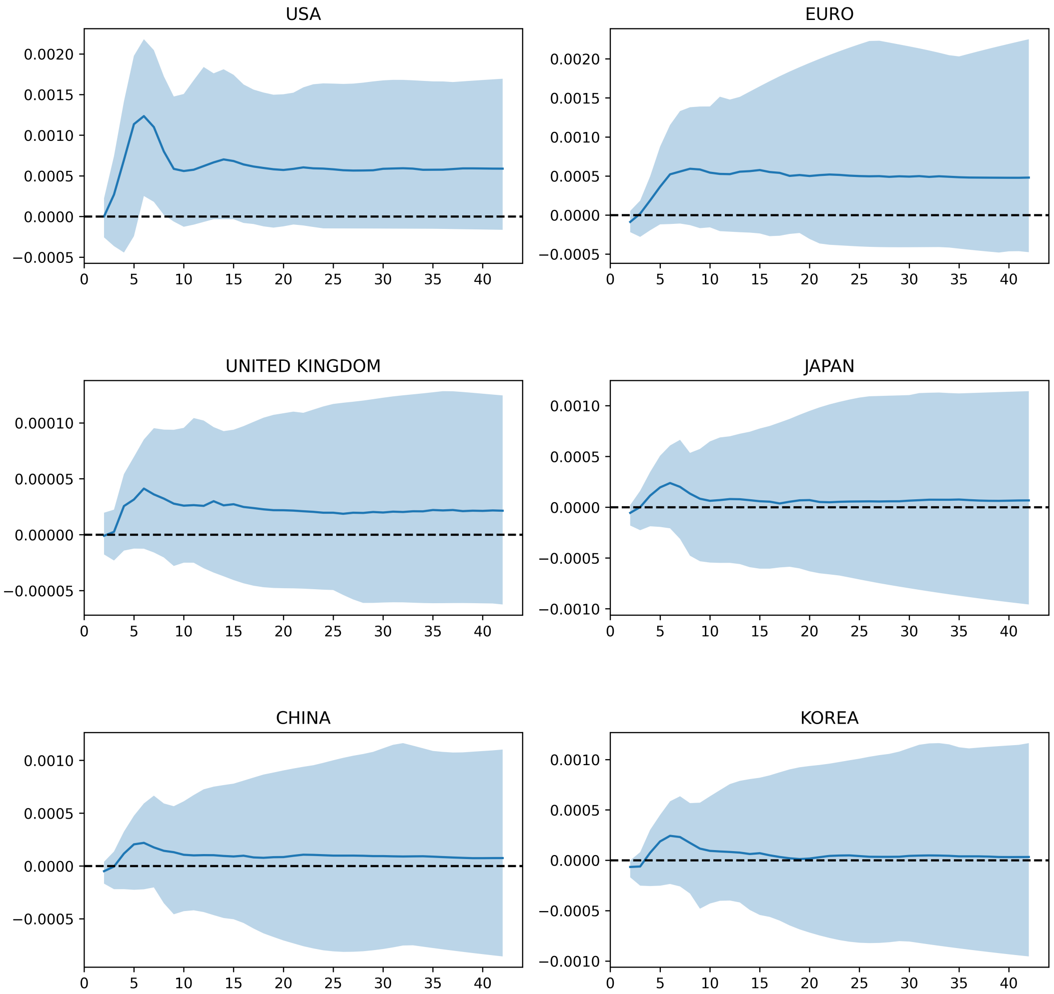

Figure 5.7: IRF of short-term interest rates to a positive US EPU shock of 1 SE

5.3 Monthly data models

The results of the model above are not fully satisfactory as they generally do not lead to very significant results. This may either be indicative of nonexistent relationship or it might just be, that we need a more detailed dataset. We address this problem in the following section. All of the time series mentioned in the beginning of this section are available with monthly frequency except for GDP, which limits our dataset significantly. We will therefore try to overcome this with interpolation of GDP using industrial production index. This is a popular choice for proxy variable/interpolation of GDP in a similar VAR setting (Jurado *et al.* 2015; Azad & Serletis 2022). The data sample in the following exercises ranged from Jan 1997 to Apr 2017. This increased the sample size almost 3 times, which we expect to result in tighter confidence intervals and higher number of lags achievable with a stable models.

5.3.1 GDP interpolation

Interpolation of the GDP was used for the first time in Burns & Mitchell (1946) with aim of producing a variable representing "state of economy", by obtaining a higher frequency time series from an underlying time series of lower frequency. There are number of approaches to this issue with different degrees of complexity and use cases. Three distinct streams of literature using interpolation can be distinguished. Firstly, indirect methods, that do not use any additional information and the generated data points arise from mathematical properties of the method applied. This was mainly used in 1960s and later for countries with scarce data, e.g. Lisman & Sandee (1964); Boot *et al.* (1967). Another strand of literature used an alternative high-frequency time series. Numerous approaches were developed in various periods, e.g. Chow & Lin (1971); Di Fonzo (1990); Guerrero & Martínez (1995); Silva & Cardoso (2001). Among them, the Chow-Lin method from Chow & Lin (1971) and its extensions have become widely used by many economic institutions in Europe and beyond (Miralles *et al.* 2003). Finally, Bernanke *et al.* (1997); Cuche & Hess (1999); Mönch & Uhlig (2004) used the state space approach and Kalman filter. These techniques were often used to analyse business cycles or produce forecasts/nowcasts. Recently, a similar approach was applied in Issler & Notini (2016).

In our analysis we used Chow-Lin interpolation with the maxlog criterion, mainly due to its simplicity of application in time series of multiple countries with different data availability and reliably good performance. Aware of the limitations (Miralles *et al.* 2003), that the method and the high-frequency indicator bring, we argue, that relevance of the results of the following model is not significantly impaired by the additional uncertainty as we interpolate only 1 out of 5 or 6 time series. Moreover, manual inspection of the resulting GDP time series did not indicate any abnormalities in the interpolated series.

5.4 5-variable model

This model was an extension of the model presented in the section above - we used the same 5 variables with monthly frequency.

$$\left.\begin{aligned} epu_{it} &= \left(EPU_{it}/\sum_{t=1}^{t=T} EPU_{it} * T * 100\right) \\ er_{it} &= ER_{it} * CPI_{USDt}/CPI_{it} \\ \pi_{it} &= \ln(CPI_{it}) - \ln(CPI_{it-12}) \\ r_{it} &= 0.25 * \ln\left(1 + R_{it}/100\right) \\ y_{it} &= \ln\left(GDP_{it}/CPI_{it}\right) \end{aligned}\right\}$$

In contrast to the previous exercise we opted for year-on-year inflation (CPI data are not seasonally adjusted) to avoid biases from unaccounted seasonality. Indeed, when run on the month-on-month data the model overfits the seasonal patterns and no real effects can be spotted.

We estimated it both with aggregation for the eurozone and without it, but the results did not differ significantly, despite objections against aggregation. We therefore report IRFs from model with eurozone only for exchange rates. All other variables including market interest rates behave independently, moreover, literature expects interest rates to react even without regard to NCBs' policy rates in the short run (before NCBs can react).

Below we explore the model using responses to 1 SE positive shock to US EPU. We present results of models without aggregation, for exchange rates we use model with eurozone aggregated.

5.4.1 EPU reaction

Uncertainty behaves very similarly, with uncertainty shock fading in about 4 months 5.8, which is almost identical to the response from quarterly model 5.3. One notable exception in this context is China (we see indication of similar development in the previous model), which experiences a lag in the uncertainty spillover. The local authoritarian regime might be the delaying factor in the context of policy uncertainty: the uncertainty does not travel immediately via news but only intermediated more slowly via other channels. Chinese also tend to live in their own environment (technology, internet, show business, universities), which often does not overlap with one of western like cultures and may cause the delay in Chinese EPU response. This is unique to China as no other country has the tools (propaganda, political power of state leadership, ...) available to isolate the economy from news abroad.

In contrast to the previous exercise, the long-term response is significant in some countries at 90% level, indicating some long-term persistence of uncertainty. The evidence for such behavior is not very string, e.g. "persistent, but mean reverting" Plakandaras *et al.* (2019); Solarin & Gil-Alana (2021), therefore given the narrow (90%) confidence intervals and their occurrence at around 20th prediction period we would need additional evidence to conclude, that EPU is persistent.

Shock spillovers are smaller, than the initial shock in the US. Response amplitudes in 5.8 are directly discernible and comparable from the IRFs despite variable EPU measurement methodology across countries thanks to normalisation to $\mu = 100$.

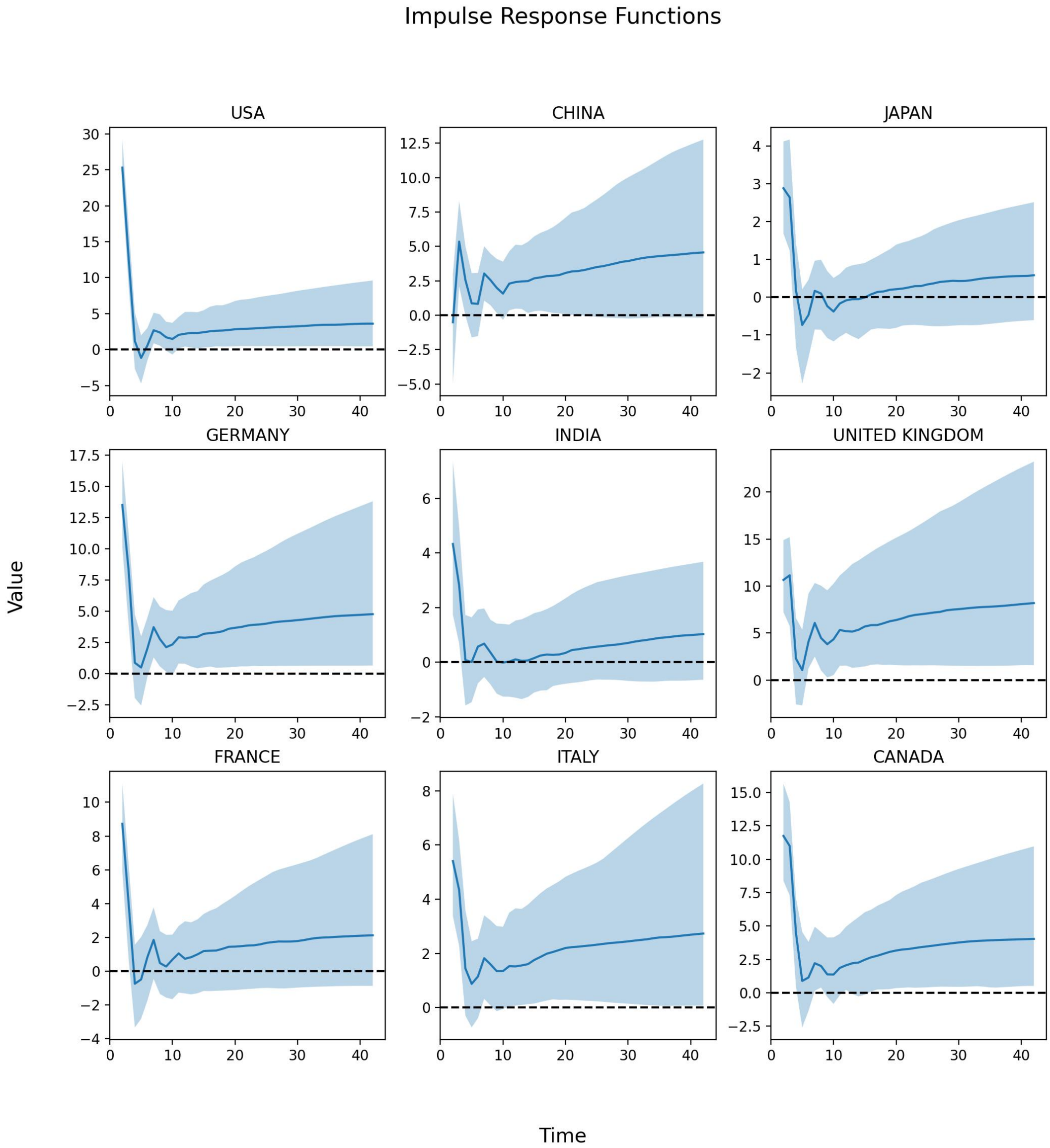

Figure 5.8: IRFs of EPU to +1SE shock to US uncertainty

5.4.2 Response of the GDP

Generally, results are very similar to those from the previous model, but more significant, in line with expectations thanks to larger dataset. There is a strong decrease in local GDP, which is equivalent to output growth trajectory of the "uncertainty" effect in 5.1 from Bloom (2009). The decrease is most significant for the US with significant negative impact also in China or Japan, Netherlands and Mexico. We attribute reaction of Japan to their high development and low growth and therefore due to lower prospects inability to exploit positive impacts of the shock and the negative ones are stronger. Further below we will also see,

that is might be cause by ZLB limitation on interest rates.
A surprising effect occurs for the Netherlands, which features significant output decrease, despite other eurozone countries stay unaffected. We speculate this might be due to tax haven status of the country, where in case of decrease of foreign GDP the Dutch GDP may simply decrease because of reduced income of companies resident there for tax purposes only inflating the perceived effect on Dutch numbers. With exports and imports are high with respect to local GDP and with oil-related commodities and goods forming a backbone of Dutch trade it is also highly exposed to reaction of global economy to the US shock. Additionally, as a small eurozone country, Netherlands can not possibly adjust monetary policy to any local economic developments, which could otherwise help alleviate the effects on output.
Finally, there is a strong, instant output decrease in Mexico, which is on par with that of the US. Reasoning here is straightforward, 83% of Mexican exports goes into the US and the ties certainly range beyond trade, e.g. remittances, mostly from the US, are worth almost 4% of Mexican GDP, which is the second (to India) highest value in the world, (increased recently, it was around 2% for most of the sample period, but this was third worldwide only to China and India). In the context of Mexican response, lack of significant negative response of Canada is surprising. The share of trade with the US is similar, however, the goods traded are vastly different, remittances do not play the same role as in Mexico, etc. Data on trade and remittances above come from the COMTRADE database and WB data.

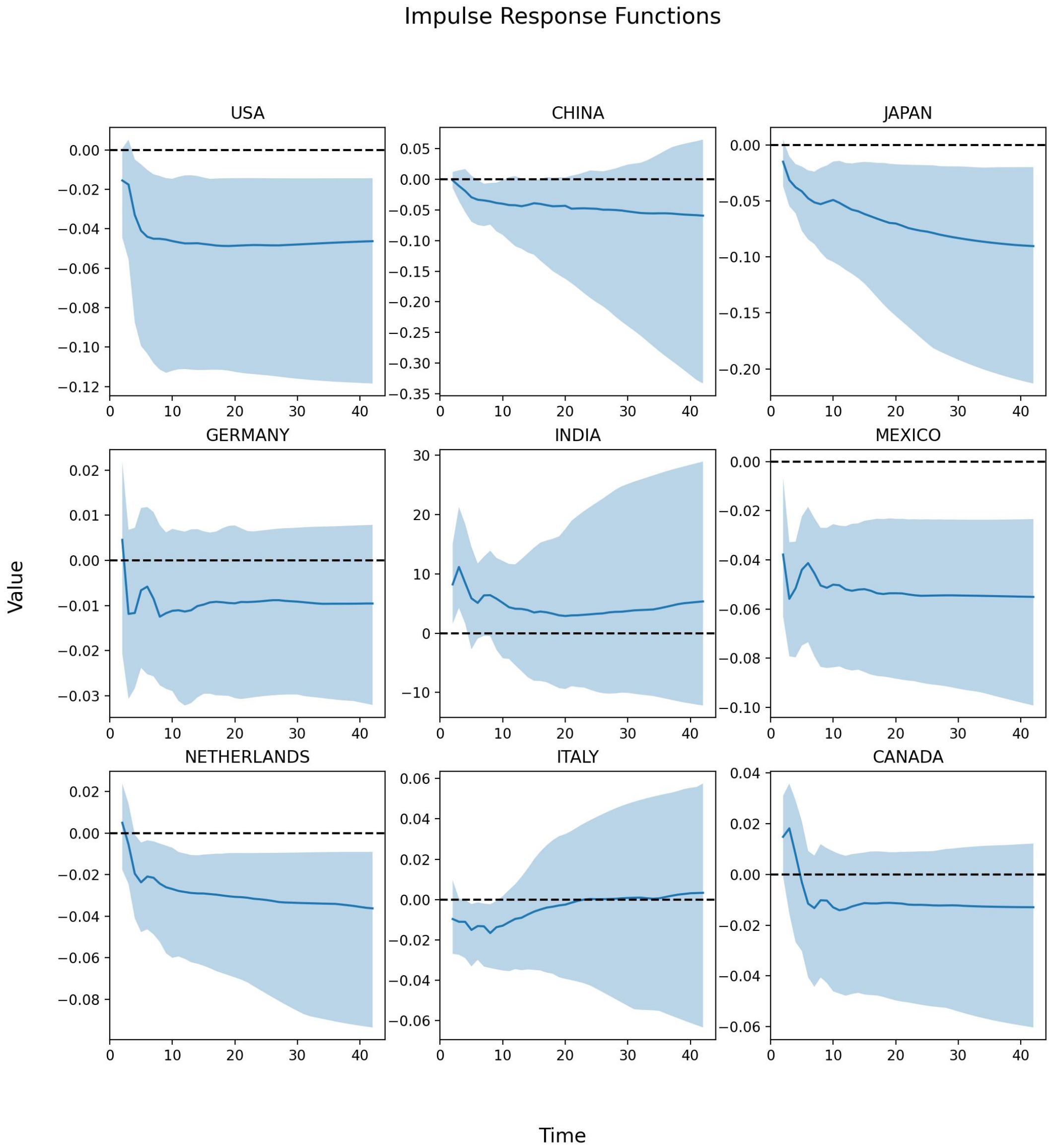

Figure 5.9: IRFs of GDP to +1SE shock to US uncertainty

5.4.3 Response of the inflation

As mentioned in the previous chapter, the inflation was not entirely an I(1) variable in our preliminary tests. We chose to use it based on use in Dees *et al.* (2007b) but there were numerous other papers using inflation instead of CPI in levels (Jiménez-Rodríguez* & Sánchez 2005; Balcilar *et al.* 2016). Still, we decided to run the same model with CPI in levels instead of inflation as a robustness check and it gave identical results (usually steady continuous long-term decline in CPI with an insignificant hump in the beginning of the prediction period for some countries, which corresponds to contemporary positive effect on inflation with subsequent decrease below 0, which is exactly what we see in the IRFs below.

Inflation therefore decreased long term with varying degrees of significance 5.10. A significant result was apart from the US achieved in Mexico, which corresponds to output drop described above. Chile is an interesting example as the output response was practically absent, but in inflation the response is significant.

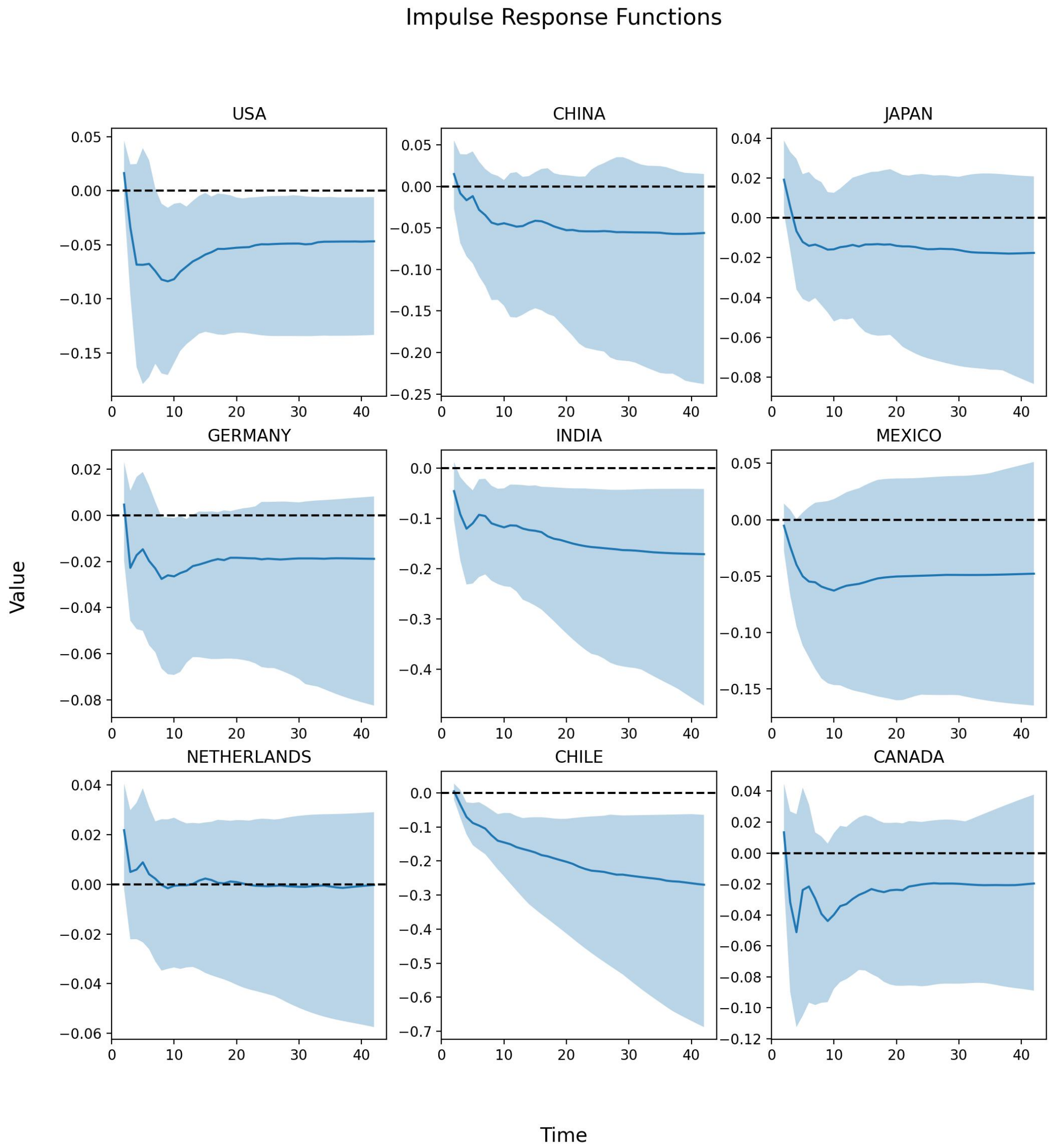

Figure 5.10: IRFs of inflation to +1SE shock to US uncertainty

5.4.4 Response of interest rates

Similarly to inflation, we can see a decrease in interest rates throughout the world, with significance for USA, Netherlands, Canada, Mexico, China and Spain 5.11, which is consistent with literature.

In the context of China and Japan we notice, that Japanese decrease in output was bigger than that of China, with much lower response from interest rates. Despite all the difference in their economies and their exposure to the US uncertainty, this is a reflection of the Japanese low policy rates at the zero lower bound - Japanese average short-term interest rate in our sample was 0.13%, Chinese was 2.86%. QE of Bank of Japan (BoJ) used extensively during sample period targets mainly long interest rates and ZLB applies also to market rates directly, so QE can not undermine this hypothesis. The 0.13% is clearly a reflection of ZLB being practically hit in money markets in Japan and therefore the rates could not have reacted to uncertainty as they did in China, even if they would in higher IR environment. Although for China money market rate was not available, the alternative rate, corporate lending rate should be very close to MMR, therefore it does not invalidate our conclusion.

Another interesting observation is Korea, which (not displayed in the GDP graphs) experienced a "positive zero" response of GDP. Here we can see, that it might have been a consequence of the interest rate decrease.

Finally, this result is inconsistent with the quarterly model. In 5.6 we see barely any movement in foreign IRs, but slightly above 0. This result comes at least partially from aggregation to quarterly variables, which therefore achieve less extreme values. Attempt to overcome this restriction by using maximum instead of average for the quarterly value yielded unrealistic results.

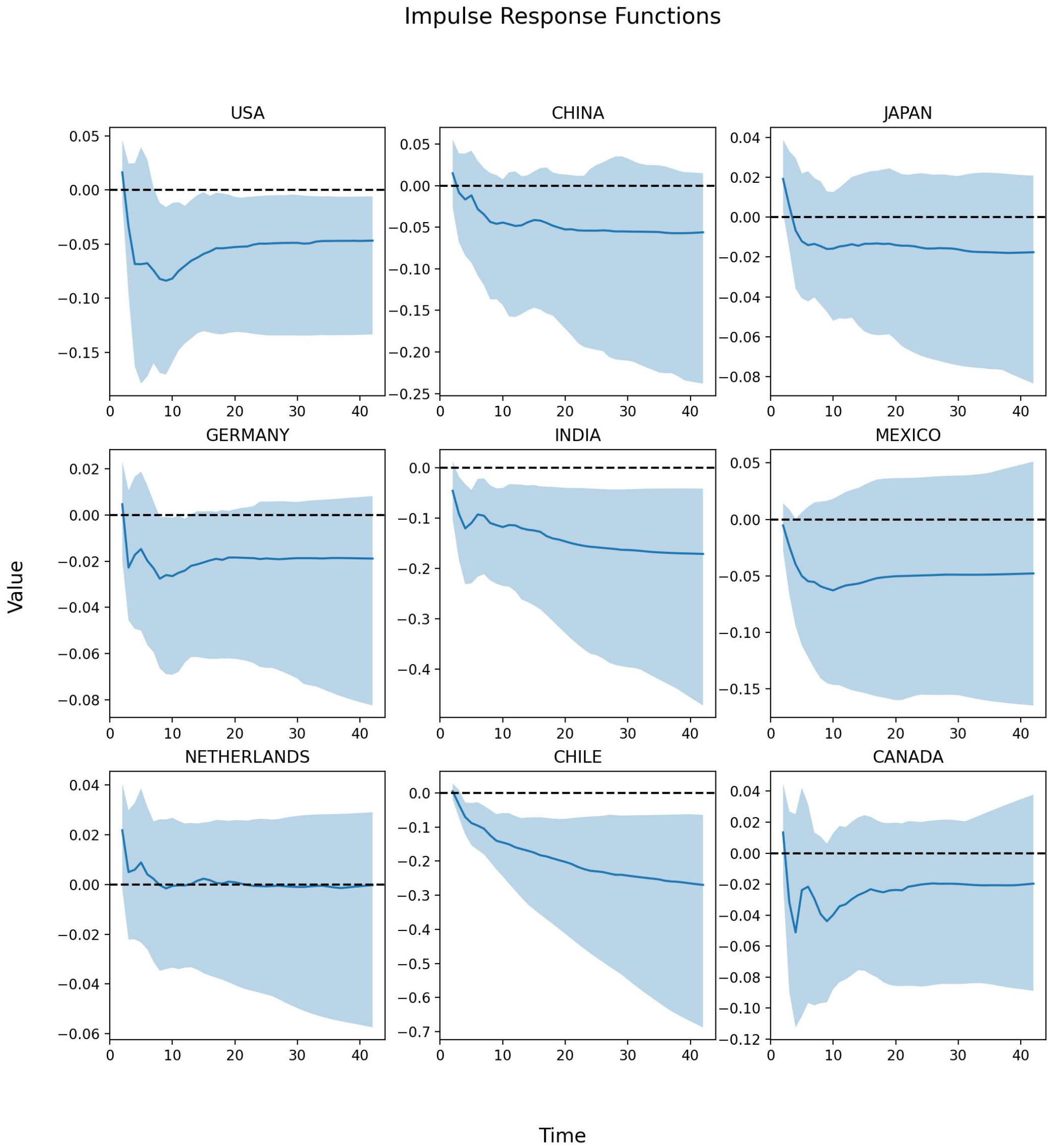

Figure 5.11: IRFs of IRs to +1SE shock to US uncertainty

5.4.5 Response of exchange rates

Despite exchange rates are crucial for our model to work, they do not provide any clues for interpretation. Most IRFs are insignificant, except for India, where depreciation occurred 5.12. However, for India we lacked interest rates in our model! Interestingly only other country, that experiences depreciation is Japan. Both Japan (due to ZLB) and India (due to absence of the variable) can not use IR drop to accommodate the EPU-induced slowdown of the economy, therefore it is being accommodated here via ERs.

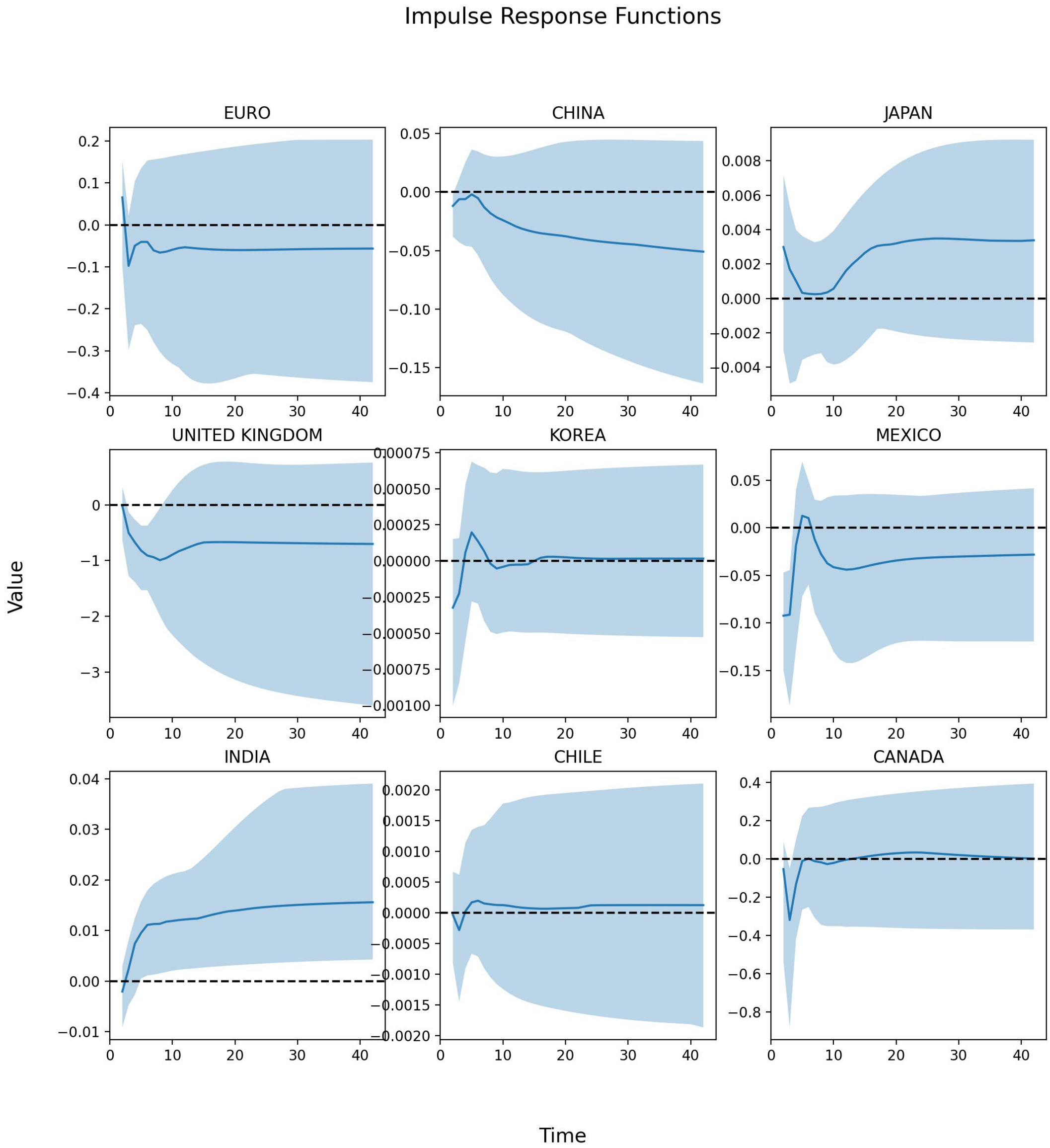

Figure 5.12: IRFs of ERs to +1SE shock to US uncertainty

5.5 6 variables model

Here we add another variable - equity prices, we order it second in the VARX* models after the EPU.

$$\left.\begin{aligned} epu_{it} &= \left(EPU_{it}/\sum_{t=1}^{t=T} EPU_{it} * T * 100\right) \\ ep_{it} &= MSCI_{it} \\ er_{it} &= ER_{it} * CPI_{USDt}/CPI_{it} \\ \pi_{it} &= \ln(CPI_{it}) - \ln(CPI_{it-12}) \\ r_{it} &= 0.25 * \ln(1 + R_{it}/100) \\ y_{it} &= \ln(GDP_{it}/CPI_{it}) \end{aligned}\right\}$$

This addition will allow another variable capable of immediate reaction to accommodate the uncertainty shock. In contrast to exchange rates or interest rates, equity prices themselves probably do not affect real variables as much (at least not in a way, that our model could easily capture) - they are not known to influence international trade like exchange rates, they do not affect interest rates as opposed to the opposite effect, etc. We are resorting to 2 lags in this case as opposed to 4 above, as IRFs become very volatile with more lags.

5.5.1 EPU reaction

Here again we see very fast fading of the EPU and the lag effect in China described above. There is almost no difference from the previous model. **??**

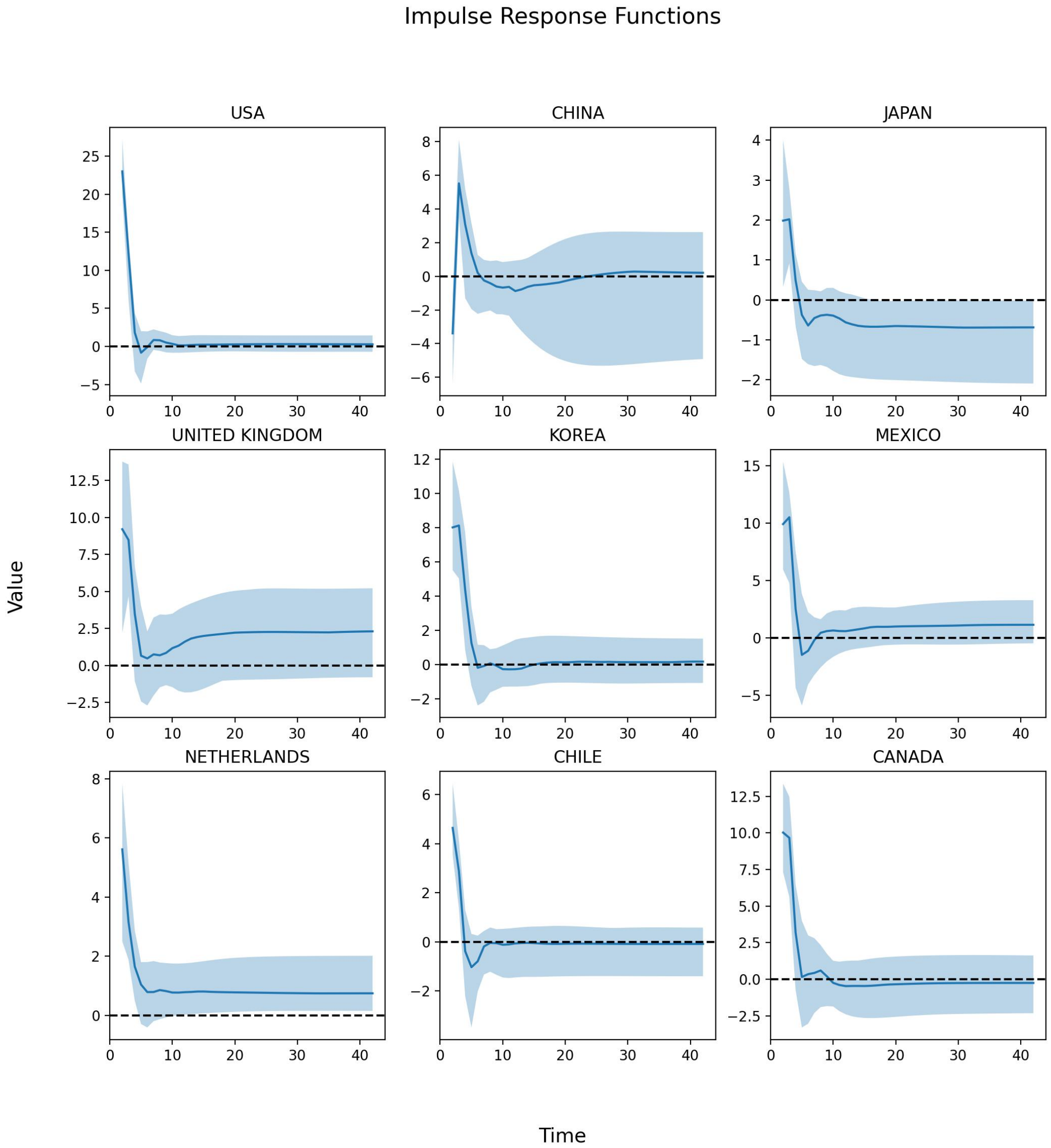

Figure 5.13: IRFs of EPU to +1SE shock to US uncertainty

In GVAR local variables react to the shock from the "rest of the world" block, which means all other countries in the model. US shock is in practice a shock to the "rest of the world" block (different for each country) with size given by the SE of the US EPU and and weight US has in the basket of countries (here we use trade weights). The relevant contemporaneous coefficient then determines the size of the instant spillover to the country. These coefficients are then essentially impact elasticities of a shock from foreign to domestic variables. Therefore, higher coefficient means higher responsiveness to "rest of the world" shock, but it does not correspond directly to the size of the spillover,

	Coefficient	White's t-ratio
BRAZIL	**0.443**	3.363
CANADA	**0.750**	9.006
CHINA	**0.265**	2.883
CHILE	**0.450**	4.819
FRANCE	**0.927**	9.602
GERMANY	**1.314**	8.977
INDIA	**0.359**	3.601
ITALY	**0.486**	6.735
JAPAN	**0.201**	3.321
KOREA	**0.713**	5.183
MEXICO	**0.872**	6.668
NETHERLANDS	**0.390**	5.904
SPAIN	**0.240**	5.294
SWEDEN	**0.230**	7.028
UNITED KINGDOM	**1.080**	4.263
USA	**0.889**	9.342

Table 5.1: Contemporaneous coefficients of EPU

because it is modified by weight of the US in the specific "foreign" block.

The table below 5.1 offers a number of surprises. It reveals high susceptibility of developed economies to uncertainty spillovers from other countries. We hypothesize, that less developed countries experience higher "neutral" levels of EPU, therefore foreign shocks are perceived as relatively big. It can also be said, that these countries are simply "used to" higher uncertainty. Unfortunately we can not test for this as firstly EPU is not internationally comparable, secondly, even normalizing for identical mean and variance does not ensure full comparability as different languages would have different use for different keywords used for construction of the EPU. Our hypothesis on Chinese isolation is also confirmed by this set of coefficients.

5.5.2 Response of the GDP

Responses to the shock here are generally less significant than before. Although they are very similar in shape, e.g. Mexico experiences much less significant output decline. France and Germany respond more, whereas Spain responds less. We will try to interpret this at a later stage with reactions of interest rates and equity prices.

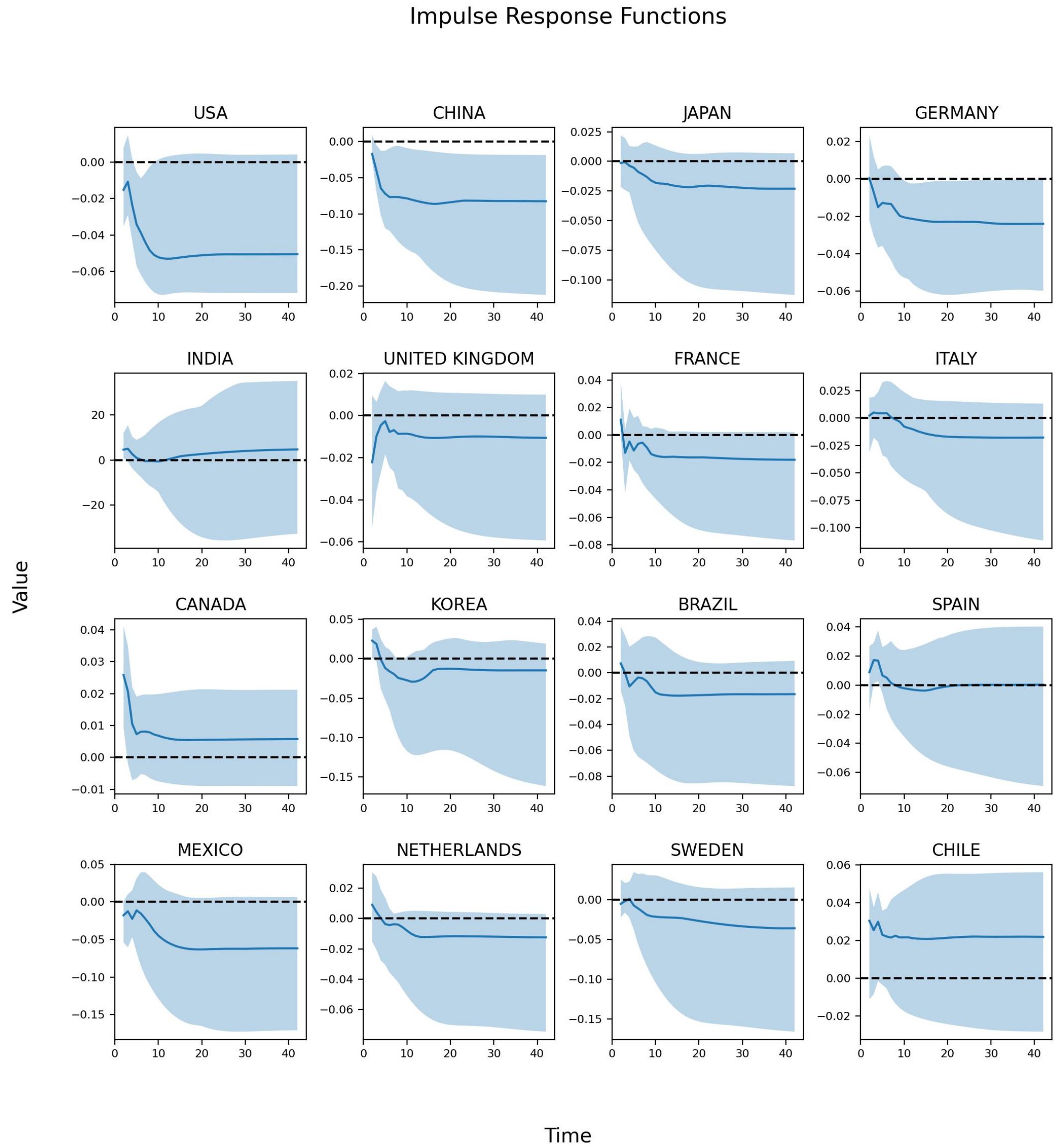

Figure 5.14: IRFs of GDP to +1SE shock to US uncertainty

5.5.3 Response of inflation

Here we see basically any response of inflation wiped out for most countries - China, Japan, Chile and getting more significant for a few: Korea, Spain and Mexico.

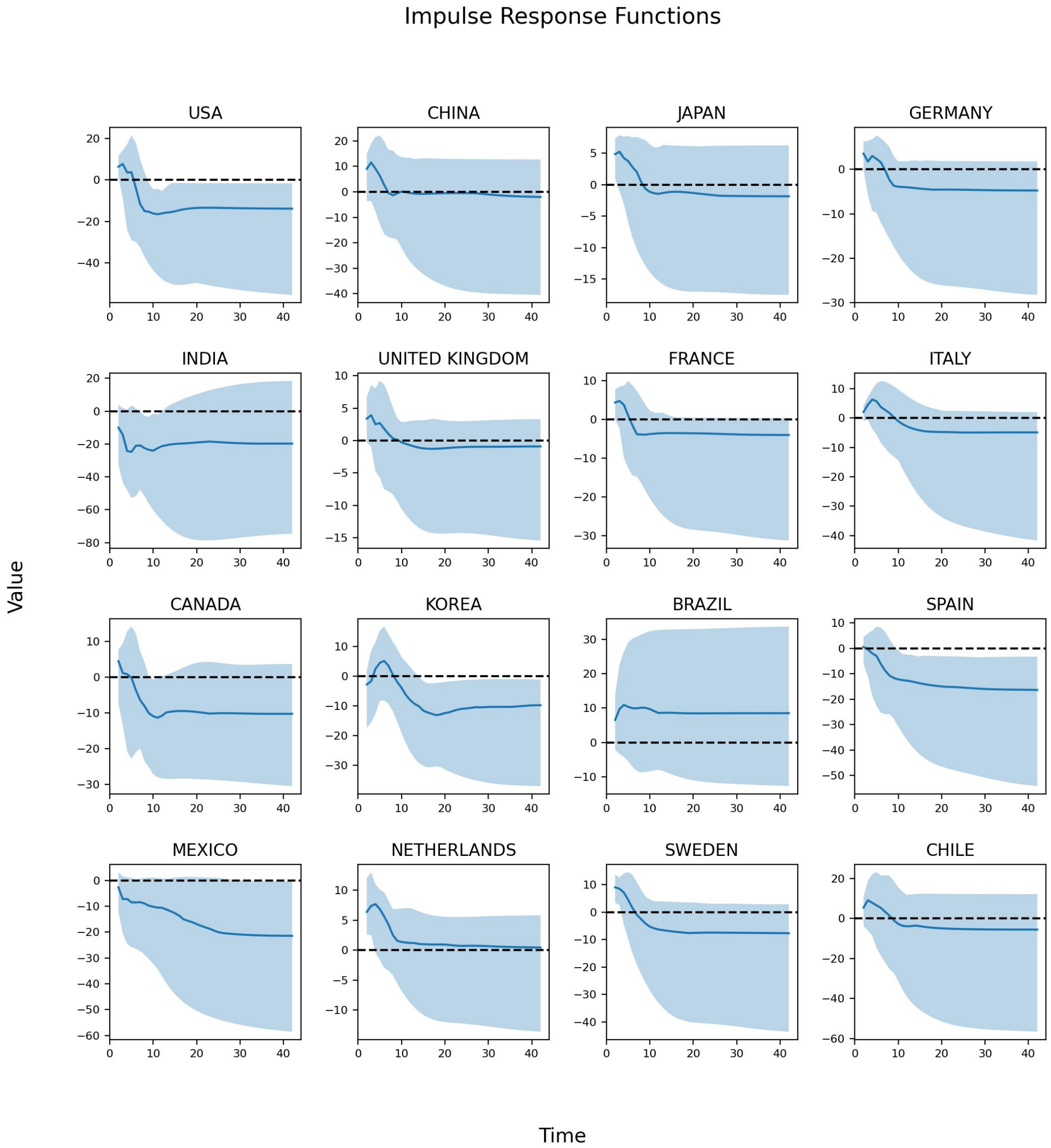

Figure 5.15: IRFs of inflation to +1SE shock to US uncertainty

5.5.4 Response of interest rates

Interest rates were affected by the model change in a similar manner: significance disappeared, here uniformly, there is no country, that would get a more significant answer here, than before.

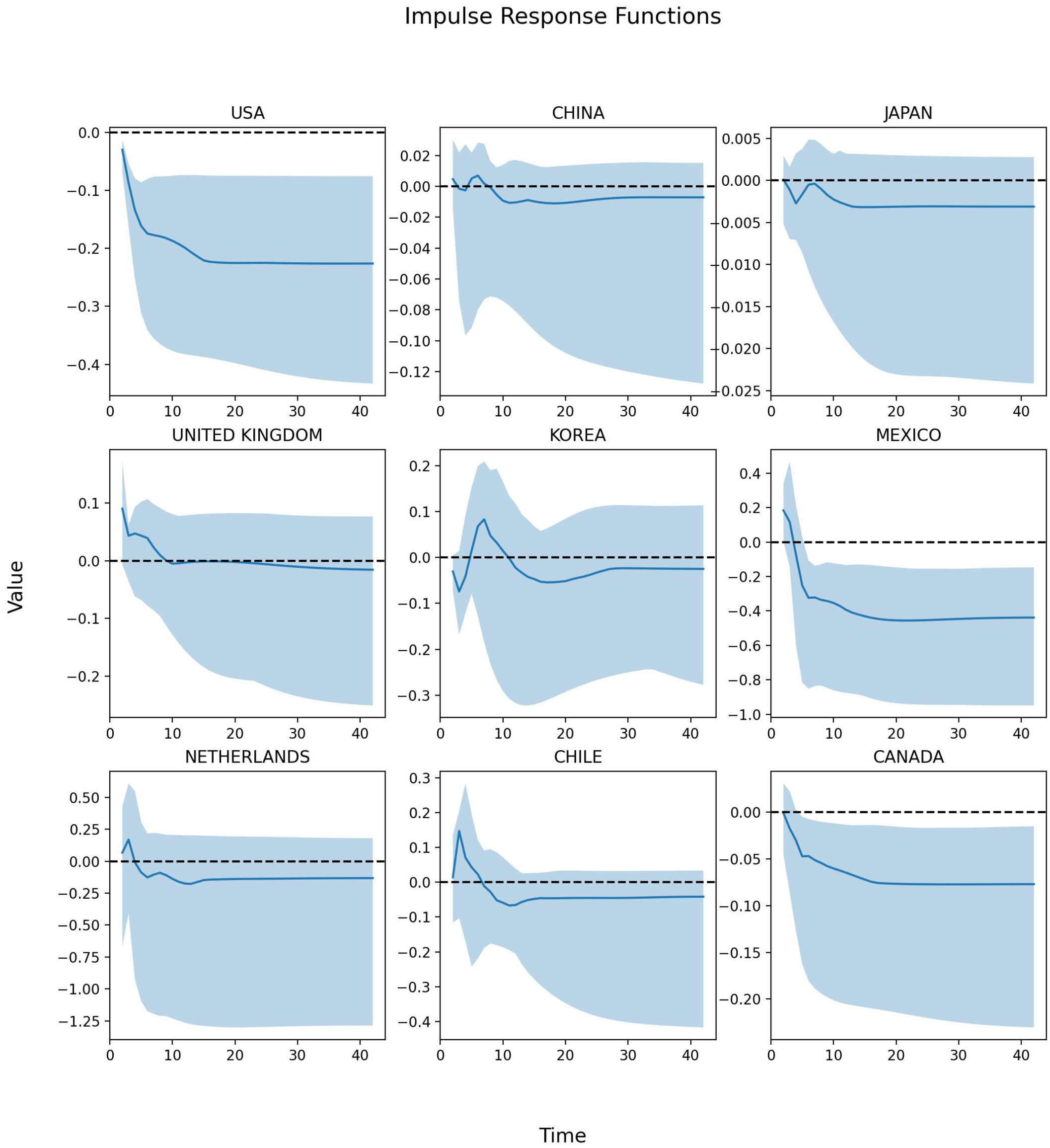

Figure 5.16: IRFs of interest rates to +1SE shock to US uncertainty

5.5.5 Response of equity prices

Here we can see, that equity prices take over a big part of the adjustment that would otherwise occur in inflation, interest rates or output. They indeed react immediately, like exchange rates, therefore reducing impact of uncertainty on other parts of the economy.

When we compare the impact of the shock in model with equity prices and without them for China and Japan, in the model without Japan clearly suffered more output loss due to lack of interest rates adjustment. Here it was the opposite: China lost more output as interest rate responses of both countries were negligible and Japanese equity prices reacted faster motivating additional investment and increasing potential upside for investors (as it is investment, that suffers the most from uncertainty shocks).

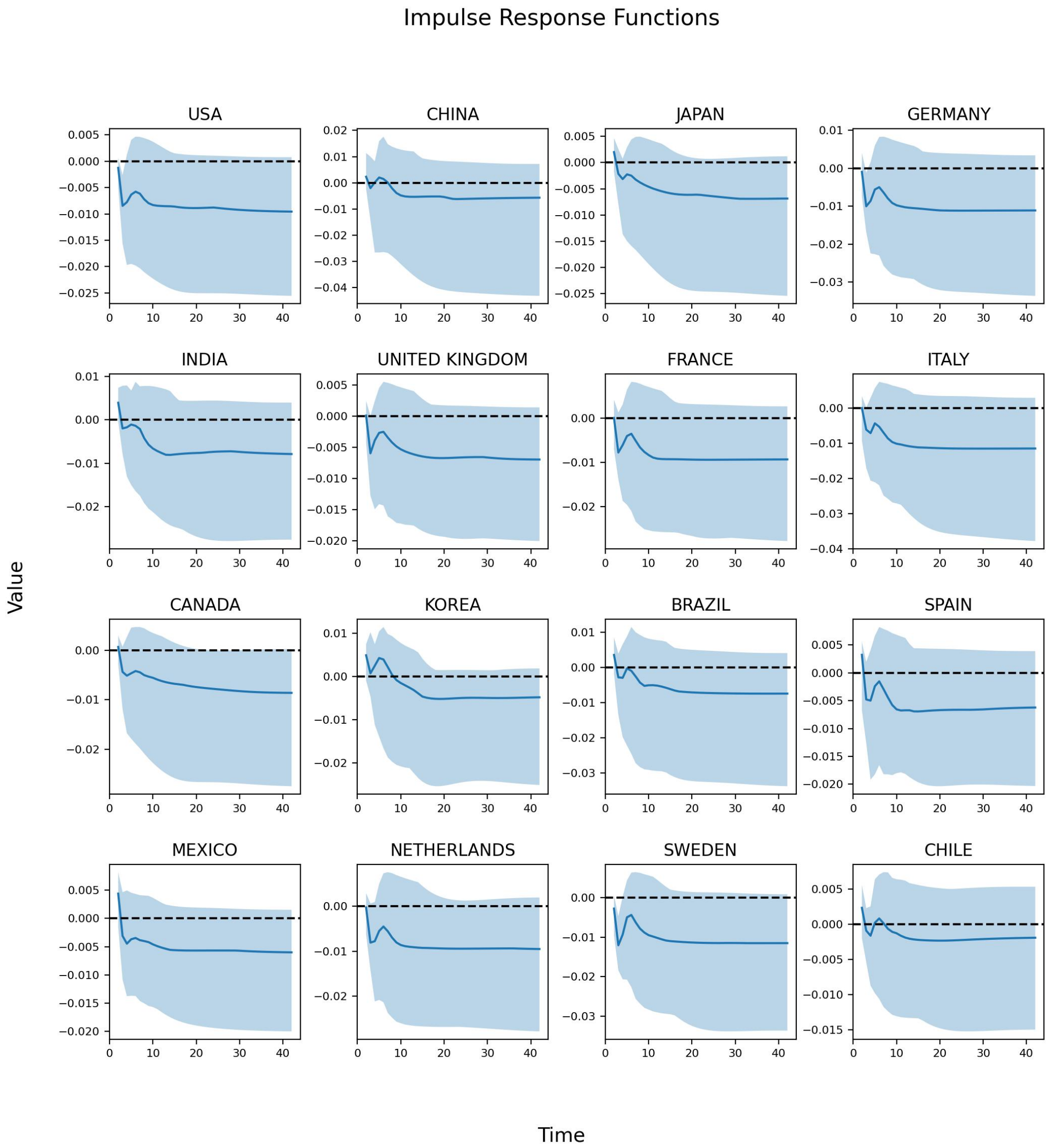

Figure 5.17: IRFs of equity prices to +1SE shock to US uncertainty

5.5.6 Response of exchange rates

Just like in the last model, there are no major changes in exchange rates. Euro appreciates insignificantly as it probably overtakes some of the funds from US dollar, which were stored there as in a safe haven, the same for JPY. Just like before, an interesting response comes from India. Although we did not expect this as an effect of absenting interest rates, almost no output decrease, big drop in inflation and appreciation of ER all together give a coherent, albeit we think incorrect, explanation as we would expect output drop in absence of IR adjustment.

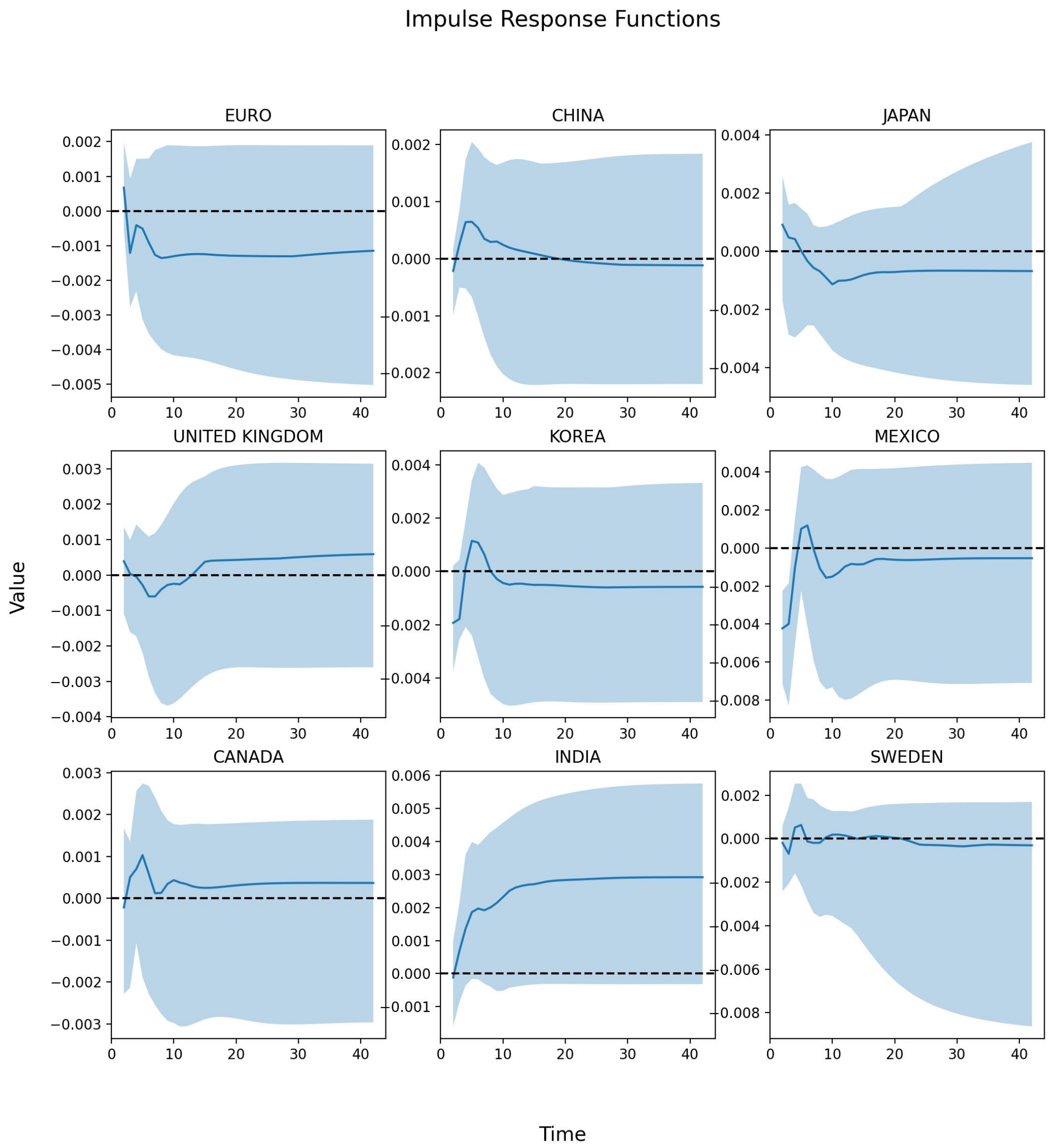

Figure 5.18: IRFs of exchange rates to +1SE shock to US uncertainty

5.6 Shock to global uncertainty

This is a very handy opportunity to test, which currencies act as a safe haven and which equity markets count as such. In a global uncertainty crisis we would expect investors to flee towards both safe currencies and safe markets. We simulate a global uncertainty shock to all included economies and investigate responses of ERs and equity prices.

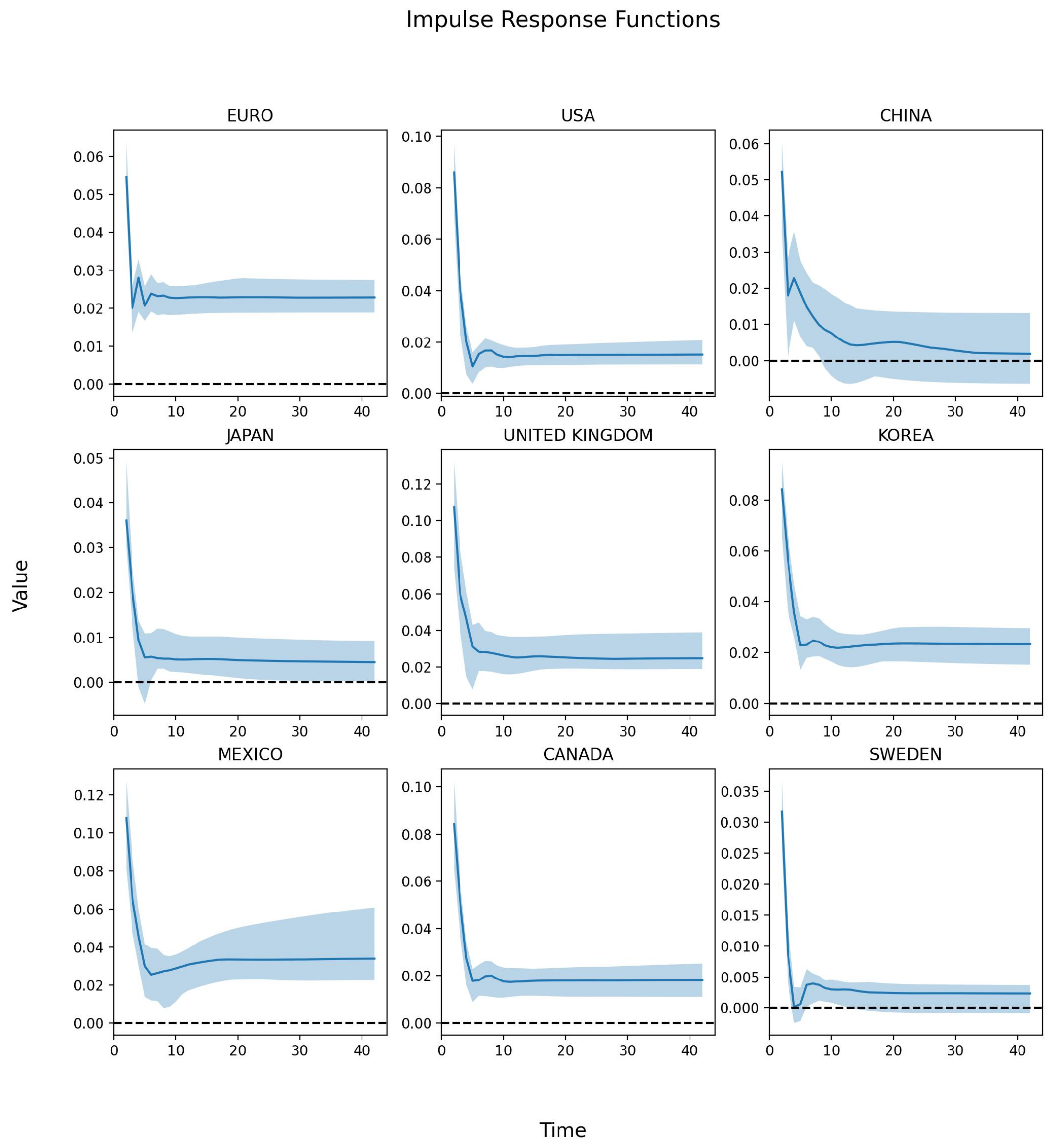

Figure 5.19: IRFs of EPU to +1SE shock to global uncertainty

We are quite surprised by the global responses to the global EPU shock. There is a level of uncertainty that persists with quite tight confidence intervals, especially in the eurozone. This might be due to a few things. Firstly, it might be, that a global shock can not be compensated by movements in IRs, ER, equity prices, etc. as it hits whole world at once. Secondly, especially the response of the EU brings seems very weird, as if the EPU did not fade away.

We believe, that despite the common ER, monetary policy and economic ties, European countries still have their own local policy events.

Local EPUs, as media based indices necessarily capture a lot of local uncertainty, which can be associated with local (national) politics, policies with only local relevance (education, most of taxation issues, ...) and despite all ties within the eurozone correlation of the EPUs of these countries is low and therefore in the aggregate EPU we will not see sufficient variation for the model to "learn" the behavior of the index well. This would mean, that it is simply inappropriate to model eurozone uncertainty as a whole since the uncertainty events differ too much. It would also mean, that modelling exchange rate of euro is very unreliable in GVAR, as it is crucial for the model, as apparent above.

To test this we will simply look for correlation of eurozone EPU series. in 5.2 we present correlation of the EPU in the eurozone countries, also those, that are not part of our analysis, in the applicable sample of countries and with Singapore, which has as little common uncertainty event with the eurozone as possible. Despite that, we see, that the within-eurozone correlations are certainly not higher than those with Singapore or other countries. In this case it is not even necessary to statistically test these results, as the intra eurozone correlations are even lower(!) than those with Singapore. This necessitates very cautious approach to these models, where eurozone is combined into one block, especially then eurozone results.

This however does not invalidate our results above. Even if the data for eurozone EPU are unrealistic all other coefficients for other variables might still be close to reality. Eurozone variables affect other countries via their respective "foreign" variables, which means it is just one of the potential channels of spillover of a shock from abroad (e.g. US). In consequence, results from above are valid, but eurozone reactions are likely underestimated in the aggregated models.
We will not attempt to simulate a shock into eurozone uncertainty for this reason as it would probably give unreliable results.

Despite the above mentioned, we believe, that we can cautiously draw conclusions on our flight-to-quality hypothesis from this model. In 5.20 we see a picture completely inconsistent with literature. We would expect most currencies to depreciate as a reflection of USD appreciation. We could also think of JPY appreciation according to the literature. Here we see exactly the opposite (we checked a few times, how the ERs are noted to make sure we do

	FR	DE	GR	IRE	ITA	NETH	ESP	SING
France	1							
Germany	0.653	1						
Greece	0.196	-0.123	1					
Ireland	0.689	0.696	-0.129	1				
Italy	0.439	0.301	0.289	0.319	1			
Netherlands	0.225	0.157	0.278	0.142	0.534	1		
Spain	0.738	0.601	0.113	0.648	0.468	0.342	1	
Singapore	0.741	0.759	-0.137	0.720	0.482	0.266	0.691	1

Table 5.2: Correlations of eurozone countreis and Singapore

not interpret this "upside down"): JPY depreciation and appreciation of developing countries' currencies: INR, BRL, CLP. GBP and CAD appreciation is not unrealistic but not expected (Ranaldo & Söderlind 2010). Theoretically it might be, that the liquid funds that investors move between currencies in reaction to EPU shock are not accumulated in developing countries' currencies anyway, therefore they do not experience instant outflow and depreciation.all other variables are the same as outlined above.

Still, we find this could be due to model properties. Although the model capture global interlinkages, the simplification of world in "local" and "foreign" blocks for each country is critical in this case. For each country, this model does not realized, that the shock is global, it just simulates a big (1 SE) shock to the "foreign" uncertainty and the same shock to domestic uncertainty. Therefore, the "globality" is not reflected otherwise, than in size of the shock and presence in both model components, which probably can not capture complex character of a global shock. In light of what we found above however, we think this will rather be simply wrong as a consequence of failure to accurately capture the "globality" and the eurozone uncertainty.

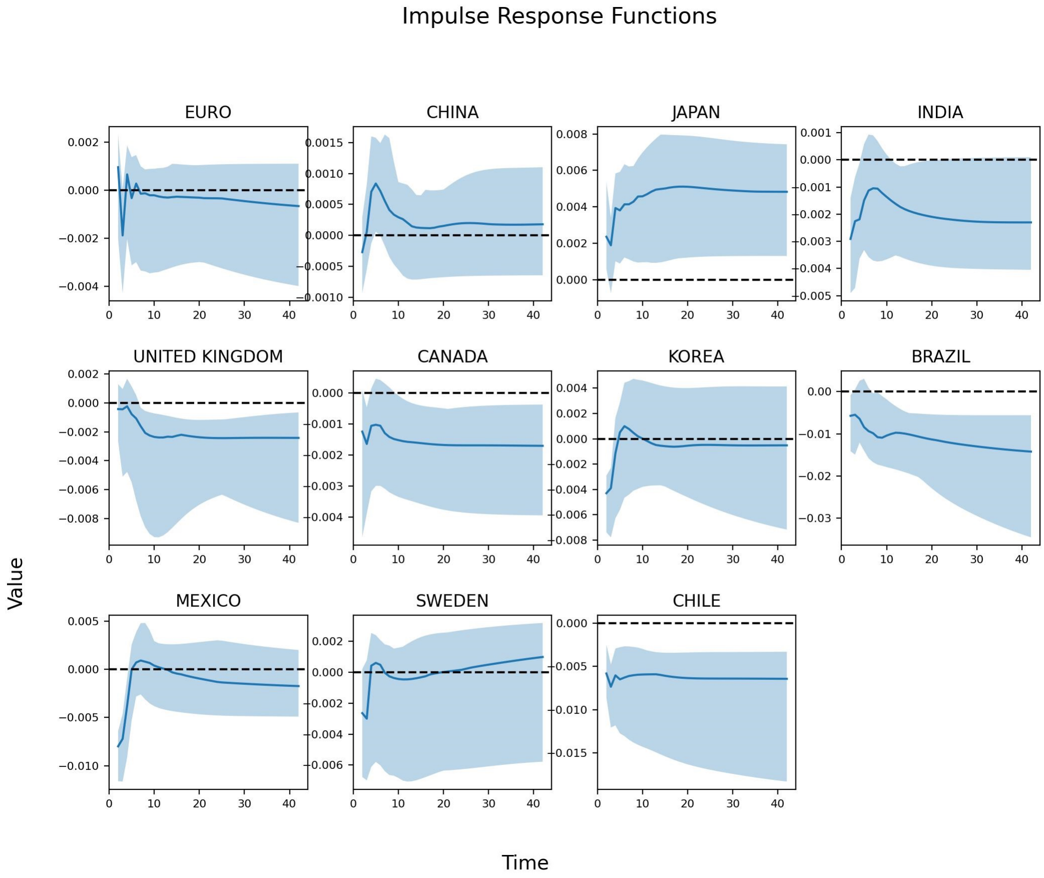

Figure 5.20: IRFs of exchange rates to +1SE shock to global uncertainty

Equity prices in 5.21 follow the picture in exchange rates. The same countries, that experienced appreciation see here the smallest drops in equity prices and Japanese drop is by far the most significant.

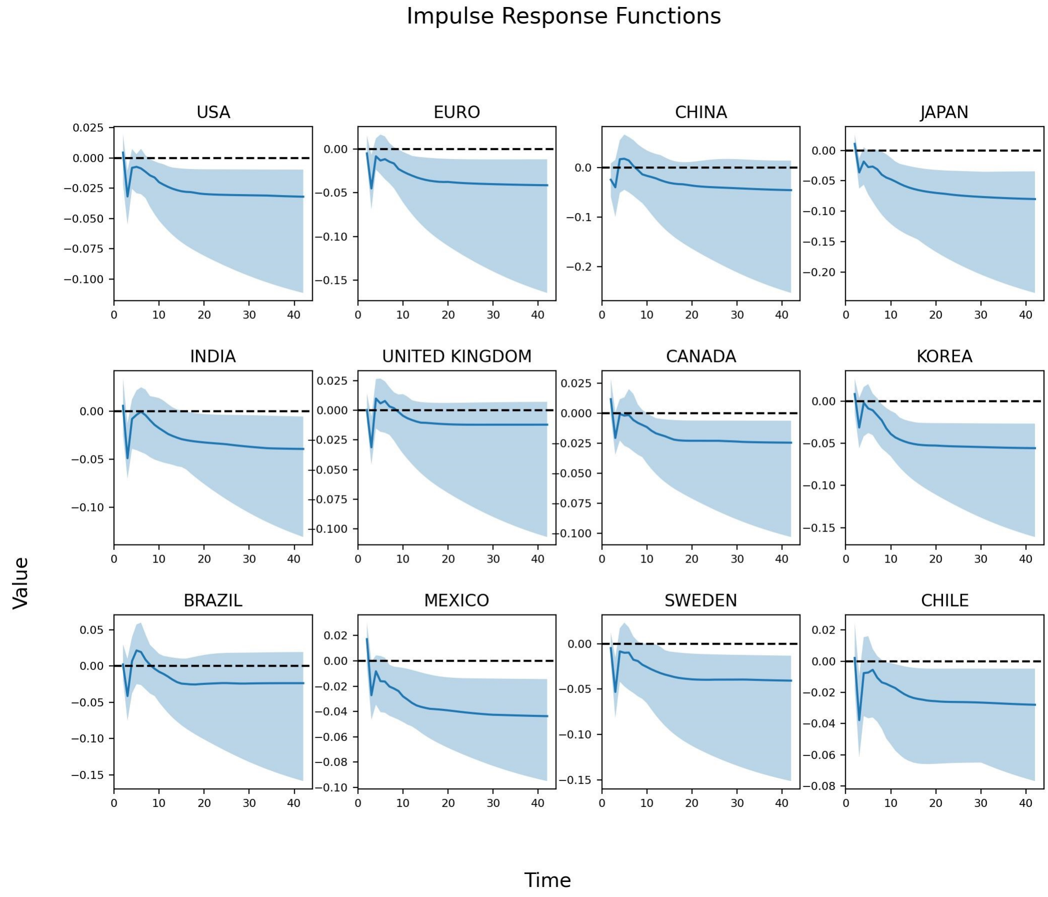

Figure 5.21: IRFs of equity prices to +1SE shock to global uncertainty

5.7 Discussion

After finding, that simple 4-variable model does not reflect reality well we began the analysis in 5-variable quarterly setting followed by 5- and 6-variable models on monthly data. We found compelling evidence for immediate spillover of uncertainty, except for China, where we find a 1-month delay in transmission. Further effects include decrease in output, inflation, interest rates and equity prices, impact on exchange rates was inconclusive, but supportive of depreciation of local and appreciation of foreign currencies after a local uncertainty shock. These responses are consistent with expectations and literature.

Among the relevant theories reviewed in the literature review section we find evidence for real options hypothesis. Drop in output, interest rates and inflation are all consistent with decrease of investment and to a lesser extent consumption.

Our results have shown heterogeneity in responses between countries we would expect to react similarly, i.e. Mexico and Canada or Netherlands and Germany (or France, which react almost identically).

We attribute the first difference to ties that go beyond trade: migration, remittances, political relations, etc. During the period of our sample, there were notable differences in the dynamics of US-Mexican and US-Canadian relations, primarily due to the nature of the relationships and the issues that each country faced during that time.

US-Canadian relations are based on economic cooperation and partnership focusing on expanding economic ties. US-Mexican relations are more complex due to issues such as drug trafficking, illegal immigration, and border security. While trade between the United States and Mexico also grew during sample period, tensions and challenges surrounding border enforcement and immigration probably contributed to inequality of the relationship. In a situation, where the stronger party experiences uncertainty shock, it is of much more concern to the weaker party of an agreement, that if both sides were acting as equals. The inequalities between the two states are both economic (e.g. investment flows mainly from the US to Mexico) and non-economic (e.g. US forcing Mexico to strengthen border controls).

The case of Germany and Netherlands is much less obvious. These countries feature so many similarities - policy relationship with the US, currency, interest rates, part of diplomatic relations, that it is hard to justify this difference. We attribute it to firstly general exposure of economy to trade - Dutch economy is smaller and international trade constitutes a higher percentage of it. Secondly, major Dutch trade articles are oil-related goods or oil or gas itself, which may be impacted more by global spillover of the US shock. Finally, It may be, that companies doing their business elsewhere but residing in Netherlands for tax purposes are impacted more than Dutch companies, which decreases formally Dutch output albeit not having that impact in reality.

The model also reflected presence of the ZLB constraint in Japanese economy, where the interest rates could not react to uncertainty shock, which impacted other variables.

We can also conclude a policy-relevant message from this model. Our model indicates existence of trade-off between output, inflation, interest rates and equity prices. For policymaker, it is highly desirable to direct the response into equity prices and interest rates rather than into GDP. Trade-off between inflation and GDP probably does need any comments or recommendations to make as Philips curve is being researched for decades and every possible policy recommendation was made. The trade-off with equity prices and interest rates indicates the need for functional local stock markets and a central bank willing to adjust interest rates and even exchange rates before models can reflect the impact.

5.8 Possible extensions

The analysis above certainly provides some insights into how uncertainty affects real economy and how it spills over into other countries. Apparently the role of the financial markets in spreading the uncertainty is crucial as they can react immediately and they channel a big part of effects on output. They are usually available on daily or even higher frequency. Running GVAR on these high-frequency variables, unfortunately without GDP and other real but low-frequency variables, could explain how these financial variables interact together and which of them are relevant in this context. This would require higher frequency EPU, which is not available, but it seems like an alternative composed of daily google searches or twitter mentions of specific words or another similar internet-based indicator could be a viable alternative here. This is an complex task, it would certainly require cleaning from seasonality but for the index it would be also weather, which demonstrably affects moods of internet users, major social events, concerts, elections, etc. Dependent on word selection it could also serve to determine, which topics cause economic consequences and which are irrelevant.

Chapter 6

Conclusion

Uncertainty is a phenomenon with extensive research on its origins and implications for the real economy, but much scarcer literature on its spillovers. We extend that strand of literature by using Global Vector Autoregressive Model (GVAR) to analyse economic policy uncertainty spillovers among countries quantified by the Economic Uncertainty Policy Index (EPU). We then make conclusions based on the impulse response functions to shocks to the EPU.

Our results are consistent with literature. We find, that EPU spillovers occur immediately with only exception in China, where they occur with one month lag. Financial markets play a crucial role in the shock transmission as they can adjust immediately in response to an uncertainty shock.

Output decreases as a response to an uncertainty shock in both target and spillover countries. Interest rate also decrease in response to such shock. Inflation generally decreases, but it may increase in some countries due to supply side effects. Equity prices also generally decrease. We believe, that the effect spreads between the GDP, interest rates, inflation and equity prices together and stronger response of one of them evens out weaker response of another one, i.e. if interest rates or equity prices decrease more, GDP decreases less (opposite for inflation). These results support the "real options" hypothesis stating, that the impact is cause by increased attractiveness of "wait and see" approach in investment decisions.

We also found, that vast majority of effects of local shocks is insignificant in this model. We could not find any significant responses for shocks to China, India or Japan, and we did not simulate shocks to eurozone uncertainty as we found this aggregation is not applicable for uncertainty analysis. This does not mean they do not exist, but this methodology can not distil them from noise.

Our main two findings: immediate spillovers and significant negative effect on foreign output, which can be mitigated by well-functioning equity markets or adjustment in interest rates are highly relevant implications for future policymakers when facing a foreign uncertainty shock.

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