INTERNATIONAL CO-MOVEMENTS IN RECESSIONS

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Abstract

Business cycle correlations are state-dependent and higher in recessions than in expansions. In this paper, I suggest a mechanism to explain why this is the case. For this purpose, I build an international real business cycle model with occasionally binding constraints on capacity utilization which can account for state-dependent cross-country correlations in GDP growth rates. The intuition is that firms can only use their machines up to a capacity ceiling. Therefore, in booms the growth of an individual economy can be dampened when the economy hits its capacity constraint. This creates an asymmetry that can spill-over to other economies, thereby creating state-dependent cross-country correlations in GDP growth rates. Empirically, I successfully test for the presence of capacity constraints using data from the G7 advanced economies in a Bayesian threshold autoregressive (T-VAR) model. This finding supports capacity constraints as a prominent transmission channel of cross-country GDP asymmetries in recessions compared to expansions.

Keywords: international business cycles, business cycle asymmetries, GDP co-movement, capacity constraints, occasionally binding constraints.

JEL classification: E32, E60, F41, F44, F47.

Resumen

La correlación entre los ciclos económicos depende del estado de la economía y es más alta en recesiones que en expansiones. En este documento sugiero un mecanismo para explicar la causa. Para este propósito, construyo un modelo de ciclo económico real internacional con restricciones de capacidad vinculantes ocasionalmente, que puede explicar las correlaciones cíclicas dependientes del estado entre países en las tasas de crecimiento del PIB. La intuición es que las empresas solo pueden usar su maquinaria hasta un umbral de capacidad. Por lo tanto, en los períodos de auge el crecimiento de una economía individual se puede atenuar cuando la economía alcanza su límite de capacidad. Esto crea una asimetría que puede extenderse a otras economías, creando así correlaciones entre países en función del estado de las tasas de crecimiento del PIB. Empíricamente, compruebo con éxito la presencia de restricciones de capacidad utilizando datos de las economías avanzadas del G-7 en un modelo autorregresivo de umbrales bayesianos (T-VAR). Este hallazgo respalda las limitaciones de capacidad como un canal de transmisión destacado de las asimetrías del PIB entre países en recesiones en comparación con las expansiones.

Palabras clave: ciclos económicos internacionales, asimetrías del ciclo económico, sincronización de movimientos del PIB, restricciones de capacidad, restricciones de capacidad ocasionales.

Códigos JEL: E32, E60, F41, F44, F47.

Non-technical summary

This paper is motivated by the empirical observation that GDP growth correlations among developed countries are significantly higher if the US economy is in a recession compared to the US economy being in an expansion. This means that developed countries tend to experience recessions at the same time, while recovery phases are less synchronized. While this empirical finding has been the subject of some studies in the literature, possible explanations of this phenomenon that can account for the observed GDP growth correlation differences in a standard international macroeconomic model have been less researched. In this paper, I suggest a mechanism to explain these differences. For this purpose, I build an international real business cycle model in which producers face a short-term ceiling to their production capacity. The intuition is that in the short-run, firms can only use their machines up to a capacity ceiling and building new machines to increase capacities takes time. Therefore, in booms the GDP growth of an individual economy can be dampened in comparison to an economy in which such a capacity constraint is not present, while a decrease in utilization in a recession remains unconstrained. This so-called occasionally binding constraint on capacity utilization causes an asymmetry in country specific business cycles that can spill-over to other economies via trade channels. Thereby it creates state-dependent cross-country correlations in GDP growth rates such as those observed in the data. In the benchmark model calibrated to a quarterly sample of OECD countries and the US in a time period from 1961 to 2016, the model can account for a quarter of the observed differences in GDP correlations between recessions and expansions, while alternative calibrations show that the more the two countries in the model depend on trade with each other the higher the explained difference in GDP growth correlations. In an empirical exercise I successfully test for the presence of this type of capacity constraints using quarterly data from the G7 advanced economies for the time period from at least 1980 to 2016, depending on data availability. I use an empirical method that can track spillovers of aggregate productivity shocks from one-country to another and can also account for differences in these spillovers depending on the shock being of a positive or a negative nature (threshold autoregressive model, T-VAR). The empirical analysis yields that US as well as Foreign utilization adjustments are dampened for positive productivity shocks, while adjustment is stronger and recessions are deeper for negative aggregate productivity shocks compared to positive ones of the same size. This mirrors the asymmetric shock responses generated by the model with the mechanism of an occasionally binding capacity ceiling. The finding strongly supports capacity constraints as a prominent transmission channel of cross-country GDP asymmetries in recessions compared to expansions. The analysis of asymmetries in spillovers is crucial for policy-makers, as their presence implies that there are differences in the magnitude of an economy's responses to economic shocks, depending on whether this economic shock is positive or negative. As a consequence a policy-maker will have to adjust the magnitude of a policy response to a given shock depending on the positive or negative nature of the shock.

1 Introduction

This paper is motivated by the empirical finding that business cycle co-movements across countries are higher during economic contractions than during economic expansions (e.g. Yetman, 2011; Antonakakis and Scharler, 2012, as well as my own empirical evidence). In an international real business cycle framework I investigate the reasons and potential mechanisms that cause co-movements of GDP across countries to be state-dependent. In the data, I find that the average pairwise correlation of GDP growth rates between 20 OECD countries in a quarterly sample from Q1:1961 to Q4:2011 is between 5.4 and 22.7 percentage points higher during recessions compared to expansions.[1] The main purpose of the paper is to build a framework in which country-specific shocks and their spillovers to other countries endogenously lead to higher cross-country co-movements in GDP during recessions. To achieve this asymmetry, I am introducing a friction in the form of an occasionally binding capacity utilization constraint in an otherwise standard 2-country, 2-goods large-open economy model (e.g. Heathcote and Perri, 2002). The intuition is that in the short-run, firms can only use their machines up to a capacity ceiling and building new machines to increase capacities takes time. Thus, the friction can be interpreted as an occasional inability to adjust capacity utilization beyond a certain degree within a given period. At least in the short-run, this maximum capacity cannot be increased. The implication of the occasionally binding constraint is that following a sequence of good shocks, a given country's machines reach their maximum capacity and the increase in production is dampened compared to an unconstrained economy. After a sequence of bad shocks, machines can be left idle and the economy remains unconstrained. This introduces asymmetric responses to shocks in the sense that negative shocks to one country have stronger effects on this country's economy than positive ones. The crucial feature of the mechanism to create state-dependent cross-country correlations is that the asymmetries also spill over internationally because terms-of-trade and real exchange rate movements are not capable

[1] Since the latest financial crisis led to a historical high in cross-country GDP correlations, the magnitude of the result depends on whether this time period is included in the sample or not. Furthermore, different procedures to disentangle recessions and expansions are compared.

of cushioning these asymmetries in spillovers. Therefore, the full asymmetry is transmitted internationally. Asymmetries can even be amplified by the presence of a similar occasionally binding constraint in the other country. Countries are interlinked through trade in intermediary production goods, as each country produces one of these intermediary goods and uses the domestic as well as the foreign intermediary good in the production of a final consumption good. Therefore, a positive (negative) shock to a given economy affects the production of intermediary goods of both countries positively (negatively). Due to the fact that negative shocks have higher effects than positive ones in this model with occasionally binding capacity constraints recessions spill-over more intensively than expansions between countries and this leads to state-dependent cross-country correlations. I show that the proposed mechanism can match the differences in cross-country GDP growth correlations between expansions and recessions observed in the data if tradable intermediary goods are to a certain degree complementary. Lastly, I find empirical evidence for threshold effects in the capacity utilization rate of the US economy and use the resulting threshold estimates in a Bayesian threshold autoregression (T-VAR) to obtain asymmetric empirical responses of the G7 advanced economies' variables to positive, as well as negative US TFP shocks. The resulting impulse response functions mirror the impulse responses of the theoretical model and are taken as evidence of the importance of occasionally binding capacity constraints to explain the observed asymmetries in cross-country GDP correlations between expansions and recessions. The necessity of such an extension of the workhorse 2-countries, 2 goods model arises from the fact that the standard model is not capable of producing asymmetries in cross-country correlations, because it is absolutely symmetric and usually solved using linear perturbation methods. Taking these asymmetries into account explicitly is relevant for economic policy conclusions drawn from international real business cycle (RBC) models. Thus, economic policy conclusions drawn from linear and symmetric models might be misleading if in the real world agents anticipate international asymmetries in the business cycle and adjust their decisions to their expectations. The question of why business cycle co-movements are significantly higher during recessions compared to expansions has to the best of my knowledge not received much attention in the literature. From a financial frictions perspective Perri and Quadrini (2011) and Bacchetta and Wincoop (2016) aim to explain the extraordinary co-movements in the last financial crisis. However, in this study I provide evidence that this phenomenon is not only limited to the last global recession but holds over a number of US recession. Furthermore, I advertise capacity utilization constraints as an important mechanism underlying this observations over the long run. This channel can be viewed as complementary to the effects of financial frictions that the above studies investigate. The empirical fact that business cycle co-movements across countries are increasing in recessions has been pointed out by Yetman (2011). He takes the US cycle and US recessions as reference data and shows that the co-movement of different country groups (G7, Europe, Asia-Pacific) with the US business cycle is only positive and significantly different from zero if the US is in a recession. Using a dynamic conditional correlations (DCC) approach, Antonakakis and Scharler (2012) find that the cross-country correlations between a number of developed countries significantly increases during US recessions in the years between 1960 and 2009. Moreover, there are other references in the literature which find that business cycles in the G7 countries become more similar in recessions (for instance Canova et al., 2007) or that individual countries' cycles are more affected by the global cycle in global recessions (e.g. Claessens et al., 2013; Helbling and Bayoumi, 2003). The mechanism put forward in this paper as a cause of state-dependent co-movements in an international real business cycle model is an occasionally binding constraint on capital utilization. These types of constraints have already been used to explain within country business cycle asymmetries, i.e. the fact that recessions are usually sharper and shorter than expansions (e.g. Hansen and Prescott, 2005; Knueppel, 2014). In this paper, I show that within-country asymmetries can also be a cause for international correlations to become asymmetric between recessions and expansions. The threshold tests I perform on US utilization rates support this mechanism and the T-VAR evidence obtained using these test results are in line with the theoretical model results, further strengthening the relevance of the proposed mechanism.

2 Empirical analysis

To establish the fact that business cycle co-movements are higher during recessions than during expansions, I obtain quarterly data on GDP for the time span of Q1:1961 to Q4:2011 from the OECD's Quarterly National Accounts database.[2] Due to data availability considerations, I restrict the analysis to 20 out of 34 OECD countries, which I aggregate to the country groups EU-13[3], G7, NAFTA and Oceania. A list of the countries included in these groups is given in section 10 in the appendix. All of the series are at constant 2005 prices (OECD reference year), seasonally adjusted and converted to US dollar values. Furthermore, I obtain annual population data from the OECD.Stats database and normalize all observations of a year by population to obtain per capita values and take logarithms of the series.[4] To assess the patterns in international co-movement in US recessions and expansions, I calculate different measures of correlation and co-movement in the business cycles.

2.1 Disentangling expansions and recessions

Most of the empirical work on business cycle correlation during expansions and recessions identify the US business cycle as a reference cycle for the analysis of co-movement in recessions and expansions. Therefore, to identify recessions of the US economy most authors in the literature use the NBER recession dates to disentangle expansions and recessions. Because in this paper I additionally investigate the sources of asymmetries in business cycle correlations, I need a procedure that can be applied to the empirical data as well as to the model generated data in the same way. Therefore, to disentangle recessions and expansions, I use the turning point algorithm developed by Harding and Pagan (2002).

[2] I also obtain annual data for the same time period from the Annual National Accounts database to perform some illustrations and robustness checks.

[3] Greece and Ireland had to be excluded from the EU-15 because of data availability.

[4] Since population data is only available at annual frequency and GDP data is quarterly, I use linear interpolation to obtain population size for the quarters within a given year.

The algorithm identifies turning points in the log-series of GDP. If a given observation is a maximum among the previous and the following 2 observations, the algorithm identifies this observation as a peak. Similarly, if a given observation is a minimum among the previous and the following 2 observations, the algorithm identifies this observation as a trough. Along the business cycle, expansions are defined as the time span between a trough to a peak, while recessions are the time span between a peak to a trough. The algorithm also performs validity check to ensure for instance that a trough is always followed by a peak and vice versa. To see how the algorithm compares to the NBER recession dates, table 1 shows the recession dates identified by the turning point algorithm, as well as the NBER recession dates.

Table 1 – Recession periods in the US, 1961-2011

NBER recessions	TP recessions
Q1:1961	
	Q2:1962 - Q4:1964
	Q2:1966 - Q4:1967
Q4:1969 - Q4:1970	Q2:1969 - Q4:1970
Q4:1973 - Q1:1975	Q3:1973 - Q1:1975
	Q2:1976 - Q4:1976
Q1:1980 - Q3:1980	Q1:1979 - Q3:1980
Q3:1981 - Q4:1982	Q2:1981 - Q4:1982
	Q4:1985 - Q1:1987
Q3:1990 - Q1:1991	Q2:1990 - Q4:1991
	Q1:1993 - Q3:1993
	Q1:1995 - Q1:1996
Q1:2001 - Q4:2001	Q3:2000 - Q1:2003
	Q4:2005 - Q1:2006
Q4:2007 - Q2:2009	Q1:2008 - Q2:2009

The algorithm matches the dates and lengths of the NBER dated recessions well. At the same time it identifies more recession periods than the dating committee at NBER. Most likely, these episodes are downturns that the NBER did not find severe enough to term them recessions, but they do fulfill the dating criteria of the turning point algorithm.[5]

[5]To check robustness I increased the time span to identify peaks and troughs from ± 2 periods around a given observation to ± 3 and ± 4. Although the identified recession episodes tend to get shorter, the number of identified peaks and troughs does not change. Since ± 2 is the number of periods used by Harding and Pagan (2002) and this specification covers the NBER recession dates best, I use this specification.

2.2 Conditional Correlations

First, I calculate correlations of GDP growth rates between the identified country blocks and the US, as well as between the individual G7 countries and the US, conditional on the US being in an expansionary or recession period. I also test the difference between correlation coefficients using a Fisher r-z-transformation of the coefficients.[6] The results are shown in table 2. All the correlations within the country groups increase in US recessions compared to expansions. This is true for recessions identified by both NBER and the TP algorithm. These correlation differences are highly significant for the EU-13 and the G7, mainly because there are more countries in these groups and thus the sample size is larger. Moreover, the differences for expansions and recessions identified by the TP algorithm tend to be more significant since the number of expansion and recession (114 vs. 89) periods is more balanced than using the NBER dates (169 vs. 35). Also for the individual countries in the G7 group all correlation coefficients are larger in recessions compared to expansions. Calculating the average correlation difference between all countries in the sample with the US during the identified US business cycle states, I find differences of 22.4 percentage points using the NBER recession dates and 24.7 percentage points using the TP algorithm. Both of them are significantly different from zero at the 1% confidence level. As it is very likely that the global recession of 2007-2009 has a large impact on the cross-country correlations in recessions and expansions in the time period investigated here, I do the same calculations as above, excluding the years 2007-2011 from the sample. The results are shown in table 3. As expected, the differences decrease in general, but overall correlations in recessions are still significantly higher than in expansions. For the individual G7 countries this result is reversed for Canada and Germany when recessions are identified by NBER dates, while for the country blocks it is reversed for the NAFTA using NBER dates. For the other countries and country blocks the main effect keeps its direction. Over the whole sample the average correlation is 10.5 percentage points higher during NBER dates and 17.1 percentage points higher during TP recessions. Both differences are significantly different from zero at least at the 5% confidence level.

[6] This is necessary as correlation coefficients are defined on $[-1, 1]$, while the test statistic on the difference between coefficients is defined on $(-\infty, +\infty)$.

Table 2 – Conditional Correlations - GDP Q1:1961 - Q4:2011

	NBER			TP		
Country	Exp	Contr	C > E	Exp	Contr	C > E
Individual G7						
Canada	0.2910	0.4007	Yes	0.2795	0.4279	Yes
France	0.0332	0.3729	Yes*	-0.0256	0.4270	Yes***
Germany	0.1244	0.2923	Yes	0.0026	0.2336	Yes
Italy	0.0031	0.2704	Yes	0.0935	0.3206	Yes*
Japan	0.1111	0.3705	Yes	0.1165	0.4382	Yes**
Co UK	0.0797	0.4580	Yes**	0.0742	0.4276	Yes***
Observations	169	35		114	89	
Country Blocks						
EU 13	0.1370	0.3805	Yes***	0.1318	0.3871	Yes***
G7	0.2346	0.4521	Yes***	0.2201	0.4678	Yes***
NAFTA	0.4552	0.5655	Yes	0.4209	0.5471	Yes
Oceania	0.3701	0.4620	Yes	0.3802	0.4458	Yes
Observations	Cou*169	Cou*35		Cou*114	Cou*89	
Average						
All 20	0.1177	0.3413	**0.2236*** **	0.1096	0.3562	**0.2466*** **
p-value (2s)			0.0000			0.0000
Observations	20*169	20*35		20*114	20*89	

$***$,$**$ and $*$, indicate $p < 0.01$, $p < 0.05$, $p < 0.1$, respectively. The table shows cross-country correlations of GDP growth rates between the given country or country block and the US during expansions (Exp) and contractions (Contr). Expansions and contractions are found using the NBER recession dates in the NBER columns and the Harding and Pagan (2002) turning point algorithm in the TP columns. The columns titled $C > E$ indicate if the correlation coefficient is higher during contractions compared to expansions. For the country blocks, Cou is the number of countries within a given country block, excluding the US. For EU13 $Cou = 13$, for G7 $Cou = 6$, for NAFTA $Cou = 2$ and for Oceania $Cou = 2$.

Table 3 – Conditional Correlations - GDP Q1:1961 - Q4:2006

	NBER			TP		
Country	Exp	Contr	C > E	Exp	Contr	C > E
Individual G7						
Canada	0.2890	0.2873	No	0.2332	0.3394	Yes
France	0.0263	0.2462	Yes	-0.0562	0.3222	Yes***
Germany	0.1413	0.1134	No	0.0154	0.1140	Yes
Italy	-0.0199	0.1669	Yes	0.0239	0.1905	Yes
Japan	0.0871	0.1946	Yes	0.0683	0.3172	Yes*
UK	0.0534	0.3791	Yes	-0.0127	0.3187	Yes**
Observations	155	28		99	83	
Country Blocks						
EU 13	0.1267	0.2592	Yes**	0.0994	0.2775	Yes***
G7	0.2253	0.3411	Yes	0.1817	0.3717	Yes***
NAFTA	0.4595	0.4539	No	0.4107	0.4728	Yes
Oceania	0.3658	0.4660	Yes	0.3672	0.4338	Yes
Observations	Cou*155	Cou*28		Cou*99	Cou*83	
Average						
All 20	0.1099	0.2145	**0.1046****	0.0809	0.2516	**0.1707*****
p-value (2s)			0.0215			0.0000
Observations	20*155	20*28		20*99	20*83	

$***$,$**$ and $*$, indicate $p < 0.01$, $p < 0.05$, $p < 0.1$, respectively. Footnotes of table 2 apply.

2.3 Yetman Synchronization

The literature has also proposed alternatives to correlation measures. For instance co-movement measures, i.e. indicators if business cycles are in the same phase, have been proposed (see for instance Yetman (2011) or de Haan et al. (2007)). Here, I am concentrating on a measure proposed by Yetman (2011). The co-movement measure of Yetman (2011) is defined as the product of z-scores of annual GDP growth rates, i.e

$$\rho_{ijt} = z_{it} z_{jt} \tag{1}$$

where

$$z_{it} = \frac{(y_{it} - \bar{y}_i)}{\sqrt{\frac{1}{T-1}\sum_{t=1}^{T}(y_{it} - \bar{y}_i)^2}} \tag{2}$$

and y are GDP growth rates. The z-score normalization thus ensures that positive co-movement is indicated if both countries are growing above or below their mean growth rate and negative co-movement is indicated if one country grows above its mean growth rate while the other grows below its mean growth rate. Despite the degree of freedom adjustment used in calculating the Yetman measure, the time average across co-movements corresponds to the uncorrected correlations. Thus, the average Yetman measure is very similar to the correlations above. Therefore, I do not state the results here explicitly. The advantage of the co-movement measure is that it can be calculated at each point in time. Concentrating on the co-movement between the European aggregate and the US, and using annual data for illustrative purposes[7], I follow Yetman (2011) and regress the co-movement measure of 13 European countries with the US reference cycle on country fixed effects and time dummies such that the coefficients of the time dummies indicate an average estimator of European co-movement with the US reference cycle at a given point in time and the standard deviations of these estimators indicate their significant difference from zero.

Figure 1 shows that even before the global financial crisis of 2007-08, significantly positive spikes in the co-movement measure in most cases coincide with the NBER recession dates of the US economy, while co-movement is moderately positive the remaining time.

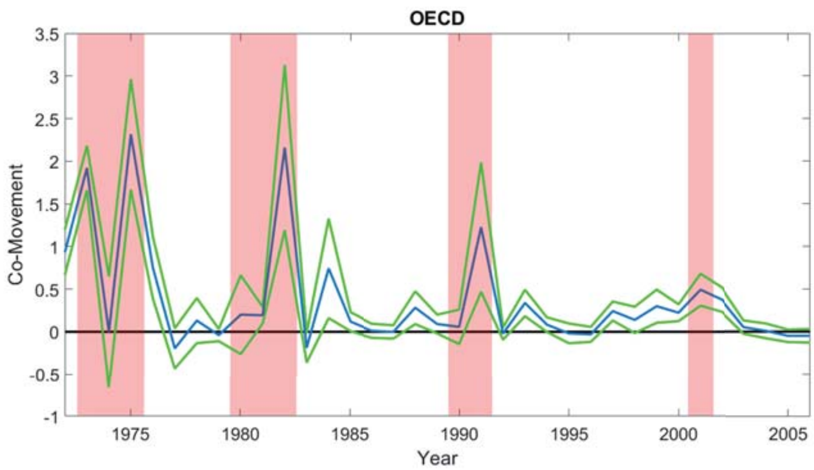


Figure 1 – GDP Co-Movement with the US (1970 - 2006), NBER recession dates - Yetman (2011)

In Figure 2 the crisis period is added to the previous figure. It is evident that the global financial crisis of 2007-08 was an extraordinarily synchronized recession across developed countries.

[7]Observations on the measure calculated with quarterly data is too frequent to create a nice and clear plot.

2.4 Average correlations of country pairs in US recessions

So far, the focus has only been on correlations of the countries and country blocks in the sample with the US economy during US recessions. Now, I look at the average cross-country

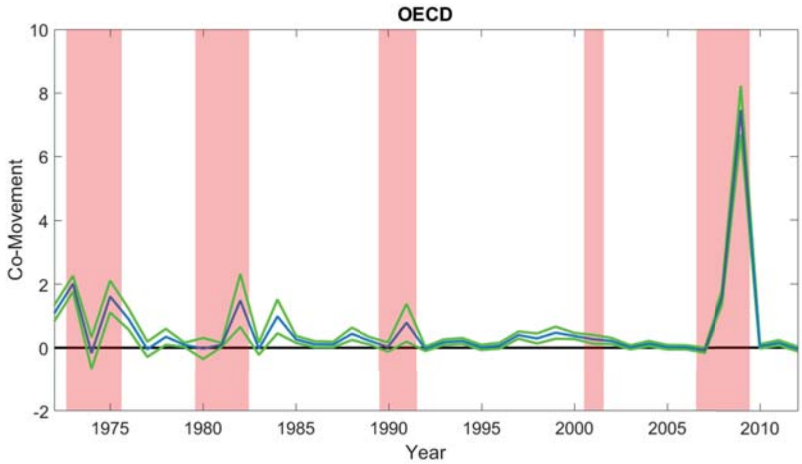


Figure 2 – GDP Co-Movement with the US (1970 - 2011), NBER recession dates

GDP correlations of all these countries with each other during US recession periods. To obtain a clear picture of the state-dependent correlations in recessions and expansions of all country-pairs on average, table 4 shows the average correlations across all country-pairs for both considered time spans, as well as both recession identification methods. It shows that cross-country correlations across all countries are significantly higher during US recessions compared to US expansions. It also shows that the cross-correlations have increased due to the recent global financial crisis, but that the most conservative measure still indicates that cross-country correlations increased by at least 5.44 percentage points during US recessions compared to US expansions if we exclude this recent crisis. In fact though, the difference in correlations might have been as high as 22.7 percentage points, if the recent financial crisis is considered a part of the underlying data generating process of the global economy. Given the findings in this section, it is crucial that we understand what might be driving differences in observed cross-country correlations during expansions and contractions. In the following section, I propose a mechanism which can account for these observed differences.

Table 4 – Correlations of country pairs

	NBER			TP		
1961-2011						
Country	Exp	Contr	Diff	Exp	Contr	Diff
Avg. Correlation	0.1910	0.3973	**0.2270*******	0.1994	0.3389	**0.1535*******
P-Value			**0.0000**			**0.0000**
Obs.	210*169	210*35		210*114	210*89	
1961-2006						
Avg. Correlation	0.1862	0.2479	**0.0679*******	0.1901	0.2395	**0.0544*******
P-Value			**0.0000**			**0.0000**
Obs.	210*155	210*28		210*99	210*83	

$***$,$**$ and $*$, indicate $p < 0.01$, $p < 0.05$, $p < 0.1$, respectively. The table shows cross-country correlations of GDP growth rates between all 20 countries during US expansions (Exp) and US contractions (Contr). Expansions and contractions are found using the NBER recession dates in the NBER columns and the Harding and Pagan (2002) turning point algorithm in the TP columns. The columns titled 'Diff' give the difference in correlation coefficient calculated for expansions and contractions. The results are calculated for the full sample of Q1:1961 to Q4:2011, as well as for a subsample from Q1:1961 to Q4:2006 which excludes the recent financial crisis.

3 Theoretical Analysis

Why do we observe that business cycle co-movements are significantly higher during recessions compared to expansions and what are the consequences of this fact on the decisions of economic agents and policy-making? Despite some studies of the most recent global recession, the fact that these observations hold across a number of US recession have to the best of my knowledge not been investigated in the literature. An understanding of these differences is important because agents that anticipate systematic differences in economic outcomes across the business cycle will adapt their economic decisions to these differences. The standard international real business cycle model (IRBC), i.e. the workhorse model with which economist model economic decisions in international macroeconomics, cannot generate asymmetries between countries of the magnitude observed in the data. Although, for instance through the concavity of the utility function, the model can produce non-linearities of some degree, due to their smoothness they are typically small. Furthermore, these models are commonly solved using linear perturbations around its deterministic steady state which by construction neglects non-linearities. Policy recommendations drawn by economists who base their conclusions on linear models when in fact important non-linearities are present in the data might be misled. In this theoretical section, I am building a framework in which country-specific shocks and their spill-overs to other countries endogenously lead to higher cross-country co-movements in recessions compared to expansions. For this purpose, I am introducing a friction in the form of an occasionally binding capacity utilization constraint in an otherwise standard 2-country, 2-goods large-open economy model (e.g. Heathcote and Perri, 2002). To solve the model, I use the solution algorithm for models with occasionally binding constraints developed by Guerrieri and Iacoviello (2015), which is able to capture non-linearities arising from the occasionally binding constraints. For the model to match the observed asymmetries well, I choose to target the most conservative measure obtained by the empirical analysis. Therefore, the targeted difference in line with the data is the increase of 5.44 percentage points between expansions and recessions obtained by applying the TP algorithm on data excluding the global financial crisis. This number is also broadly in line with the findings of Antonakakis and Scharler (2012). I will show that the model produces systematically higher cross-country correlations in contractions compared to expansions. In order to match the targeted magnitude, tradable intermediate goods have to be complements to a certain degree.

4 International Model with Occasionally Binding Capacity Constraints

The model economy consists of Home country (1) and Foreign country (2). Despite the occasionally binding capacity constraint it follows the exposition of Heathcote and Perri (2002). Within these countries there is an identical measure of infinitely lived households. Moreover, in each country, there exists a representative producer of a final consumption good and a representative producer of intermediate goods. The intermediate goods can be traded internationally, Foreign and Home intermediate goods are imperfect substitutes in the production process of the final good. Final goods can only be invested or consumed in the country they are produced in. The model economy experiences a random event $s_t \in S$ every period t. S is a possibly infinite set of states of the world. The history of events up to and including date t is given by s^t. At date 0 $\Pi(s^t)$ denotes he probability that any particular history s^t has realized up to t. Households choose to supply capital and labor to intermediate-good-producing firms (i-firms). These firms are perfectly competitive. It is assumed that households' labor as well as their capital cannot be exchanged internationally, i.e. it is internationally immobile. The capital stock $k_i(s^t)$ of each country i is owned by that country's households at any point in time t. Moreover, they choose the intensity with which firms can operate the households' machines. Households can only save in an international uncontingent bond and therefore financial markets are incomplete. Households in each country obtain their utility from consumption, $c_i(s^t)$, and leisure $1-n_i(s^t)$. In the definition of leisure, $n_i(s^t)$ is the amount of labor supplied and total period time endowment is fixed at 1.

4.1 The maximization problems of the agents

In each country $i = 1, 2$ there is a representative final good producer, an intermediate good producer and a representative household.

4.1.1 Intermediate good firms

The intermediate good firms produce country i's intermediate good. They are termed a for country 1 and b for country 2. For the production process they hire labor and rent capital from the households, which own all the resources of the economy. Intermediate good firms operate a Cobb-Douglas production technology

$$F(z_i(s^t), k_i(s^t), n_i(s^t), u_i(s^t)) = e^{z_i(s^t)} \left(u_i(s^t)k_i(s^t)\right)^{\theta} n_i(s^t)^{1-\theta} \tag{3}$$

where $z_i(s^t)$ is an exogenous technology shock. The rental rate on capital and the wage rate in country i are given by $w_i(s^t)$ and $r_i(s^t)$. They are denoted in terms of country i's intermediate good. After history s^t, the static maximization problem an intermediate firm in country i is

$$max_{k_i(s^t), n_i(s^t)} \{F(z_i(s^t), k_i(s^t), n_i(s^t), u_i(s^t)) - w_i(s^t)n_i(s^t) - r_i(s^t)u_i(s^t)k_i(s^t)\}$$
$$\text{subject to } k_i(s^t), n_i(s^t), u_i(s^t) \geq 0. \tag{4}$$

4.1.2 Final good firms

Investment adds to country i's capital stock as follows:

$$k_i(s^{t+1}) = \left[1 - \delta(u_i(s^t))\right] k_i(s^t) + x_i(s^t). \tag{5}$$

Here, $\delta(u_i(s^t))$ is the depreciation rate, which depends on the degree of capital utilization in this model, and $x_i(s^t)$ is country i's investment in terms of final goods. Final goods are produced using intermediate goods a and b as inputs. They operate a constant returns to scale technology and are perfectly competitive:

$$G_i(a_i(s^t), b_i(s^t)) = \begin{cases} [\omega_1 a_i(s^t)^{\frac{\sigma-1}{\sigma}} + (1-\omega_1) b_i(s^t)^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}} & \text{if } i = 1, \\ [(1-\omega_1) a_i(s^t)^{\frac{\sigma-1}{\sigma}} + \omega_1 b_i(s^t)^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}} & \text{if } i = 2. \end{cases} \tag{6}$$

The elasticity of substitution between goods a and b is σ and $\omega_1 > 0.5$ denotes the home bias in the production of domestic final goods. The maximation problem of country i final good firm's after history s^t is

$$max_{a_i(s^t), b_i(s^t)} \{G(a_i(s^t), b_i(s^t)) - q_i^a(s^t) a_i(s^t) - q_i^b(s^t) b_i(s^t)\}$$
$$\text{subject to } a_i(s^t), b_i(s^t) \geq 0 \tag{7}$$

for $i = 1, 2$. $q_i^a(s^t)$ and $q_i^b(s^t)$ denote the country i prices of intermediary goods a and b in units of country i's final good.

4.1.3 Households

The per-period utility for the country i household after history s^t is given by the standard Cobb-Douglas utility function introduced by Heathcote and Perri (2002):

$$U\left[c_i(s^t), 1 - n_i(s^t)\right] = \frac{1}{\gamma}\left[c_i(s^t)^{\mu}(1 - n_i(s^t))^{1-\mu}\right]^{\gamma}. \tag{8}$$

The budget constraints of households in country i is denoted in terms of the final good produced in country i, where $i = 1, 2$. For the representative Home household this budget constraint is given by

$$\begin{aligned} &c_1(s^t) + x_1(s^t) + q_1^a(s^t) Q(s^t) B_1(s^t) \\ &\quad = q_1^a(s^t)\left(w_1(s^t) n_1(s^t) + u_1(s^t) r_1(s^t) k_1(s^t)\right) + q_1^a(s^t)\left(B_1(s^{t-1}) - \Phi(B_1(s^t))\right). \end{aligned} \tag{9}$$

For the representative Foreign household it is

$$
\begin{aligned}
& c_2(s^t) + x_2(s^t) + q_2^a(s^t)Q(s^t)B_2(s^t) \\
& \qquad = q_2^b(s^t)\left(w_2(s^t)n_2(s^t) + u_2(s^t)r_2(s^t)k_2(s^t) + q_2^a(s^t)\left(B_2(s^{t-1}) - \Phi(B_2(s^t))\right)\right). \quad (10)
\end{aligned}
$$

Here, $c_i(s^t)$ denotes consumption and $x_i(s^t)$ is investment in country i. Both are denominated in i's final good. The holdings of the international bond $B_i(s^t)$ are denoted in terms of the Home intermediate good a. The price of the international bond is $Q(s^t)$. The wage rate $w_i(s^t)$ and the rental rate $r_i(s^t)$ are denoted in country i's final good. $n_i(s^t)$ is the amount of labor supplied by the household to intermediate firms and $k_i(s^t)$ is the amount of capital rented out to intermediate firms. $u_i(s^t)$ is the rate of capital utilization. Intermediate firms pay the rental rate for each unit of effective capital $u_i(s^t)k_i(s^t)$ in their use. $\Phi()$ is a small adjustment cost on bond holdings that ensures the determinancy of the international bond positions as for instance in Schmitt-Grohe and Uribe (2003). The functional form of the depreciation function is assumed to be

$$\delta(u_i(s^t)) = \delta u_i(s^t)^\eta. \quad (11)$$

I assume that there is an upper bound on capital utilization. The upper bound is motivated by fact that individual machines cannot be used over their capacity of 100%. For the economy as a whole, I assume that in the short-run total capacity utilization cannot be above Φ which is expressed as a percentage of total production capacity in the economy. Therefore it holds that

$$u_i(s^t) \leq \Phi. \quad (12)$$

The maximization problem of the representative country i household is

$$max_{c_i(s^t),n_i(s^t),x_i(s^t),k_i(s^{t+1}),B_i(s^t),u_i(s^t)} \sum_{t=0}^{\infty} \beta^t \sum_{s^t} U\left[c_i(s^t), 1 - n_i(s^t)\right] \quad (13)$$

subject to the budget constraint (9) or (10) for country 1 or 2, the respective law of motion for capital (5) as well as the occasionally binding capacity utilization constraint (12).

4.2 Equilibrium Conditions

The first-order optimality conditions for the households and firms are obtained from the agents' maximization problems outlined above. They are given in the Technical Appendix. Next, I define the stochastic disturbances and the market clearing conditions.

4.3 Market Clearing Conditions

The bond market clearing condition states that the international bond is in zero net supply:

$$B_1(s^t) + B_2(s^t) = 0. \tag{14}$$

For the intermediate good market the supply has to be equal to demand from Home and Foreign:

$$a_1(s^t) + a_2(s^t) = e^{z_1(s^t)} \left(u_1(s^t)k_1(s^t)\right)^{\theta} n_1(s^t)^{1-\theta} = y_1(s^t) \tag{15}$$

$$b_1(s^t) + b_2(s^t) = e^{z_2(s^t)} \left(u_2(s^t)k_2(s^t)\right)^{\theta} n_2(s^t)^{1-\theta} = y_2(s^t). \tag{16}$$

For the final good market consumption and investment demand from households has to be equal to the supply of the final good within a given country (as final goods are not internationally traded):

$$c_i(s^t) + x_i(s^t) = G_i(a_i(s^t), b_i(s^t)) \tag{17}$$

for $i = 1, 2$.

4.4 Exogenous process

The vector of shocks $z(s^t) = [z_1(s^t), z_2(s^t)]$ follows the law of motion

$$z(s^t) = Az(a^{t-1}) + \epsilon(s^t) \tag{18}$$

with A being a 2×2-matrix and $\epsilon(s^t)$ being a 2×1-vector of independently distributed random variables with variance-covariance matrix Σ.

4.5 Equilibrium

The equilibrium of the model is given by a set of policy functions for the Home household $c_1(s^t), n_1(s^t), x_1(s^t), k_1(s^{t+1}), u_1(s^t), B_1(s^t)$, and the same policy functions for the Foreign household $c_2(s^t), n_2(s^t), x_2(s^t), k_2(s^{t+1}), u_2(s^t), B_2(s^t)$, obtained from the households' first-order conditions, a set of choice functions of the Home and Foreign intermediary and final good firms $a_1(s^t), a_2(s^t), b_1(s^t), b_2(s^t),\ G_1(s^t), G_2(s^t),\ y_1(s^t), y_2(s^t)$, and prices $Q(s^t), r_1(s^t), r_2(s^t),\ w_1(s^t), w_2(s^t),\ q_1^a(s^t), q_2^a(s^t), q_1^b(s^t), q_2^b(s^t)$, such that, given the realizations of the random disturbances $z_1(s^t), z_2(s^t)$ and the Lagrange multipliers on the occasionally binding constraints $\lambda_1(s^t), \lambda_2(s^t)$,

1. goods markets for intermediary and final goods clear,
2. factor markets for labor and capital clear,
3. the international bond market clears.

5 Solution Method

I am using the algorithm developed by Guerrieri and Iacoviello (2015) (the 'OccBin' toolkit) to solve the dynamic stochastic general equilibrium (DSGE) model with occasionally binding constraints. In essence the solution algorithm relies on the fact that a model including an occasionally binding constraint can be represented by a model with different regimes. The model under investigation is log-linearized around the same point of approximation under each of these regimes. The algorithm combines the information about which regime prevails for the model economy in a given state and the dynamics within as well as across these regimes. In this way a model with occasionally binding constraints can be solved and simulated. As Guerrieri and Iacoviello (2015) point out it is important that the algorithm does not only result in the model switching from one linear regime to another. Rather, the anticipation effects of when a certain regime prevails and for how long it is expected to prevail can create high degrees of non-linearity. In the following I briefly describe how the algorithm works. In principle it implements a piecewise-linear approximation to the agents' policy rules. Guerrieri and Iacoviello (2015) describe the algorithm mostly for an example with one occasionally binding constraint. Since in an international model there are two identical countries, the model investigated here has two occasionally binding constraints. A model with two constraints has four regimes, one in which both constraints are slack, two in which one constraint binds and the other one is slack, and one in which both constraints bind. Under each of these regimes the model is log-linearized around its non-stochastic steady state. Following the notation of Guerrieri and Iacoviello (2015), the regime that prevails at the steady state is called 'reference regime' or $(M1)$, the other regimes are called 'alternative regimes' or $(M2),(M3)$ and $(M4)$. Which combination of the constraints bind or are slack at the reference regime does not matter for the algorithm. But two conditions have to be satisfied in order for the algorithm to be applicable:

1. The Blanchard and Kahn (1980) conditions for the existence of a rational expectation solution have to be fulfilled in the reference regime (not necessarily in the alternative regimes), and

2. the model has to return to the reference regime in a finite number of periods in case a shock moves it to one of the alternative regimes and agents expect no further shocks to occur.

Closely following Guerrieri and Iacoviello (2015), but extending their description to a model with two constraints, I will now define the piecewise-linear solution of such a model. The occasionally binding constraints are denoted $g_1(E_tX_{t+1}, X_t, X_{t-1}) \leq 0$ and $g_2(E_tX_{t+1}, X_t, X_{t-1}) \leq 0$. Assuming that under the reference regime neither of them binds $(M1)$ can be written

$$A_{11}E_tX_{t+1} + B_{11}X_t + C_{11}X_{t-1} + F_{11}\epsilon_t = 0, \tag{19}$$

where X is $n \times 1$ vector of all the endogenous variables in the model; E_t is the conditional expectations operator; A_{11}, B_{11}, C_{11} are $n \times n$ matrices of structural parameters for the linearized model equations; ϵ is a size $m \times 1$ vector of zero mean i.i.d. shocks and F_{11} is a $m \times n$ matrix of structural parameters. When g_1 binds and g_2 is slack, we can write $(M2)$ as

$$A_{21}E_tX_{t+1} + B_{21}X_t + C_{21}X_{t-1} + D_{21} + F_{21}\epsilon_t = 0, \tag{20}$$

where the notation is analogous to the one in $(M1)$, with the addition that the $n \times 1$ column vector D_{21} of structural parameters enters the system of equations because the linearization is taken around an approximation point in which $(M1)$ applies. Similarly, regimes $(M3)$ and $(M4)$ are defined as

$$A_{12}E_tX_{t+1} + B_{12}X_t + C_{12}X_{t-1} + D_{12} + F_{12}\epsilon_t = 0 \tag{21}$$

and

$$A_{22}E_tX_{t+1} + B_{22}X_t + C_{22}X_{t-1} + D_{22} + F_{22}\epsilon_t = 0, \tag{22}$$

where the notation is again analogous to the regimes above. **Definition 1 (Guerrieri and Iacoviello (2015)).** A solution of a model with two occasionally binding constraints is a function $f : X_{t-1} \times \epsilon_t \rightarrow X_t$ such that the conditions under system $(M1)$,$(M2)$,$(M3)$ or $(M4)$ apply, depending on whether the occasionally binding constraints $g_1(E_tX_{t+1}, X_t, X_{t-1}) \leq 0$ and/or $g_2(E_tX_{t+1}, X_t, X_{t-1}) \leq 0$ bind or are slack. I refer to the paper by Guerrieri and Iacoviello (2015) for a detailed description of the algorithm and to the OccBin toolkit for the codes to implement the solution procedure.

6 Results

6.1 Calibration

I am calibrating the model to produce quarterly simulated data. Therefore, I choose a discount factor of $\beta = 0.99$. Relative risk aversion is set to the standard value $1 - \gamma = 2$ and the capital share in intermediate good production is $\theta = 0.36$. The consumption share in utility is $\mu = 0.34$, which is also standard values in the literature. The depreciation rate is governed by two parameters, a standard linear component which I set to $\delta = 0.025$, as well as the component varying with capacity utilization η. The latter is calibrated such that the steady state utilization rate of the model matches the US mean utilization rate of 80.32% calculated over the period from Q1:1967 to Q4:2015. To match this moment, η is set to a value of 1.57. The maximum capacity utilization is set to 80.9%, which is the threshold value in the US capacity utilization rate estimated by a threshold vector autoregressive model in section 7.2. The parameter for the small bond adjustment costs and capital adjustment costs are set to standard values. This calibration, as well as the calibration of the shock processes follow Heathcote and Perri (2002). For two key parameters of the model, the home bias in consumption ω and the elasticity of substitution between home and foreign intermediate goods σ, I distinguish two calibration cases. The first case, termed 'Benchmark Calibration', includes a home bias in production ω that is calibrated to match the OECD 20 import ratio of 45% calculated over a period from Q1:1980 to Q4:2015. For the second case, termed 'High Difference' I set the home bias parameter to $\omega = 0.6$, which induces a steady state import ratio of 80% and is for instance in line with the import ratio of the Benelux nations (Belgium, Luxembourg and the Netherlands). In a robustness exercise I will show that a higher import ratio induces higher differences between business cycle correlations in recessions and expansions. For the elasticity of substitution between home and foreign intermediate goods in the production of final good the two cases differ as well. For the 'Benchmark Calibration', I choose a value of $\sigma = 0.7$, which is an intermediate value between the value chosen by Heathcote and Perri (2002) ($\sigma = 0.9$) and the lower value

Table 5 – Calibration

Parameter	Description	Calibration	Target*
β	discount rate	0.99	
Φ	utilization threshold	80.9%	estimated US threshold
θ	capital share	0.36	
ω	home bias in production	[0.755,0.6]	Import ratio (OECD 20)
σ	substitution elasticity	[0.7,0.5]	Robustness check
$1-\gamma$	relative risk aversion	2	
μ	cons. share in utility	0.34	
δ	depreciation	0.025	
η	depreciation	1.57	US mean utilization
ϕ	bond adj. costs	0.0005	
Shock process			
ρ_{ii}	persistence	0.95	
ρ_{ij}	shock spillover	0.025	
Σ_{ii}	standard deviation	0.0073	
Σ_{ii}	shock correlation	0.29	

*The parameters for which no target source is given follow Heathcote and Perri (2002).

used by Corsetti et al. (2005, 2008). In the 'High Correlation' calibration, I take the value directly from Corsetti et al. (2005, 2008) who estimate it to be $\sigma = 0.5$. Estimated values for σ vary throughout the empirical literature. While Taylor (1993) estimates a value of $\sigma = 0.39$ for the US, Whalley (1984) estimates a value of $\sigma = 1.5$. Thus, the chosen values are well in range with the data. The benchmark parameter values are summarized in Table 5.

The occasionally binding constraint on capital utilization invokes that there is a physical limit such that machines cannot be utilized more than their full capacity and that constructing new machines takes one time period. In the model, as a result of shocks, the economy can be driven into situations in which the constraint binds and producers cannot increase utilization to a level that would be optimal in the absence of the constraint. In the next sections, I investigate the consequences of this physical bound on the symmetry of business cycles and the cross-correlations of international business cycles created by the model.

6.2 Disentangling expansions and recessions

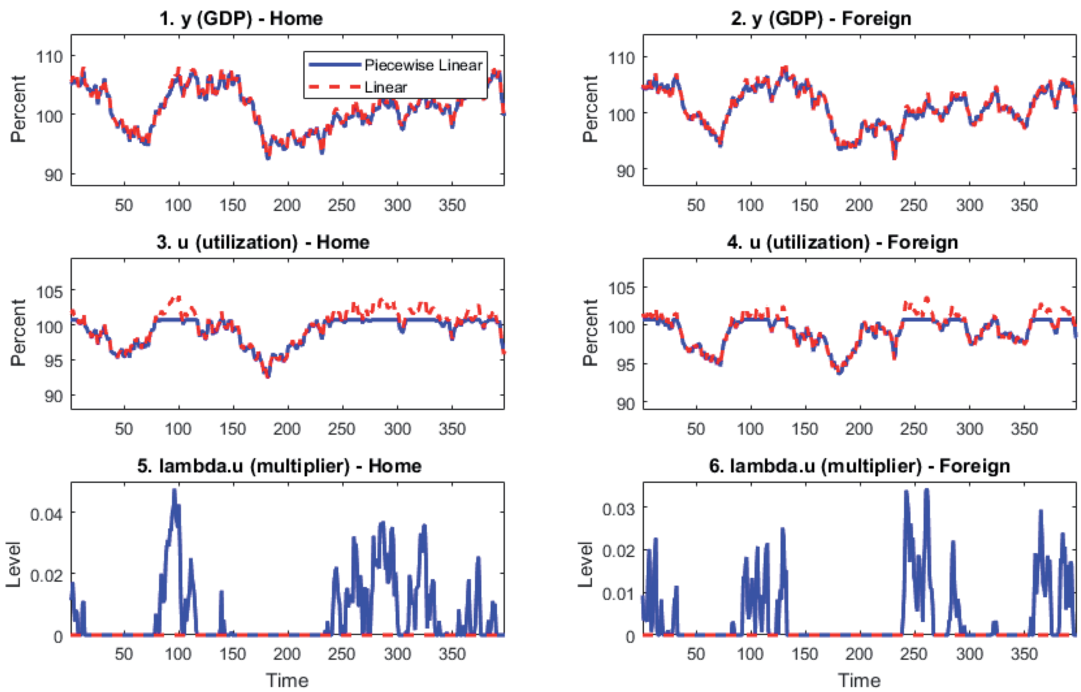
Since I am foremost interested in whether my model can replicate the asymmetry of business cycle correlations between expansions and recessions, I need to find a reasonable way of disentangling business cycle phases in the simulated model data. For comparability I use the exact same approach on the simulated data as I applied to the empirical data in section 2.

6.3 Simulations

To investigate the cross-country correlations of GDP and other macroeconomic variables I run 1000 simulations of 1400 periods each. I am dropping the first 1000 periods of each simulation, such that the simulation results are not influenced by the initial conditions. Therefore, in essence 1000 world economies consisting of two countries are simulated for 100 years. Both countries' random disturbances are assumed to have a persistence parameter of $\rho = 0.95$ and a standard deviation of $\sigma_e = 0.0073$. For illustration purposes I plot series of the 400 valid periods out of the last simulation for the calibration using $\sigma = 0.755$.

Figure 3 shows the simulations of GDP, capital utilization and the Lagrange parameter on the occasionally binding constraint for Home on the left-hand and Foreign on the right-hand side. The dashed line gives the simulations of the unconstrained model and the solid line shows the simulations with the constraint imposed. Notice that GDP in booms is decreased in comparison to the unrestricted model due to the binding capacity constraints. This creates a negative skewness of GDP of the two individual countries. Another important point is that the constraints on capacity utilization do not bind necessarily at the same time. Moreover, one can see that the correlation of GDP is high for both countries, but the effect of the constraint on cross-country correlations is difficult to interpret in this figure.

Figure 3 – Simulations



6.4 International Correlations

First, I turn to the simulation moments in recessions and expansions overall in the unconstrained model, as well as in a model in which the constraint is occasionally binding. In table 6 I summarize the correlations calculated from the simulated data in recessions and expansions, using the benchmark calibration in the first column and the High Difference calibration in the second column. In both cases, recession and expansion episodes are determined using the turning point algorithm by Harding and Pagan (2002) applied to simulated time series from the model. The first row gives the results for the unconstrained symmetric model, while the second row shows the results for the model in which the constraint is invoked. The third row contains the correlation results obtained from the data. In the linear model of the first row, the level of cross-country GDP correlations in recessions, as well as expansions is around 0.19 in the Benchmark calibration case and increases to around 0.56 in the High Difference calibration case. The higher level of international

Table 6 – Conditional Correlations from the Model - GDP

	Benchmark			**High Diff**		
	Contr		**Exp**	**Contr**		**Exp**
Linear model	0.1863		0.1857	0.5586		0.5579
Difference		0.0006			0.0007	
P-Value		0.4554			0.4862	
Non-linear model	0.1603		0.1476	0.5073		0.4725
Difference		**0.0127*****			**0.0348*****	
P-Value		0.0000			0.0000	
Data	0.2395		0.1901			
Difference		**0.0544*****				
P-Value		0.0000				

$***$,$**$ and $*$, indicate $p < 0.01$, $p < 0.05$, $p < 0.1$, respectively. Results are averaged over 1000 simulations of 1400 periods, dropping 1000 initial periods. The table shows cross-country correlations of GDP growth rates between Home and Foreign produced by simulations of the model. The 'Home' column shows the results for contractions (Contr) and expansions (Exp) determined using the Home GDP series. The 'Foreign' column shows the same results using the Foreign GDP series. Expansions and contractions are found using the Harding and Pagan (2002) turning point algorithm. The left column gives the results for the Benchmark calibration, while the second column given the results for the High Difference calibration. Moreover, the first row gives the results for the unconstrained symmetric model, while the second row shows the results for the model in which the constraint is invoked. The third row contains the correlation results obtained from the data.

GDP correlation in the High Difference calibration case is induced by a higher degree of international dependence between the two model countries compared to the Benchmark calibration case. The difference if Home is in recession is slightly positive, but not significantly different from zero. This is true for both calibration cases. In the non-linear model, for which simulation results are shown in the second row, the correlations if Home or Foreign are in recession increase to 0.0127 and 0.0348 for the Benchmark calibration case and the High Difference correlation case, respectively. In both cases these differences are significantly different from zero at the 1% confidence level. Due to this significant difference, the level of cross-country GDP correlations in the non-linear model increases during recession periods compared to the linear model, while it decreases in expansions. This result also holds for both calibration cases.

6.5 Robustness

To further explore how the difference in cross-country GDP correlations that the model produces react to changes in the two crucial calibration parameters σ, the elasticity of substitution between intermediate tradables, as well as ω, the home bias in final good production, I calculate the correlation difference for distinct combinations of these parameters. Figure 4 shows the results of this robustness exercise. It shows the cross-country GDP correlation difference produced by the model on the y-axis and the value chosen for the elasticity of substitution between intermediate goods σ on the x-axis. Furthermore, the home bias in the production of final goods is chosen to match domestic import ratios of 45% (blue line), 60% (red line) and 80% (green line), respectively. The results show that in general the more the two model economies depend on each other through trade interlinkages, the higher the difference in cross-country GDP correlations between recessions and expansions that the model can reproduce. In more detail, the lower the elasticity of substitution between Home and Foreign intermediate inputs, i.e. the more they are complementary, the higher the average difference in GDP correlations between recessions and expansions. The same holds true the higher the targeted import ratio, which is set using a lower degree of home bias in the final goods production sector of a given country.

The model is able to replicate a difference in cross-country correlations of around 3.5 percentage points for the High Difference calibration case, which sets $\sigma = 0.5$ and targets a high import ratio of 80%. This is at the lower end of the calibration range for the elasticity of substitution and means that international intermediary goods have to have a certain degree of complementarity in order to make international correlations higher in recessions than in expansions. For a higher degree of substitutability producers are more flexible in their choice of inputs, output is not depressed as much and spillovers are more symmetric. This is the case for instance in the Benchmark Calibration case, which can produce an average cross-country GDP correlation difference between recessions and expansions of 0.0127.

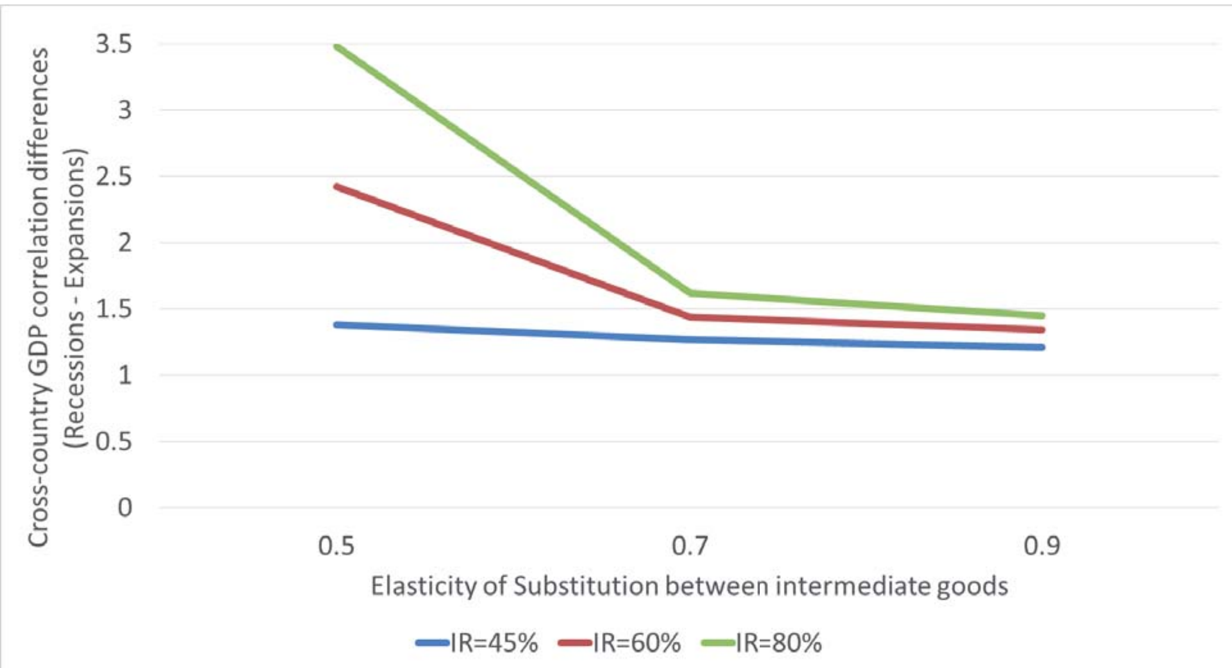


Figure 4 – Robustness of Correlation Differences

6.6 Business Cycle Moments

In this section I am comparing the business cycle moments of the Benchmark and High Difference calibration cases with their respective symmetric models, as well as with the data. The symmetric models correspond to the case in which the occasionally binding constraints on capacity utilization do not apply. The first column of table 7 shows the volatilities of aggregate variables calculated from the model, as their standard deviation or relative to GDP.

Output volatility is higher in the symmetric Benchmark calibration case than in the High Difference calibration case. Furthermore, if there are occasionally binding constraints in the model the volatilities decrease as the binding constraints dampen GDP movements on the upside. The model simulated terms of trade in both non-linear calibration settings fare better than their linear model counterparts, but are too low in comparison to the data. The High Difference calibration fares better than the Benchmark calibration. Similarly, the real interest rate is substantially lower than observed in the data and in the High Difference calibration cases an even lower RER volatility is observed. Regarding exports, and symmetrically imports, the High Difference calibration gets closer to the data, but both calibration cases yield a lower volatility level than the data. In the non-linear solution case these volatilities decrease in comparison to the linear case.

Still, the volatility of net exports in the non-linear High Difference case get closest to the observed data and the import ratio for both non-linear cases are an improvement in comparison to the linear model. The introduction of a non-linearity such as an occasionally binding constraints on capacity utilization improves the model fit to the data in several dimensions, while falling short to match the data better in a few other dimensions. In general, the volatilities the model produces fall short of the data moments, despite in the case of net exports.

The second part of Table 7 shows the volatilities of aggregate consumption, investment and labor relative to GDP. For consumption the introduction of non-linearities slightly improve the ratio of consumption volatility explained by the model. Investment volatility is best fit by the linear High Difference model, but also the non-linear High Difference model has a better fit compared to the Benchmark calibration cases. The share of labor volatility with respect to GDP generated by the High Difference calibration of the non-linear model is slightly better than in the linear model, but all calibrations only explain around a third of the volatility actually present in the data.

Table 8 shows the model generated correlations between macroeconomic aggregates and output in the first part of the table and cross-country correlations of macroeconomic aggregates in the second part of the table.

In terms of consumption-output correlation, the Benchmark calibration of the non-linear model fits the data very well. In the benchmark calibration, the induced non-linearity can help to improve on the common issue of real business cycle models that consumption and output move too close together. The High Difference calibration induces a lower correlation between output and consumption than in the data.

Table 7 – Model Fit: Standard deviations

	Data	Benchmark		High Diff	
		sym.	asym.	sym.	asym.
Volatilities	(std in %)				
Output	1.67	1.12	1.03	0.97	0.90
TOT	2.99	1.13	1.15	1.60	1.75
RER	3.73	0.42	0.43	0.16	0.18
Exports	3.94	1.01	0.90	1.06	0.96
Imports	5.42	1.01	0.90	1.06	0.96
Net exports	0.45	2.03	1.80	1.21	1.09
Import ratio	4.07	0.79	0.80	0.80	0.87
Volatilities	relative to y				
Consumption	0.81	0.34	0.35	0.40	0.41
Investment	2.84	4.24	4.09	3.07	3.37
Labor	0.66	0.22	0.21	0.25	0.26

For investment correlations with output, both benchmark calibrations and the linear High Difference model fit the data almost perfectly, while the non-linear High difference model produces a lower level of correlation. Labor correlations with output are too high in the Benchmark calibration models compared to the data, while they lower than the data moment in the High Difference calibrations. Non-linearity tends to lower this moment. For exports and imports the Benchmark calibration has a fairly good data fit. In the High calibration case export correlation is higher than in the data, which might be due to the high international dependencies in this model calibration. At the same time for the High Difference non-linear case the import to output correlation is too low.

Regarding net exports, the Benchmark calibration case yields higher negative correlation than observed in the data, while the High Difference case yields lower negative correlation. The symmetric High Difference calibration gets closest to the data however. For the terms of trade and the real exchange rate also the High Difference calibration is closest to the data. Regarding the terms of trade especially, even the High Difference calibration fails to overturn a positive correlation generated by all model calibrations to a negative one observed in the data.

For capacity utilization the Benchmark calibration of the non-linear model fits the correlation of utilization and output well, while the correlation is lower in the High Difference case.

Table 8 – Model Fit: Correlations

	Data	Benchmark		High Diff	
		sym.	asym.	sym.	asym.
With Output					
Consumption	0.86	0.91	0.89	0.77	0.70
Investment	0.95	0.93	0.94	0.94	0.68
Labor	0.87	0.97	0.96	0.66	0.52
Exports	0.32	0.40	0.45	0.94	0.87
Imports	0.81	0.94	0.90	0.93	0.42
Net exports	-0.49	-0.61	-0.63	-0.40	-0.28
TOT	-0.24	0.61	0.63	0.43	0.47
RER	0.13	0.61	0.63	0.43	0.47
Utilization	0.78	0.94	0.83	0.72	0.60
Cross-country					
Output	0.21(all)/0.58(US)	0.21	0.18	0.63	0.55
Consumption	0.36	0.88	0.88	0.88	0.83
Investment	0.3	-0.42	-0.41	0.47	0.13
Labor	0.42	0.55	0.56	0.70	0.48
Utilization	0.70	0.62	0.56	0.80	0.72

The cross-country correlations of the macroeconomic aggregates show some interesting patterns. The High Difference calibration is the only model that matches the US GDP correlations with other countries well (0.58). At the same time, the Benchmark model and the linear model better match the empirical cross-country GDP correlations calculated on a broader set of OECD country pairs, as presented in the Empirical Section (0.21). Non-linearity decreases this correlation slightly. It has always been regarded as a shortcoming of the international real-business cycle model that it cannot generate enough cross-country GDP correlation. My model shows that with non-linearities and a certain degree of international dependency, the High correlation case matches the US GDP correlations originally targeted by studies such Heathcote and Perri (2002) very well.

On cross-country consumption correlations all models generate too high correlations. For investment the High Difference calibration is actually the only model of the three that can generate a negative cross-country investment correlation as observed in the data. Finally for utilization, the non-linear High Difference model is very close to the data observed moment, while the other cases are not too far off either.

6.7 Impulse responses

To understand how the investigated mechanism works to create asymmetry, I compare the impulse response functions to shocks of different magnitudes. The shocks are chosen to have a standard deviation of $\sigma_e = 0.0073$. In this section, I compare impulse response functions (IRFs) to positive and negative shocks to Home total factor productivity (TFP), while holding Foreign TFP constant. For a one standard deviation shock, the occasionally binding constraints are not violated, thus the IRFs for positive and negative shocks are perfectly symmetric and the Lagrange multipliers remain at zero. To illustrate the workings of the model when the constraint is violated, I therefore show IRFs to five standard deviation shocks. This is a large shock that in practice will happen very rarely. Nonetheless, it should be kept in mind that during the model simulations both countries are hit by a variety of shocks and that the constraint might become binding after several small and persistent shocks hit the economy. From the simulations we saw that the constraint binds a considerable number of periods for Home as well as Foreign. To concentrate on the effects of a single shock to the Home economy, I assume a large shock to make the workings of the constraint obvious. Technically the constraint starts to bind for the Foreign economy for a three standard deviation shock, but the effects only become clearly visible for a larger shock as the one shown.

Figure 5 shows the responses of GDP, capital utilization and the intermediate good production for a 5 standard deviation shock to Home TFP for Home variables on the left-hand side, as well as Foreign variables on the right-hand side. The shown responses are obtained using the benchmark calibration and to make the asymmetries in responses obvious, all the responses to the negative shock are inverted. Therefore, the shown increase in Home GDP following a negative to Home TFP, which is shown by the dashed red line in the top left panel of figure 5, actually represents a corresponding decline in Home TFP. In figure 5,

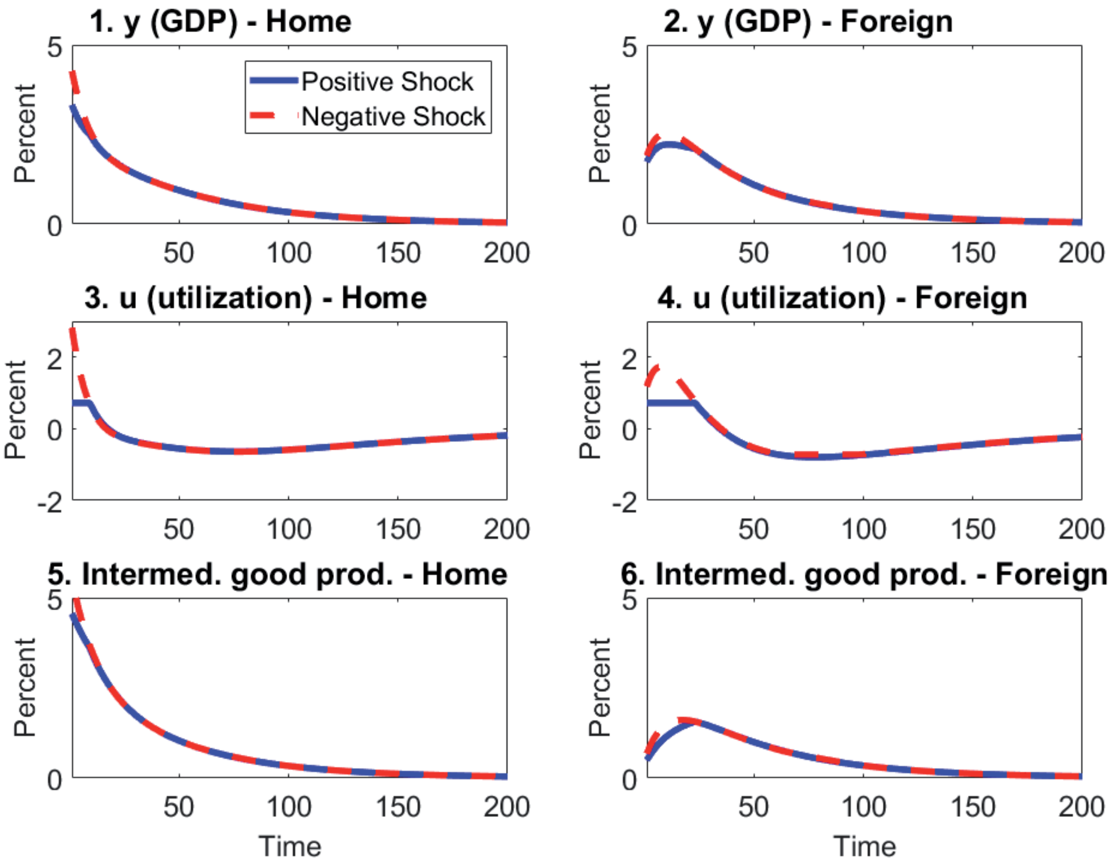


Figure 5 – Impulse responses benchmark - 5 std TFP shock to Home

the constraints bind for both countries when the shock hits. In the response plots for GDP in Home and Foreign one can see that the drop in GDP is larger for a negative shock than the increase in GDP for a positive shock of the same size. This is true for the response of Home GDP to the Home TFP shock, as well as for the spillover of this shock to Foreign GDP. Therefore, the model can indeed create asymmetric international spillovers: Home recessions have larger effects on Foreign GDP than Home expansions of the same magnitude. The responses for intermediate good production show that after a positive Home recessions have larger effects on Foreign GDP than Home expansions of the same magnitude. The responses for intermediate good production show that after a positive Home TFP shock, Home intermediate good production increases by more than Home GDP, while Foreign intermediate good production increases by less than Foreign GDP. Because GDP is defined as the value of total intermediary good production in terms of final consumption good,

$$GDP_{i,t} = \begin{cases} q_a^i * F(z_{i,t}, u_{i,t}, k_{i,t}, n_{i,t}) & \text{if } i = 1 \\ q_b^i * F(z_{i,t}, u_{i,t}, k_{i,t}, n_{i,t}) & \text{if } i = 2, \end{cases} \tag{23}$$

for Home and Foreign respectively, it varies with the value of imports through q_a^1 and q_b^2. In the Benchmark calibration case the two intermediary inputs are complements. Therefore an increase in Home intermediate good production due to an increase in productivity devalues the Home intermediate good relative to the Foreign intermediate good and in turn increases the total value of Foreign intermediary production in terms of Foreign final consumption good. As a consequence of this devaluation we observe the pattern that Home GDP increases relatively less than Home intermediate production, while Foreign GDP increases by relatively more than Foreign intermediate production. This relative devaluation of the Home intermediate good is better understood from looking at the responses of variables characterizing the international trade linkages between the two countries, which are shown in Figures 6 and 7.

Figure 6 shows the responses the terms-of-trade, the real exchange rate and the net exports of the Home as well as Foreign economies. Furthermore, in Figure 7 the responses of the relative prices q_i^j of Home intermediate good (marked with $i = a$) and Foreign intermediate good (marked with $i = b$) in terms of the Home final good (marked by $j = 1$) or the Foreign final good (marked by $j = 2$) are pictures, respectively. [8]

[8] The terms-of-trade are defined as the price of the Home export good divided by the Home import good, i.e. $ToT = \frac{q_a^1}{q_b^1}$, while the real exchange rate is given as the relative price of the Foreign final good in terms of the Home final good, i.e. $REX = \frac{q_a^1}{q_a^2}$. Net exports of Home are given by the exported amount of Home intermediate good minus the imported amount of foreign intermediate good denoted in terms of the Home intermediate good, i.e. $a_2 - ToTb_1$. Analogously, Foreign net exports are given by $b_1 - \frac{1}{ToT}a_2$.

The aforementioned relative devaluation of the Home intermediate good is a consequence of the decreasing terms-of-trade in figure 6, which is in turn caused by depreciating domestic intermediate good price in terms of Home final good (q_a^1) and an relatively more appreciating Foreign intermediate good in terms of Home final good (q_b^1), shown in figure 7. The real exchange rate appreciates after a Home TFP shock by exactly the same magnitude as the ToT depreciate. For a negative TFP shock, although the signs of the relative price adjustments change, the relative magnitudes of these changes are exactly the same, so that the ToT and the real exchange rate in this model react exactly symmetrically to TFP shocks of opposite signs. It is especially important to point out that this holds despite the asymmetries that are present between the responses to positive and negative Home TFP shocks. Thus, although in absolute magnitude the responses of relative prices are slightly higher for positive shocks compared to negative shocks, the relative magnitude of these changes when compared to one another is the same for both positive and negative

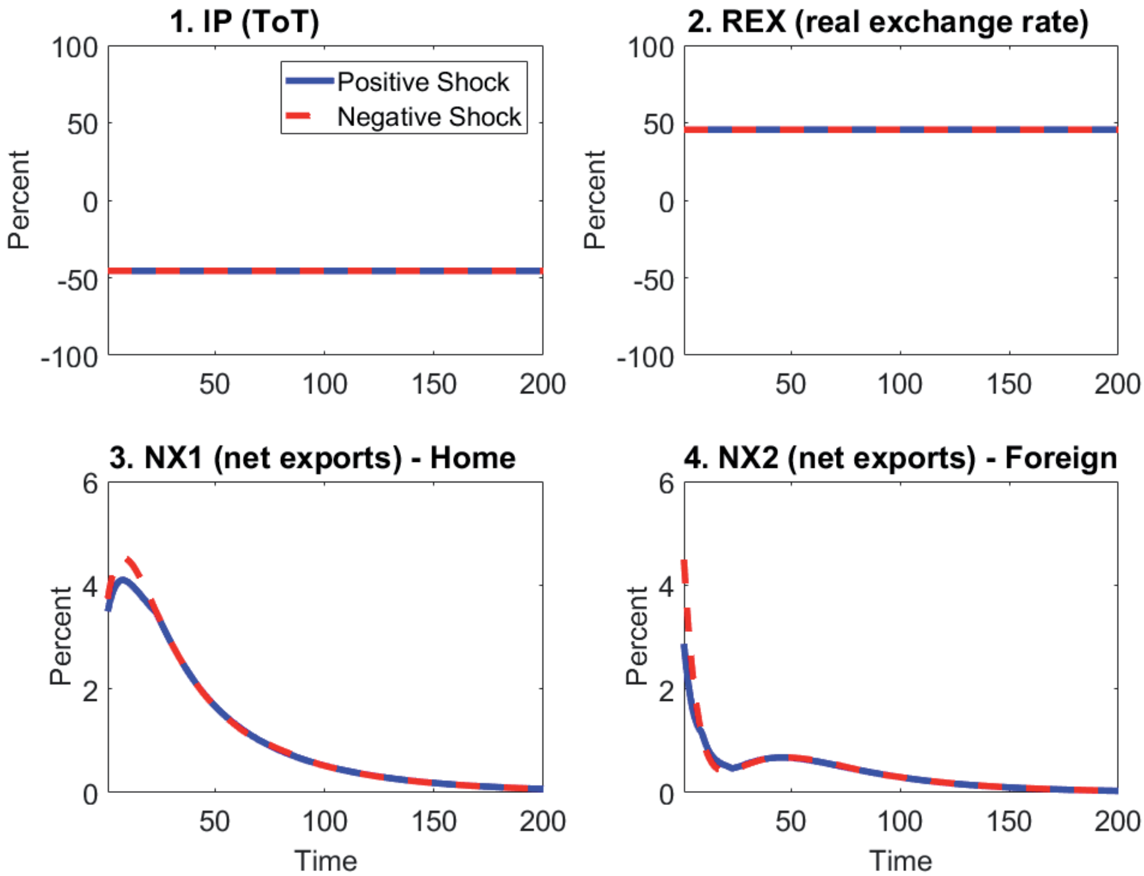


Figure 6 – Impulse responses benchmark - 5 std TFP shock to Home

ToT and the real exchange rate cannot act as a buffer to counteract them. As a consequence asymmetries created by the occasionally binding constraint in the Home economy fully spill-over internationally. This is also apparent in the response of net exports, as shown in the lower half of figure 6. Net exports increase after a positive Home TFP shock for both Home and Foreign with the response for the Home country being higher. More importantly, for a negative Home TFP shock net exports for Home decrease visibly more for a negative Home TFP shock compared to their increase after a positive Home TFP shock and the same pattern holds for the Foreign net export response.

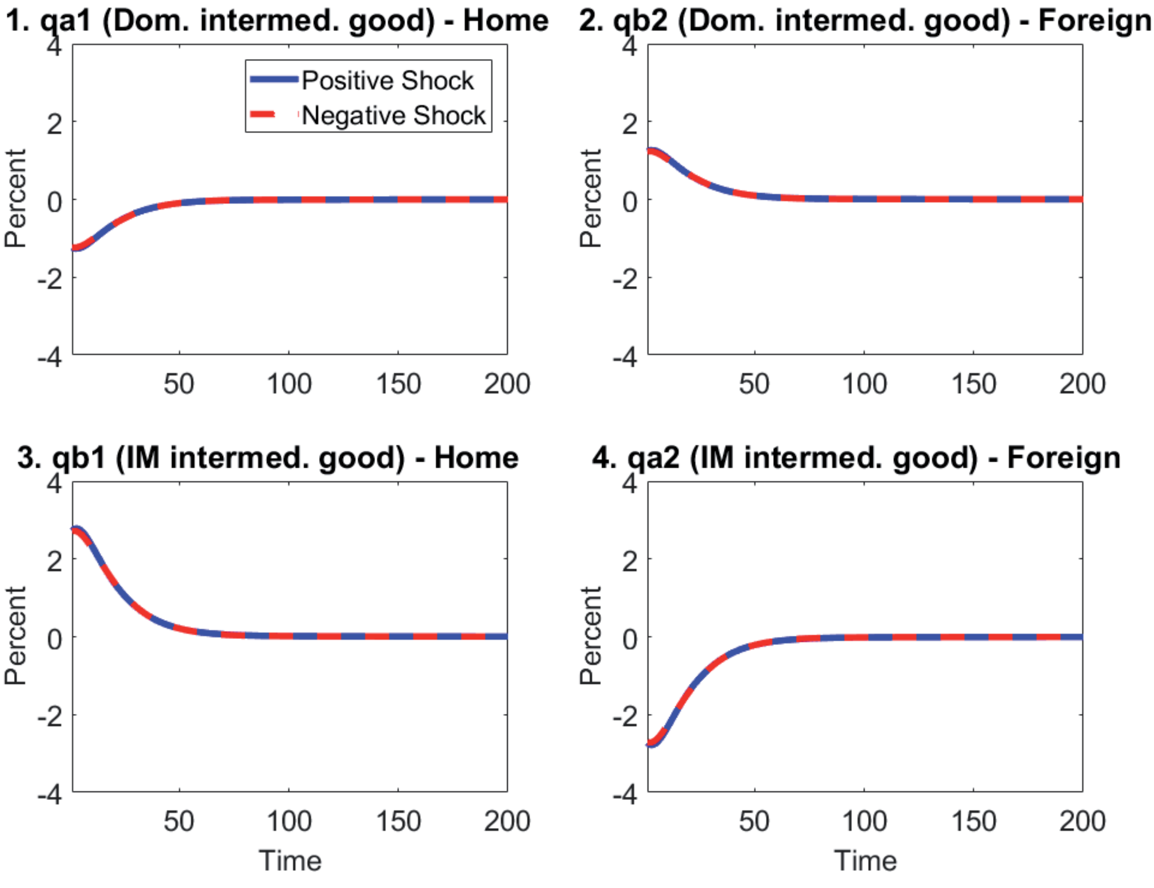


Figure 7 – Impulse responses benchmark - 5 std TFP shock to Home

For the High Difference calibration, in figures 8, 9 and 10 I show the same plots as above. Here we can see that the shocks to Home TFP spill over even more than in the Benchmark case. The responses of GDP to a positive Home TFP shock are dampend in comparison to a negative shock in both economies as expected. Note that the response of Foreign GDP to a Home TFP shock is larger than on Home GDP. At the same time, as the response for intermediate production shows, intermediate production rises much more in Home than in Foreign. In the High Difference calibration case the two intermediary inputs are more complementary than in the Benchmark calibration case. Therefore the devaluation of the Home intermediate good relative to the Foreign intermediate good is further amplified, as can be seen from figure 9. The terms-of-trade appreciates, while the real exchange rate depreciates nearly twice as much as in the benchmark calibration case. Therefore, a positive Home productivity shock in this case increases Foreign GDP by more than it increases Home GDP. Moreover, from figure 10, we can see that in the High Difference

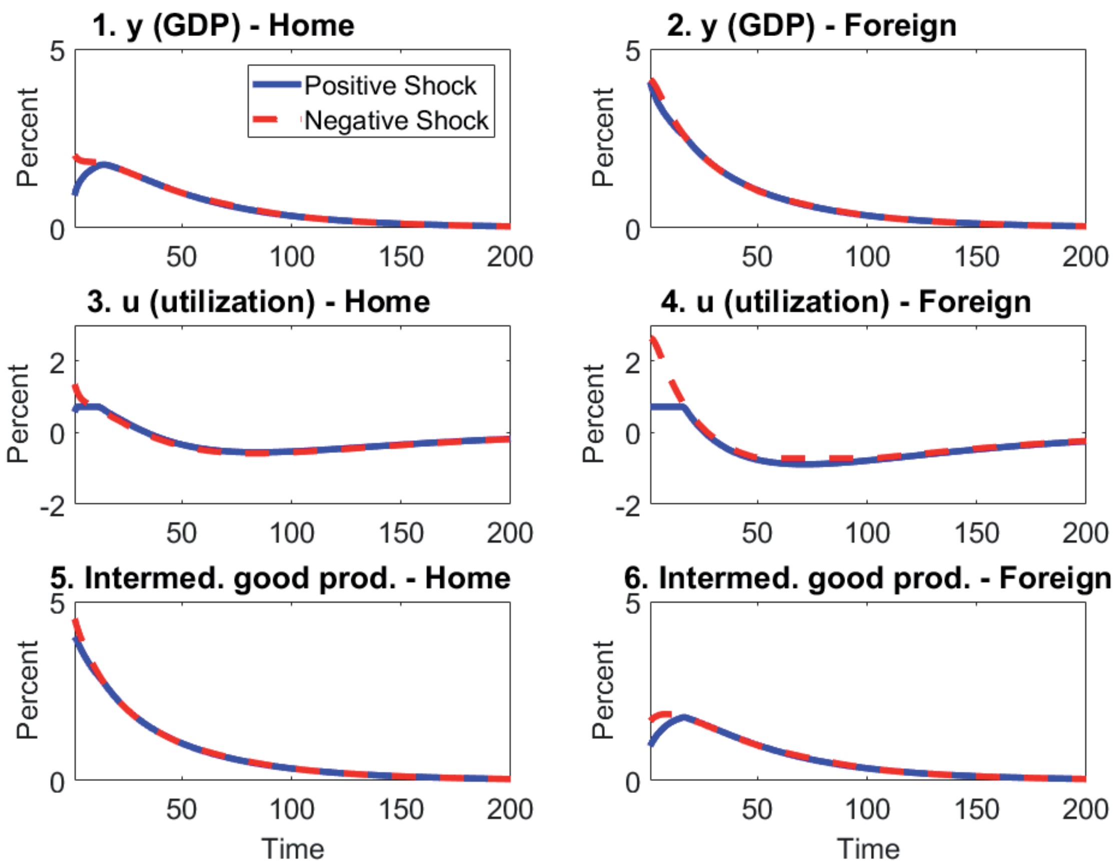


Figure 8 – Impulse responses high difference - 5 std TFP shock to Home

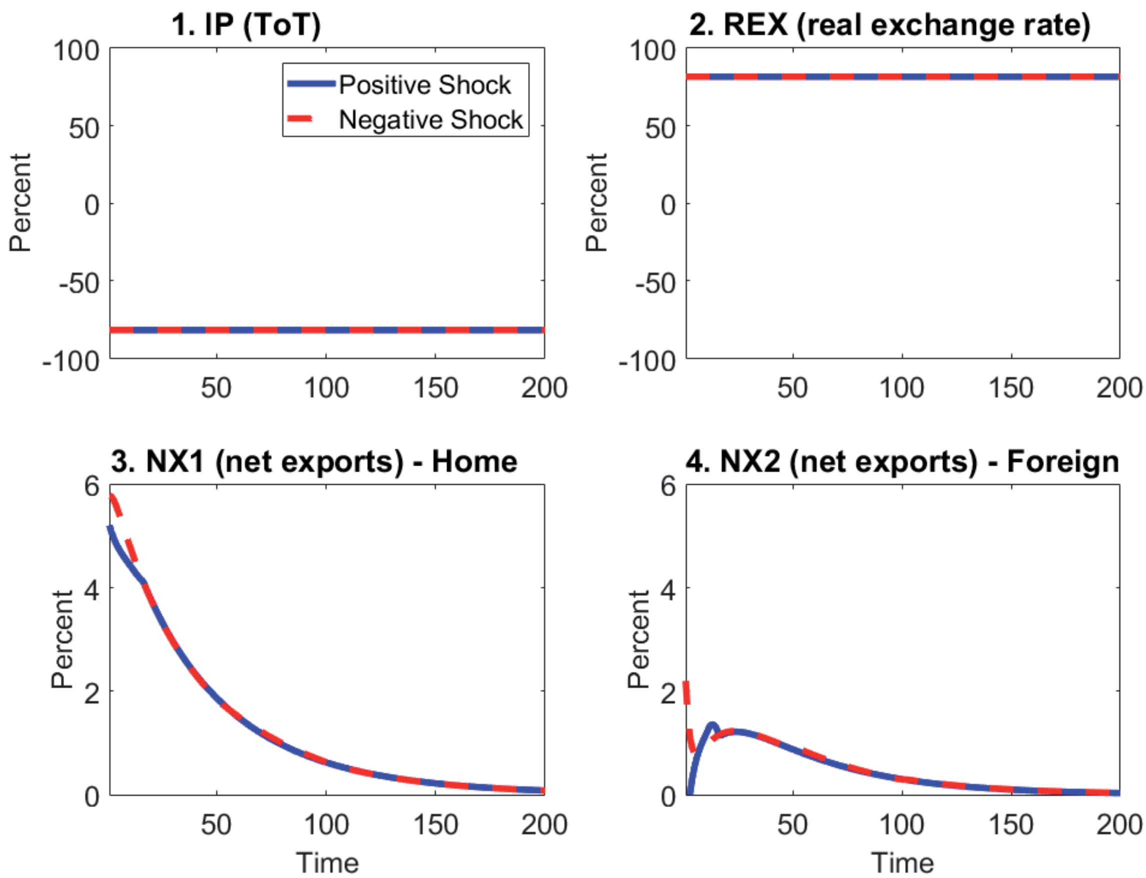


Figure 9 – Impulse responses high difference - 5 std TFP shock to Home

calibration the asymmetry in the response of the relative prices of intermediary goods q_i^j is more obvious, but at the same time it stays proportional. Thus, the real exchange rate and the terms-of-trade do not show asymmetric responses in the model. Because the magnitude of the relative price changes is less different than in the Benchmark calibration, the shift in the terms-of-trade is smaller than in the Benchmark calibration, while the shift in the real exchange rate is higher. Net exports increase for both economies after a positive shock, while they fall by a higher magnitude in response to a negative shock. Interestingly, Foreign net exports only react with a lag to a positive Home TFP shock, while they immediately fall after a negative shock.

Comparing the responses of GDP in the Benchmark and the High Difference calibration cases, one can observe that the high spillovers in the High Difference case lead GDP in both countries to jump downward on impact after a negative TFP shock in Home and then gradually recover making the GDP responses highly correlated. For the positive shock, as utilization is constrained the responses are dampened on the upside compared

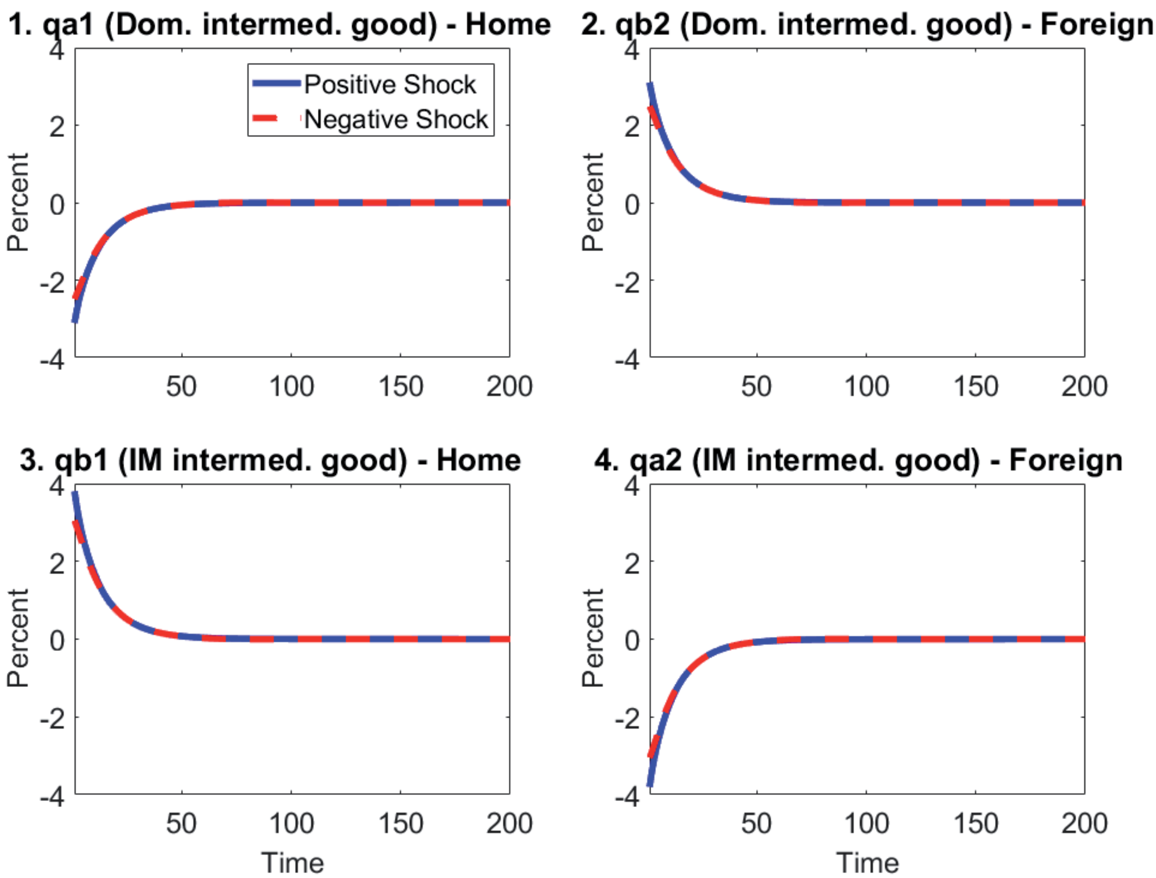


Figure 10 – Impulse responses high difference - 5 std TFP shock to Home

to the negative shocks. Crucially, in the Home economy, the full impact of the shock on GDP is only reached gradually after about two years, while for the Foreign economy the full impact is still reached immediately, making the GDP responses to a positive shock less correlated than for a negative shock. Comparing this observation with the Benchmark calibration one can observe that the foreign response is hump shaped for both positive and negative Home TFP shocks. Thus, although the dampened Home GDP response still induces a lower correlation of the GDP responses across countries, the difference in this correlation between a negative and a positive Home TFP shock is less in magnitude under the benchmark calibration compared to the High Difference calibration.

Overall, the impulse response analysis shows that the model can create asymmetric spillovers and as I showed with the simulations, these asymmetric spillovers result in state-dependent cross-country correlations that can match the observed differences in the data if I assume a sufficient amount of complementarity between internationally tradable intermediary goods.

Therefore, my empirical as well as theoretical findings show that we might miss a lot of interesting features of the world, if we do not take into account asymmetries in international RBC models.

7 VAR Evidence

After having shown that occasionally binding capacity constraints are capable of producing business cycle asymmetry and asymmetric international spillovers for sufficient complementarity between intermediary goods, in this section I motivate this channel empirically. The empirical equivalent of a regime switch due to occasionally binding constraints are threshold effects in a given time series. Therefore, the assumption of occasionally binding constraints on capacity utilization at the aggregate production level to explain state-dependent cross country GDP correlations can be justified by the existence of threshold effects in capacity utilization giving rise to business cycle asymmetries. In this section, I investigate the empirical evidence on the presence of threshold effects in the capacity utilization rate of the US economy. Moreover, the consequences that threshold effects within the US economy have on each of the remaining six G7 countries (Canada, France, Germany, Italy, Japan and UK) are explored. A complication is that the utilization series for Japan is indexed and set to 100 in Q1:2010, therefore it is not directly comparable with the other series which are given as percentage of total production capacity. The analysis proceeds as follows. In a first step, I test for threshold effects in US capacity utilization using Hansen (2000)'s threshold test. In a second step, I use the threshold estimates from Hansen's test as informative priors for the estimation of a reduced-form threshold vector autoregressive (T-VAR) model. Finally, using short-run zero restrictions, I identify a US TFP shock and track its impact on US capacity utilization, US GDP, as well as Foreign[9] capacity utilization and Foreign GDP.

[9] Foreign refers to each of the remaining G7 countries on a rotating basis.

7.1 Data

The GDP series and capacity utilization series are gathered using Thomson Reuters Datastream from various national and international organizations (see table 12 in appendix). All series are transformed to be seasonally adjusted using the X13 Census filter in EVIEWS and the GDP series are at constant 2010 prices and per capita, if not provided in this way. The US TFP series is derived Fernald (2012). To be in line with the model I use the capital-utilization adjusted TFP series. The capacity utilization series for all investigated countries despite Japan represent the percentage utilization of all available production capacities across all industries of the respective country. The data availability for each country is limited by the introduction date of a capacity utilization variable in both the respective country and the US. For the US a quarterly capacity utilization measure is available from Q1:1967, so this is the earliest possible data point for the international VAR estimation.[10] For the UK a capacity utilization measure is only available from Q1:1985 onward and thus US-UK country pair has the least observations available for the estimation and testing procedures. The latest data point available for France, Germany and Italy is Q4:2015, while for Canada it is Q3:2015 and for the UK it is Q2:2015. For the VAR estimation I work with mean adjusted utilization levels to make the series fluctuate around zero. Moreover, I work with annualized quarter-on-quarter GDP growth rates and also the TFP data of Fernald (2012) is provided in annualized quarter-on-quarter growth rates. The hypothesis of stationarity of the used variables in a standard VAR cannot be rejected for any country pair.[11] Therefore, no further adjustments to transform the variables to stationarity are necessary.

7.2 Hansen Threshold test

The threshold test is based on a regression of lagged dependent variables X_{t-d} on the independent variable Y_t. The independent variable in the regressions considered here is the US GDP growth rate, while the X's include 6 lags of first differences in US GDP and

[10] Although for instance for Germany a measure is available from Q1:1960 onward.

[11] These tests have been conducted using the standard unit root tests in EVIEWS.

Foreign GDP, as well as the mean-adjusted level of US capacity utilization and Foreign capacity utilization. The test allows for heteroscedastic residuals and is based on 1000 draws with a trimming value of 0.2 for all countries. I test for threshold effects in each of the included lags of US capacity utilization. The results are shown in table 9.

Table 9 – Hansen (2000)'s threshold test - US utilization, mean adjusted - 6 Lags, 1000 draws

	Dep.Var:	**US GDP**				
Threshold Variable	US-CAN (adj.lvl)	US-FRA (adj.lvl)	US-GER (adj.lvl)	US-ITA (adj.lvl)	US-JPY (adj.index)	US-UK (adj.lvl)
u^{US}_{t-1}	2.39	**-2.23****	**-0.22*****	**0.80*****	-0.16	**-0.08*****
p-Value	(0.32)	(0.02)	(0.005)	(0.007)	(0.170)	(0.000)
u^{US}_{t-2}	**-0.61***	**-2.13****	**-0.05*****	**-0.08****	**-0.08****	**-0.08*****
p-Value	(0.07)	(0.036)	(0.000)	(0.013)	(0.030)	(0.000)
u^{US}_{t-3}	-0.4342	**-0.43****	**-0.43*****	**-0.09*****	**1.597***	**-0.89*****
p-Value	(0.26)	(0.02)	(0.004)	(0.002)	(0.087)	(0.000)
u^{US}_{t-4}	**1.45****	**-0.83***	**1.45****	**2.39***	**2.39****	**-0.57*****
p-Value	(0.02)	(0.08)	(0.048)	(0.086)	(0.021)	(0.003)
u^{US}_{t-5}	**1.648***	**-0.58**	**2.39****	**2.50***	**2.70****	**-0.50****
p-Value	(0.09)	(0.06)	(0.042)	(0.097)	(0.038)	(0.016)
u^{US}_{t-6}	**2.385****	-1.6	**2.39****	**2.39***	**2.39*****	**-1.55***
p-Value	(0.02)	(0.16)	(0.041)	(0.078)	(0.002)	(0.069)
Avg. Thr.	**1.21**	**-0.84**	**0.92**	**1.40**	**1.79**	**-0.61**
Avg u US	80.34	79.65	80.46	80.21	80.24	79.51
Avg u FOR	81.17	84.33	83.64	75.05	112.08	80.80
Observations	192	159	193	187	190	125

$***$,$**$ and $*$, indicate $p < 0.01$, $p < 0.05$, $p < 0.1$, respectively. The specification always include six lags of US TFP, US GDP, US utilization, Foreign utilization and Foreign GDP.

A first observation from the table is that with the varying availability of the capacity utilization series, even for the US the mean utilization rate varies for each country pair, though without large deviations from 80%. Moreover, the mean utilization rates of the other G7 countries vary across countries in a range of 75% to 84%. The results of the Hansen threshold test show that there are significant threshold effects in US capacity utilization that determine the behavior of the US GDP series in all specifications. For Canada there are significant differences in the effects of US capacity utilization on US GDP depending on whether US capacity utilization was more than -0.61 percentage points below its mean two quarters before or around 1.5 to 2 percentage points above its mean four to six quarters earlier. The specifications for France, Germany and Italy all show significant threshold effects in US capacity utilization for most of the previous 6 quarters. Germany and Italy have significant threshold effects slightly below the mean of US capacity utilization with up to three quarters delay, before having significant threshold effects considerably above the mean level of US capacity utilization with over one year delay. For the specification including Japanese data the interpretation of Japanese variables is different as the utilization series for Japan is given as an index set to 100 in Q1:2010. Because in this section, I estimate threshold effects in US capacity utilization, the interpretation of the above results is the same as for the other country pairs. Similarly to the country pairs including Germany and Italy, for Japan there are significant threshold effects if the US capital utilization is slightly below its mean two quarters earlier and considerably above its mean three to six quarters earlier (about 2 percentage points higher). While for Canada, Germany, Italy, Japan the mean over all significant estimated thresholds is positive and therefore threshold effects tend to occur if the US utilization rate was above mean in the past, for France and the UK all significant threshold effects occur if the US utilization rate was below mean. This indicates that for France and the UK threshold effects rather show when US utilization was low in the past, compared to the other countries examined for which they show when US capacity utilization was high in the recent past.

In the next section, using the estimated thresholds from Hansen's test as informative priors in the estimation of a Bayesian T-VAR, I investigate the empirical impulse response functions to positive and negative US TFP shocks and their international spillovers.

If I find that in the high utilization regime GDP responses of the US and the rest of the G7 countries to a positive US TFP shock are dampened in comparison to US and Foreign GDP responses to a negative US TFP shock in the low utilization regime, this can be taken as evidence that for four out of six country pairs there is statistical evidence of capacity utilization constraints being a prominent mechanism to create GDP correlation asymmetries in the investigated economies.

7.3 Bayesian Threshold VAR

In this section, I investigate the effects of the presence of the above threshold effect on the transmission of a US TFP shock through the US economy and to the other six countries investigated here, with a special interest in the asymmetries that can arise within the US economy and how they spill over internationally. For this purpose, I estimate a Bayesian vector autoregression (VAR) that can account for the presence of different regimes depending on whether a certain threshold variable is below or above an estimated threshold value. Therefore, this type of model is called a (Bayesian) threshold vector autoregression model (T-VAR model).

7.3.1 Theory

With at least 2 regimes and at least 2 lags the threshold VAR models estimated in this paper are highly parameterized. To improve inference using these models combined with the limited data availability of macroeconomic time series, it is common in the literature to estimate unrestricted VAR models by Bayesian methods. To obtain impulse response functions, short run zero-restrictions are imposed on the responses of the variables included in the VAR. The usage of Bayesian techniques in a setting like this allows the inclusion of prior information on the parameters to be estimated in a natural way and therefore improves the inference in these models. For estimation of this type of model prior distributions for all parts of the econometric model that are treated as exogenous have to be assumed. A systematic way to do this for an underlying structural VAR model is to use natural conjugate priors for which the prior, the likelihood and the posterior have the same distributional form. This assumption allows the implementation of the dummy variable approach to elicit priors for structural VARs following Sims and Zha (1998) and Banbura et al. (2010). The posterior distributions of these exogenous model parameters are derived from the prior distributions and the model's Bayes factor. To be able to obtain the posterior distributions and do inference on the model's parameters some prior specifications require the use of simulation based techniques, such as Markov chain Monte Carlo (MCMC) procedures. These MCMC procedures create a Markov chain converging to a chain of drawings from the posterior distribution and thus allow the researcher to draw inference from posteriors that are analytically intractable. Frequently used procedures to create such converging Markov chains are the Metropolis-Hastings algorithm or the Gibbs sampler. The procedures I use to estimate the threshold VAR follow the algorithm of Chen and Lee (1995), as used by Alessandri and Mumtaz (2013).[12] This procedure uses a Gibbs sampler to create the Markov chain from which drawings from the approximate posterior distributions are obtained. The threshold VAR is given by:

$$Y_t = \left[c_1 + \sum_{j=1}^{p} A_{1,j} Y_{t-j} + \epsilon_{1,t} \right] S_t + \left[c_2 + \sum_{j=1}^{p} A_{2,j} Y_{t-j} + \epsilon_{2,t} \right] (1 - S_t) , \qquad (24)$$

with $\epsilon_{i,t}$ $N(0, \Omega_i)$ and $S_t = 1 \iff Y_{1,t-d} \geq Z$ for $t = 1, ..., T$. Y_t is the $N \times 1$ vector of endogenous variables, which includes the first differences of US total factor productivity (TFP), the level of US capacity utilization and US GDP growth rates for all presented specifications and on a rotating basis the level of Foreign capacity utilization and the first difference of Foreign GDP. Here, Foreign represents each of the G7 countries excluding the US in turn. c_i, A_i and Ω_i are a constant term, the VAR-coefficient matrix and the variance-covariance matrix of the **iid** disturbance term ϵ_t for the two regimes $i = 1, 2$, respectively.

These three matrices for the two VAR regimes contain all but two of the parameters of the T-VAR. The other two are the threshold Z and the threshold delay d, which allows the threshold to be triggered in a time period different from the realization of the threshold's effect on the dependent variables Y_t. The Z and d parameters are unobserved and thus have to be estimated. For each period, the threshold variable Z determines the prevalent regime. Because I obtained estimates of the threshold value of US capacity utilization for each country pair, I use this estimated value as initial value as priors for Z.

7.3.2 Parameters of Bayesian Estimation

To implement the Bayesian Threshold VAR estimation, parameters regarding the prior distributions on the model parameters, the number of draws, as well as the simulation horizon for the impulse response functions have to be set. I am using the mean of the significant threshold estimates of Hansen (2000)'s test for threshold effects as mean of the conjugate prior distribution on the threshold in US capacity utilization Z for each country

[12] Their codes are available under https://sites.google.com/site/hmumtaz77/code

pair. The assumptions on the estimation parameters are summarized in table 10. This parameterization is in line with standard values chosen in the literature. In this calibration I set the prior tightness parameter $\lambda_P = 0.5$, which is slightly looser than for instance the parameterization of Alessandri and Mumtaz (2013), while the values of the prior tightness on the sum of coefficients and the constant term are set according to those in Alessandri and Mumtaz (2013). As the threshold estimates from the Hansen test conducted above give a statistical indication of the threshold value in the data, I choose the variance on the threshold value to be 0.5.

7.4 Impulse Responses

I am now using the threshold estimates of Hansen (2000)'s test for threshold effects as priors and a Bayesian vector autoregression allowing for threshold effect (T-VAR) for the US and the rest of the G7 country pairs. The following figures show the impulse responses for a positive standardized US total factor productivity shock initialized at the mean levels

Table 10 – Bayesian T-VAR - Parameters

Parameter	Description	Value
Prior Threshold Z	Canada	1.21
	France	-0.84
	Germany	0.92
	Italy	1.40
	Japan	1.79
	UK	-0.61
σ^2	Variance on threshold	0.5
Reps	Simulation replications	20500
Drop	Disregarded initial draws	20000
λ_P	Prior tightness	0.5
τ_P	Prior tightness on sum of coefficients	$10 * \lambda_P$
ϵ_P	prior tightness on constant	1/10000
d	Maximum lag in threshold	2
scalein	Prior random walk variance	0.01
scaleex	Standard deviation of simulated shock	$[-0.1; 0.1]$
horzir	Horizon IRF	40

The utilization series for Japan is indexed and set to 100 in Q1:2010, therefore it is not directly comparable with the other series given in percentage of total capacity.

of each variable. The standard deviation of the shock is set to 0.01 and the investigated shock are a positive one standard deviation shock triggering the high utilization regime and a negative one standard deviation shock triggering the low utilization regime. The identification procedure is a standard Cholesky zero restriction identification scheme building on the assumption that a TFP shock contemporaneously affects all other variables in the VAR (they are first in the variable ordering), while shocks to the other variables in the VAR are not affecting US TFP contemporaneously.[13]

7.4.1 US responses to a US TFP shock

The US variables are included in the specification for each country pair. For brevity, I concentrate on the responses of these variables obtained from the US-Canada specification which are shown in figure 11.[14] Despite for the case of France and the UK, the responses are similar and the following interpretation is valid.[15]

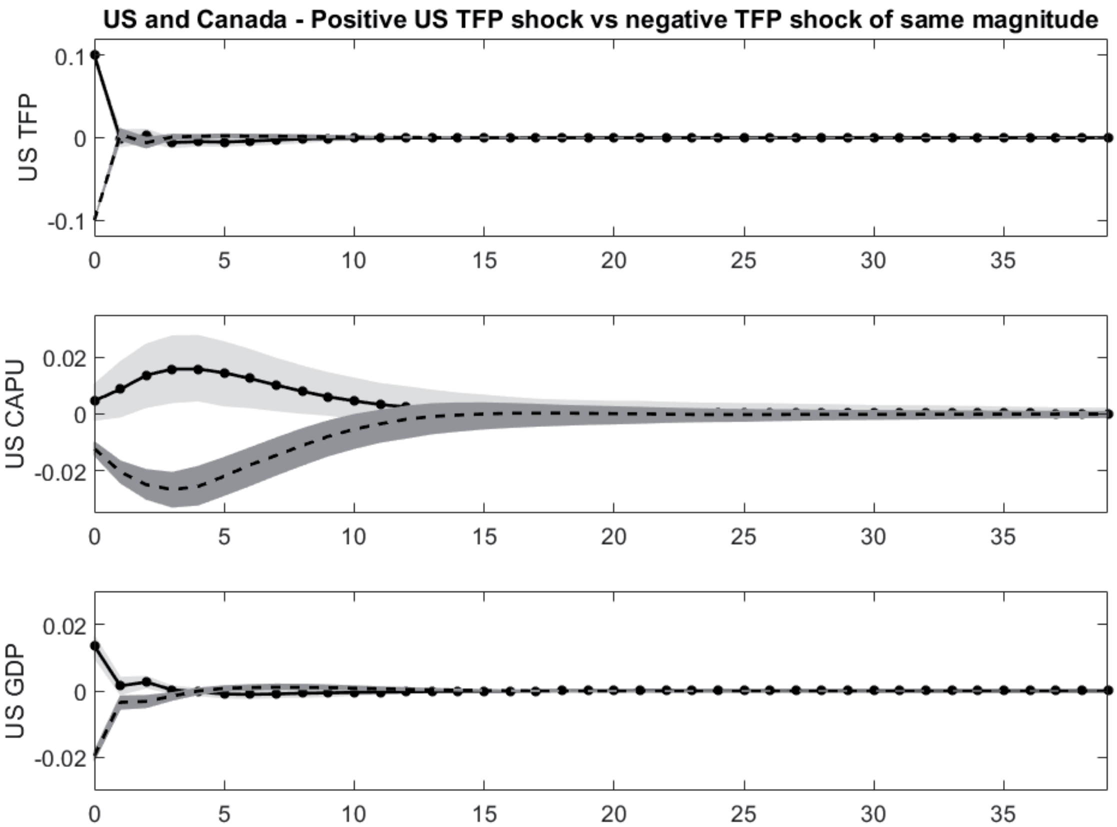
The figure shows that in responses to a positive US TFP shock (dotted lines with lighter confidence bands), US capacity utilization and US GDP growth increase, while they decrease in response to a negative TFP shock (dashed lines with darker confidence bands). Furthermore, in comparison with a negative TFP shock hitting the economy at the mean of all the specified variables, i.e. a shock that does not trigger a regime switch, the responses for the positive shock are lower. Thus, I find evidence that positive TFP shocks have lower effects on US capacity utilization and US GDP growth than negative TFP shocks of the same magnitude, if one accounts for the estimated threshold effects in US capacity utilization. I interpret this as an occasional inability to adjust capacity utilization beyond a certain degree within a given period. This is the motivation to investigate the international transmission of TFP shocks in a model with occasionally binding constraints on capacity utilization in the theoretical section of this paper.

[13] This ordering is commonly used to identify a TFP shock. In the international setting foreign TFP is a sensible candidate variable that could influence US TFP contemporaneously. However, due to the lack of quarterly capital utilization adjusted TFP series for the rest of the G7 countries, foreign TFP is not included in this analysis.

[14] The responses obtained from the other country pair specifications can be found in the appendix.

[15] For France and the UK the results indicate that a regime switch is triggered when a negative shock hits the economy, as the impulse responses are initialized at the mean levels of each variable and the threshold estimate is lower than the mean for France.

Figure 11 – US - Canada impulse response functions - US variables



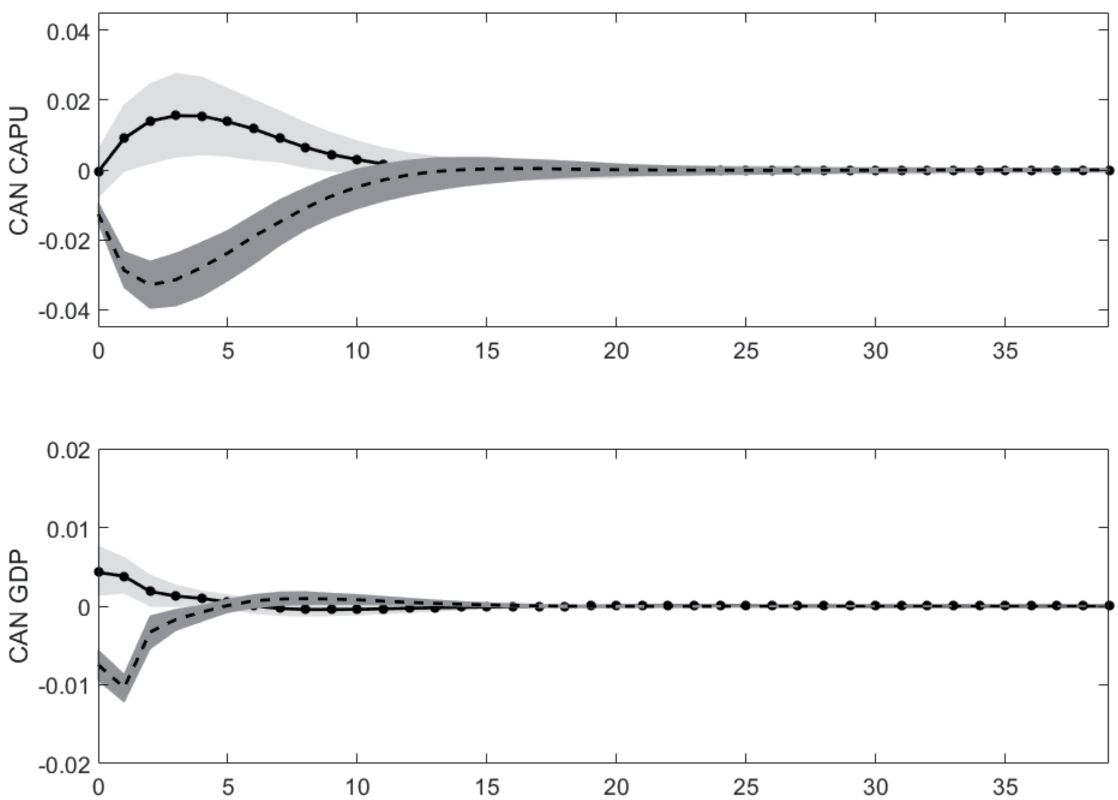
7.4.2 International responses to a US TFP shock

US - Canada

Figure 12 shows the responses of Canadian capacity utilization and Canadian GDP growth to a US TFP shock.

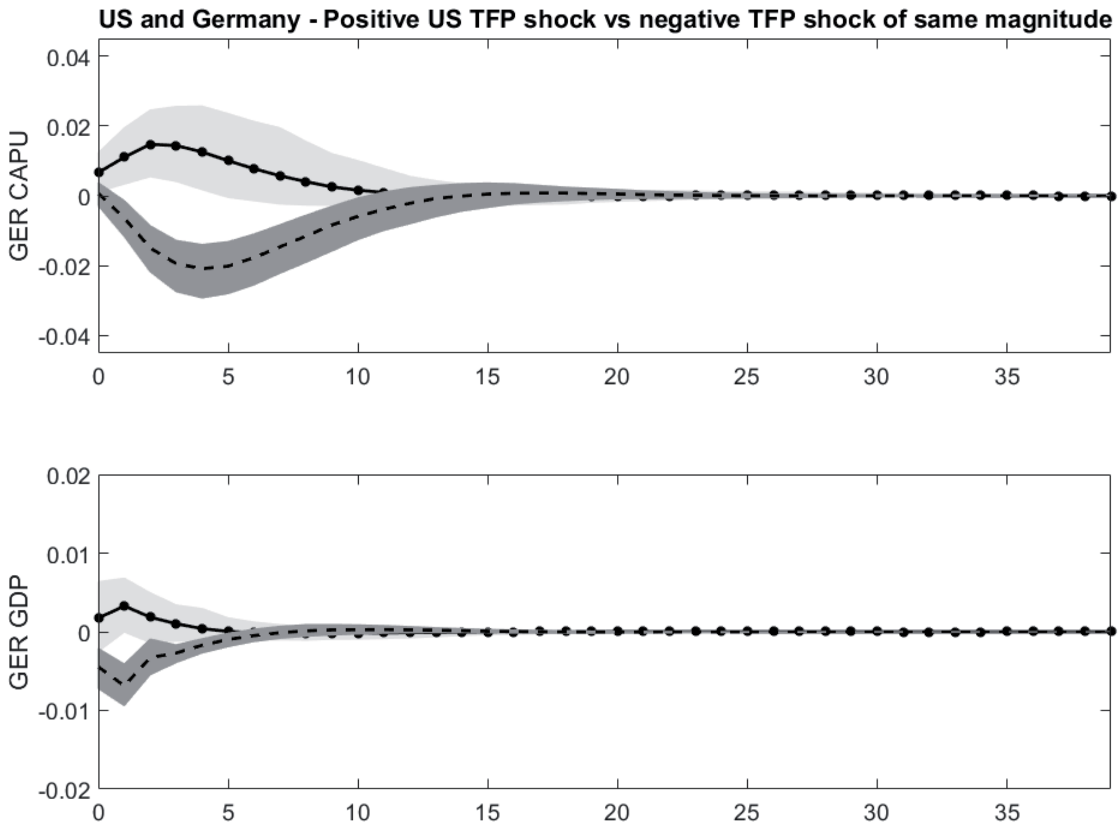
Similarly to the domestic US responses, the Canadian responses show that there are positive international spillover effects to a positive US TFP shock on Canadian capacity utilization and Canadian GDP growth (dotted lines), while there are negative international spillover effects on the same variables in response to a negative TFP shock (dashed lines). The comparison between the responses to positive and negative US TFP shocks provide evidence that negative US TFP shocks have higher international spillover effects to the Canadian economy compared to a positive US TFP shock. Therefore, spillovers show the same asymmetry that is present in the responses to US TFP shock in the US economy.

Figure 12 – US - Canada impulse response functions - Canada variables



US - Germany

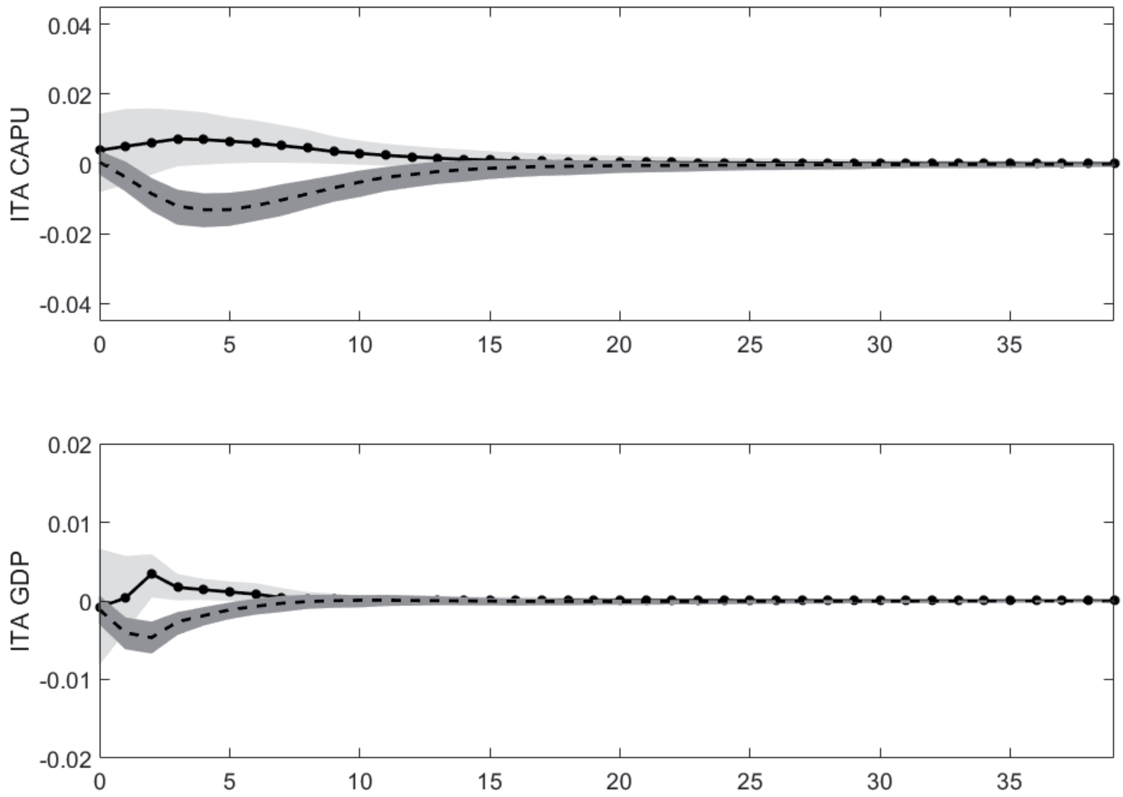
Figure 13 – US - Germany impulse response functions - German variables



Similarly to the international spillovers of a US TFP shock to Canada, the German responses show that there are positive international spillover effects to a positive US TFP shock on German capacity utilization and German GDP growth (dotted lines), while there are negative international spillover effects on the same variables in response to a negative TFP shock (dashed lines). The comparison between the responses to positive and negative US TFP shocks provide evidence that negative US TFP shocks have higher international spillover effects to the German economy compared to a positive US TFP shock. Therefore, also for Germany spillovers show the same asymmetry that is present in the responses to US TFP shock in the US economy.

US - Italy

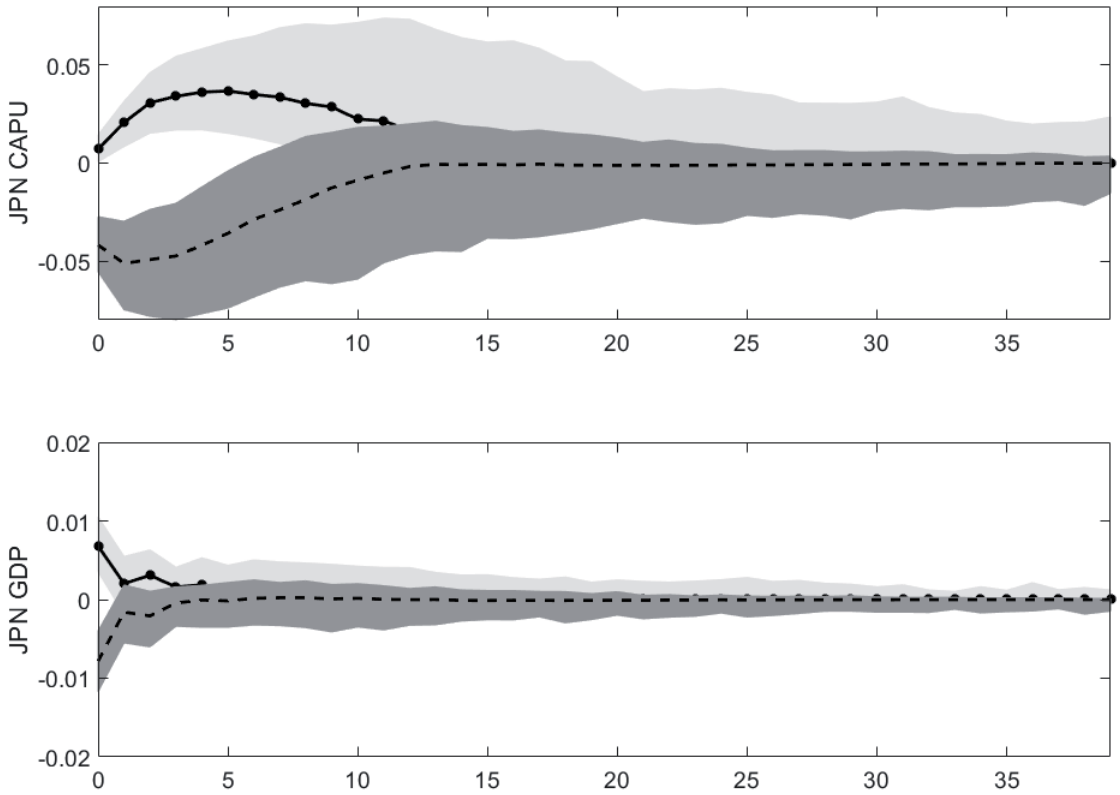
Figure 14 – US - Italy impulse response functions - Italian variables



As expected, the differences in the response of the utilization rate and partially also for GDP go in the same direction as for Canada or Germany. The utilization rate changes less after a positive TFP shock in the US in the high utilization regime, than in the low utilization regime. For the first two quarters after the shocks are triggered in the different regimes, the median negative shock response shows larger effects on GDP than the positive shock. The effect after three quarters seems to be higher for the positive shock response however. Thereafter, the responses are more or less symmetric. The aggregate effects of the two shocks are similar for Italy.

US - Japan

Figure 15 – US - Japan impulse response functions - Japan variables



The overall pattern of the US-JP responses is similar to the ones investigated above. The effects of a positive US TFP shock triggered in the high utilization regime have lower effects on Japanese capacity utilization and GDP compared to an equally sized negative shock triggered in the US' low utilization regime. Note that due to the difference in the scale of the Japanese capacity utilization variable, the magnitude of the utilization response is not directly comparable to those of the other countries. Qualitatively, however they show the same pattern as for Canada, Germany and Italy. I omit the responses of France and the UK here, they can be found in the appendix. This is the case because the threshold estimates indicate a regime switch below average values of US capacity utilization.

7.5 Summary of VAR evidence

The above analysis provides evidence that for four out of six country pairs, threshold effects in the US capacity utilization rate cause asymmetric responses to a US GDP shock both within the US economy and internationally. For these country pairs the data supports a positive threshold in the utilization rate, i.e. in booms when utilization is high the response to a US TFP shocks is dampened. The explanation of this phenomenon that I highlight in this paper is that in US booms, more and more individual producers hit a capacity utilization constrained where their machines work at their maximum production capacity and producers take time to expand their capacities. In this way the full potential of a positive TFP shock cannot transmit into production and thus dampens both the national and international shock responses, while a negative shock is fully transmitted into the production process, decreasing the utilization of existing machines. For France and the UK there is evidence that the threshold effect is below mean utilization. Note that the asymmetry in responses for France still goes in the same direction, i.e. the response to a positive shock is dampened in comparison to a negative shock. Therefore, the asymmetry in cross-country GDP correlations between France and the US in recessions and expansions can be explained using capacity constraints, but the fact that these capacity constraints are identified below mean utilization may be explained by additional channels being at work dominating the utilization channel. I leave this to further research.

8 Conclusion

In this paper I show that cross country correlations of GDP increase during recessions compared to expansions and that this phenomenon can in part be explained in a real business cycle model with occasionally binding capacity constraints. Intuitively, the constraints cause asymmetries in the business cycles of individual countries, which spill over to other countries. Thus, spill-overs of negative shocks are higher than spill-overs of positive shocks, thereby causing the same correlation pattern as in the data. To match the magnitude of the correlation differences in the observed data I assume a value for the elasticity of substitution between tradable intermediate goods suggesting that they are to a certain degree complementary. I successfully test the presence of capacity constraints as a mechanism which leads to business cycle asymmetries empirically using data from the G7 advanced economies in a Bayesian threshold autoregressive model. This finding supports capacity constraints as a prominent transmission channel of cross-country GDP asymmetries in recession compared to expansions. So far the exact consequences of asymmetric cross-country correlations for the international economy and policy choices remain largely unexplored. Exploring the consequences on agents' choices and policy recommendations is an interesting avenue for future research.

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9 Appendix

10 Country Groups

Table 11 – Country Groups

Group	Included Countries
Full Sample	Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, United Kingdom, United States
EU-13	Austria, Belgium, Denmark, Finland, France, Germany, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom
G7	Canada, France, Germany, Italy, Japan, United Kingdom, United States
NAFTA	Canada, Mexico, United States
Oceania	Australia, New Zealand

11 Equilibrium conditions

11.1 Households

First, I will derive the first-order conditions of the Home household. The Lagrangian of the country 1 household's problem is given by

$$
\begin{aligned}
\mathcal{L} = max_{c_1(s^t),n_1(s^t),x_1(s^t),k_1(s^{t+1}),B_1(s^t),u_1(s^t)} \sum_{t=0}^{\infty} \beta^t \sum_{s^t} \pi(s^t)\{\frac{1}{\gamma}\left[c_1(s^t)^{\mu}(1-n_1(s^t))^{1-\mu}\right]^{\gamma} \\
+ \lambda_1(s^t)[q_1^a(s^t)\left(w_1(s^t)n_1(s^t) + u_1(s^t)r_1(s^t)k_1(s^t)\right) + q_1^a(s^t)\left(B_1(s^{t-1}) - \Phi(B_1(s^t))\right) \\
- c_1(s^t) - x_1(s^t) - q_1^a(s^t)Q(s^t)B_1(s^t) - \frac{\phi}{2}k_1(s^t)\left[\frac{x_1(s^t)}{k_1(s^t)} - \delta u_1(s^t)^{\eta}\right]^2] \\
+ \vartheta_1(s^t)[\left(1-\delta u_1(s^t)^{\eta}\right)k_1(s^t) + x_1(s^t) - k_1(s^{t+1})] \\
+ \psi_1(s^t)\left[\Psi - u_1(s^t)\right]\}.
\end{aligned}
$$

The first-order conditions are:

$$
\begin{aligned}
&\frac{\partial \mathcal{L}}{\partial c_1(s^t)}: \quad \mu \frac{[c_1(s^t)^{\mu}(1-n_1(s^t))^{1-\mu}]^{\gamma}}{c_1(s^t)} = \lambda_1(s^t) \\
&\frac{\partial \mathcal{L}}{\partial n_1(s^t)}: \quad (1-\mu) \frac{[c_1(s^t)^{\mu}(1-n_1(s^t))^{1-\mu}]^{\gamma}}{1-n_1(s^t)} = \lambda_1(s^t) q_1^a(s^t) w_1(s^t) \\
&\frac{\partial \mathcal{L}}{\partial x_1(s^t)}: \quad \lambda_1(s^t) = \vartheta_1(s^t)\left[1-\phi\left(\frac{x_1(s^t)}{k_1(s^t} - \delta u_1(s^t)^{\eta}\right)\right] \\
&\frac{\partial \mathcal{L}}{\partial k_1(s^t)}: \quad \vartheta_1(s^t) = \beta \sum_{s^{t+1}} \Pi(s^{t+1}|s^t)\{\lambda_1(s^{t+1})[q_1^a(s^{t+1}) r_1(s^{t+1}) u_1(s^{t+1}) \\
&-\phi\left(\frac{1}{2}\left(\frac{x_1(s^{t+1})}{k_1(s^{t+1})} - \delta u_1(s^{t+1})^{\eta}\right) - \frac{x_1(s^{t+1})}{k_1(s^{t+1})}\right)\left(\frac{x_1(s^{t+1})}{k_1(s^{t+1})} - \delta u_1(s^{t+1})^{\eta}\right)] \\
&+\vartheta_1(s^{t+1})(1-\delta u_1(s^{t+1})^{\eta})\} \\
&\frac{\partial \mathcal{L}}{\partial B_1(s^t)}: \quad Q(s^t) = \beta \sum_{s^{t+1}} \Pi(s^{t+1}|s^t)\left[\frac{\lambda_1(s^{t+1})}{\lambda_1(s^t)} \frac{q_1^a(s^{t+1})}{q_1^a(s^t)}\right] - \Phi'\left(B_1(s^t)\right) \\
&\frac{\partial \mathcal{L}}{\partial u_1(s^t)}: \quad \Psi_1(s^t) = \lambda_1(s^t)\left[q_1^a(s^t) r_1(s^t) k_1(s^t) + \eta \delta u_1(s^t)^{\eta-1} k_1(s^t) \phi\left(\frac{x_1(s^{t+1})}{k_1(s^{t+1})} - \delta u_1(s^{t+1})^{\eta}\right)\right] \\
&-\vartheta_1(s^t)\eta\delta u_1(s^t)^{\eta-1} k_1(s^t).
\end{aligned}
$$

For the Foreign household the Lagrangian is

$$
\begin{aligned}
\mathcal{L} = max_{c_2(s^t), n_2(s^t), x_2(s^t), k_2(s^{t+1}), B_2(s^t), u_2(s^t)} &\sum_{t=0}^{\infty} \beta^t \sum_{s^t} \pi(s^t)\{\frac{1}{\gamma}\left[c_2(s^t)^{\mu}(1-n_2(s^t))^{1-\mu}\right]^{\gamma} \\
&+ \lambda_2(s^t)[q_2^b(s^t)\left(w_2(s^t) n_2(s^t) + u_2(s^t) r_2(s^t) k_2(s^t)\right) + q_2^a(s^t)\left(B_2(s^{t-1}) - \Phi(B_2(s^t))\right) \\
&- c_2(s^t) - x_2(s^t) - q_2^a(s^t) Q(s^t) B_2(s^t) - \frac{\phi}{2} k_2(s^t)\left[\frac{x_2(s^t)}{k_2(s^t)} - \delta u_2(s^t)^{\eta}\right]^2] \\
&+ \vartheta_2(s^t)[\left(1-\delta u_2(s^t)^{\eta}\right) k_2(s^t) + x_2(s^t) - k_2(s^{t+1})] \\
&+ \psi_2(s^t)\left[\Psi - u_2(s^t)\right]\}.
\end{aligned}
$$

The first-order conditions are:

$$\frac{\partial \mathcal{L}}{\partial c_2(s^t)}: \quad \mu \frac{[c_2(s^t)^{\mu}(1-n_2(s^t))^{1-\mu}]^{\gamma}}{c_2(s^t)} = \lambda_2(s^t) \tag{25}$$

$$\frac{\partial \mathcal{L}}{\partial n_2(s^t)}: \quad (1-\mu)\frac{[c_2(s^t)^{\mu}(1-n_2(s^t))^{1-\mu}]^{\gamma}}{1-n_2(s^t)} = \lambda_2(s^t) q_2^b(s^t) w_2(s^t) \tag{26}$$

$$\frac{\partial \mathcal{L}}{\partial x_2(s^t)}: \quad \lambda_2(s^t) = \vartheta_2(s^t)\left[1-\phi\left(\frac{x_2(s^t)}{k_2(s^t} - \delta u_2(s^t)^{\eta}\right)\right] \tag{27}$$

$$\frac{\partial \mathcal{L}}{\partial k_2(s^t)}: \quad \vartheta_2(s^t) = \beta \sum_{s^{t+1}} \Pi(s^{t+1}|s^t)\{\lambda_2(s^{t+1})[q_2^b(s^{t+1}) r_2(s^{t+1}) u_2(s^{t+1}) \tag{28}$$

$$-\phi\left(\frac{1}{2}\left(\frac{x_2(s^{t+1})}{k_2(s^{t+1})} - \delta u_2(s^{t+1})^{\eta}\right) - \frac{x_2(s^{t+1})}{k_2(s^{t+1})}\right)\left(\frac{x_2(s^{t+1})}{k_2(s^{t+1})} - \delta u_2(s^{t+1})^{\eta}\right)] \tag{29}$$

$$+\vartheta_2(s^{t+1})(1-\delta u_2(s^{t+1})^{\eta})\} \tag{30}$$

$$\frac{\partial \mathcal{L}}{\partial B_2(s^t)}: \quad Q(s^t) = \beta \sum_{s^{t+1}} \Pi(s^{t+1}|s^t)\left[\frac{\lambda_2(s^{t+1})}{\lambda_2(s^t)} \frac{q_2^a(s^{t+1})}{q_2^a(s^t)}\right] - \Phi'\left(B_2(s^t)\right) \tag{31}$$

$$\frac{\partial \mathcal{L}}{\partial u_2(s^t)}: \quad \Psi_2(s^t) = \lambda_2(s^t)\left[q_2^b(s^t) r_2(s^t) k_2(s^t) + \eta \delta u_2(s^t)^{\eta-1} k_2(s^t) \phi\left(\frac{x_2(s^{t+1})}{k_2(s^{t+1})} - \delta u_2(s^{t+1})^{\eta}\right)\right] \tag{32}$$

$$-\vartheta_2(s^t)\eta\delta u_2(s^t)^{\eta-1} k_2(s^t). \tag{33}$$

In addition, to the first order condition, also the budget constraints and the laws of motion for capital are optimality conditions. Because of the occasionally binding capacity utilization constraint, two complementary slackness conditions form part of the optimality conditions as well. They are

$$\psi_i(s^t)\left[\Psi - u_i(s^t)\right] = 0 \tag{34}$$

for $i = 1, 2$.

Now, we turn to the optimality conditions of the firms.

11.2 Intermediate Firms

The intermediate firm's static maximization problem in country i after history s^t is given by

$$\mathcal{L} = max_{k_i(s^t), n_i(s^t)}\{e^{z_i(s^t)}\left(u_i(s^t)k_i(s^t)\right)^{\theta} n_i(s^t)^{1-\theta} - w_i(s^t)n_i(s^t) - r_i(s^t)u_i(s^t)k_i(s^t)\}. \tag{35}$$

The first-order conditions are:

$$\frac{\partial \mathcal{L}}{\partial k_i(s^t)}: \quad e^{z_i(s^t)}\theta\left(u_i(s^t)k_i(s^t)\right)^{\theta-1}u_i(s^t)n_i(s^t)^{1-\theta} = r_i(s^t)u_i(s^t) \tag{36}$$

$$\frac{\partial \mathcal{L}}{\partial n_i(s^t)}: \quad e^{z_i(s^t)}(1-\theta)\left(u_i(s^t)k_i(s^t)\right)^{\theta}n_i(s^t)^{-\theta} = w_i(s^t). \tag{37}$$

This simplifies to:

$$\frac{\partial \mathcal{L}}{\partial k_i(s^t)}: \quad \theta\frac{y_i(s^t)}{k_i(s^t)} = r_i(s^t)u_i(s^t) \tag{38}$$

$$\frac{\partial \mathcal{L}}{\partial n_i(s^t)}: \quad (1-\theta)\frac{y_i(s^t)}{n_i(s^t)} = w_i(s^t) \tag{39}$$

for $i = 1, 2$, where $y_i(s^t) = F(z_i(s^t), k_i(s^t), n_i(s^t), u_i(s^t))$ $w_i(s^t)$ and $r_i(s^t)$ are denoted in local intermediary good.

11.3 Final good firms

The country 1's final good firm's maximization problem is

$$\mathcal{L} = max_{a_1(s^t),b_1(s^t)}\{[\omega_1 a_1(s^t)^{\frac{\sigma-1}{\sigma}} + (1-\omega_1)b_1(s^t)^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}} - q_1^a(s^t)a_1(s^t) - q_1^b(s^t)b_1(s^t)\}. \tag{40}$$

The first-order conditions are:

$$\frac{\partial \mathcal{L}}{\partial a_1(s^t)}: \quad q_1^a(s^t) = \frac{\sigma}{\sigma-1}[\omega_1 a_1(s^t)^{\frac{\sigma-1}{\sigma}} + (1-\omega_1)b_1(s^t)^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}-1}\frac{\sigma-1}{\sigma}\omega_1 a_1(s^t)^{\frac{\sigma-1}{\sigma}-1} \tag{41}$$

$$\frac{\partial \mathcal{L}}{\partial b_1(s^t)}: \quad q_1^b(s^t) = \frac{\sigma}{\sigma-1}[\omega_1 a_1(s^t)^{\frac{\sigma-1}{\sigma}} + (1-\omega_1)b_1(s^t)^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}-1}\frac{\sigma-1}{\sigma}(1-\omega_1)b_1(s^t)^{\frac{\sigma-1}{\sigma}-1}. \tag{42}$$

They simplify to

$$q_1^a(s^t) = [\omega_1 a_1(s^t)^{\frac{\sigma-1}{\sigma}} + (1-\omega_1)b_1(s^t)^{\frac{\sigma-1}{\sigma}}]^{\frac{1}{\sigma-1}}\omega_1 a_1(s^t)^{-\frac{1}{\sigma}} \tag{43}$$

$$q_1^b(s^t) = [\omega_1 a_1(s^t)^{\frac{\sigma-1}{\sigma}} + (1-\omega_1)b_1(s^t)^{\frac{\sigma-1}{\sigma}}]^{\frac{1}{\sigma-1}}(1-\omega_1)b_1(s^t)^{-\frac{1}{\sigma}}. \tag{44}$$

$$(q_1^a(s^t))^\sigma = [\omega_1 a_1(s^t)^{\frac{\sigma-1}{\sigma}} + (1-\omega_1)b_1(s^t)^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}}\omega_1^\sigma a_1(s^t)^{-\frac{\sigma}{\sigma}} \tag{45}$$

$$(q_1^b(s^t))^\sigma = [\omega_1 a_1(s^t)^{\frac{\sigma-1}{\sigma}} + (1-\omega_1)b_1(s^t)^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}}(1-\omega_1)^\sigma b_1(s^t)^{-\frac{\sigma}{\sigma}}. \tag{46}$$

$$a_1(s^t) = G_1\omega_1^\sigma(q_1^a(s^t))^{-\sigma} \tag{47}$$

$$b_1(s^t) = G_1(1-\omega_1)^\sigma(q_1^b(s^t))^{-\sigma}. \tag{48}$$

For country 2's final good firm's maximization problem is

$$\mathcal{L} = max_{a_2(s^t),b_2(s^t)}\{[(1-\omega_1)a_i(s^t)^{\frac{\sigma-1}{\sigma}} + \omega_1 b_i(s^t)^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}} - q_2^a(s^t)a_2(s^t) - q_2^b(s^t)b_2(s^t)\}. \tag{49}$$

The first-order conditions are:

$$\frac{\partial \mathcal{L}}{\partial a_2(s^t)} : \quad q_2^a(s^t) = \frac{\sigma}{\sigma-1}[(1-\omega_1)a_i(s^t)^{\frac{\sigma-1}{\sigma}} + \omega_1 b_i(s^t)^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}-1}(1-\omega_1)\frac{\sigma-1}{\sigma}a_i(s^t)^{\frac{\sigma-1}{\sigma}-1} \tag{50}$$

$$\frac{\partial \mathcal{L}}{\partial b_2(s^t)} : \quad q_2^b(s^t) = \frac{\sigma}{\sigma-1}[(1-\omega_1)a_i(s^t)^{\frac{\sigma-1}{\sigma}} + \omega_1 b_i(s^t)^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}}\omega_1\frac{\sigma-1}{\sigma}b_i(s^t)^{\frac{\sigma-1}{\sigma}-1}. \tag{51}$$

And this simplifies to

$$a_2(s^t) = G_2\omega_1^\sigma(q_2^a(s^t))^{-\sigma} \tag{52}$$

$$b_2(s^t) = G_2(1-\omega_1)^\sigma(q_2^b(s^t))^{-\sigma}. \tag{53}$$

12 Data Sources

Table 12 – Data Sources

Country	Variable	Source	Datastream ID (if available)
US	TFP	Fernald (2012)	-
	Capacity Utilization	Federal Reserve	USCAPUTLQ
	GDP	BEA	USGDP...D
Canada	Capacity Utilization	CANSIM	CNCAPUTLR
	GDP	OECD	CNOEXO03D
France	Capacity Utilization	OECD	FROBS076Q
	GDP	INSEE	FRGDP...D
Germany	Capacity Utilization	OECD	BDOBS076Q
	GDP	OECD	BDOEXO03D
Italy	Capacity Utilization	OECD	ITOBS076Q
	GDP	OECD	ITOEXO03D
Japan	Capacity Utilization	METI	JPCAPUTLQ
	GDP	OECD	JPOEXO03D
UK	Capacity Utilization	FRED	-
	GDP	ONS	UKGDP...D

13 Domestic US responses in specifications with Germany, Italy and the UK

Figure 16 – US - Germany impulse response functions - US variables

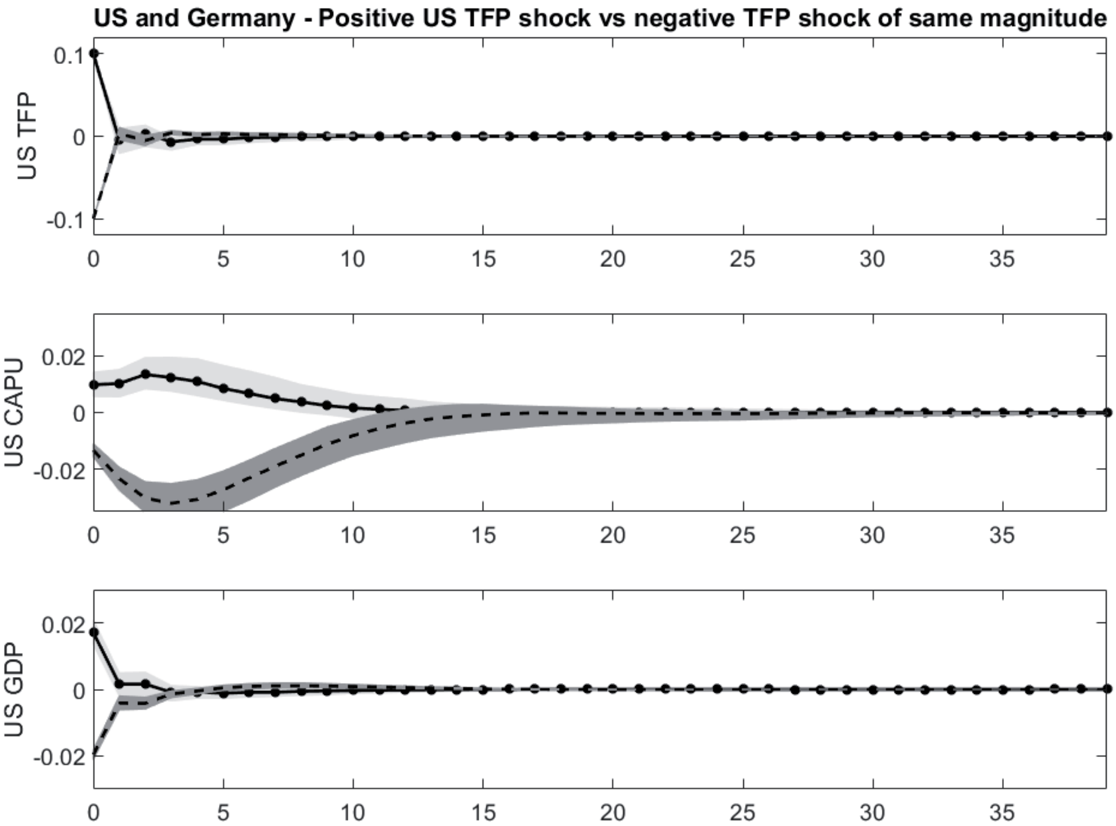


Figure 17 – US - Italy impulse response functions - US variables

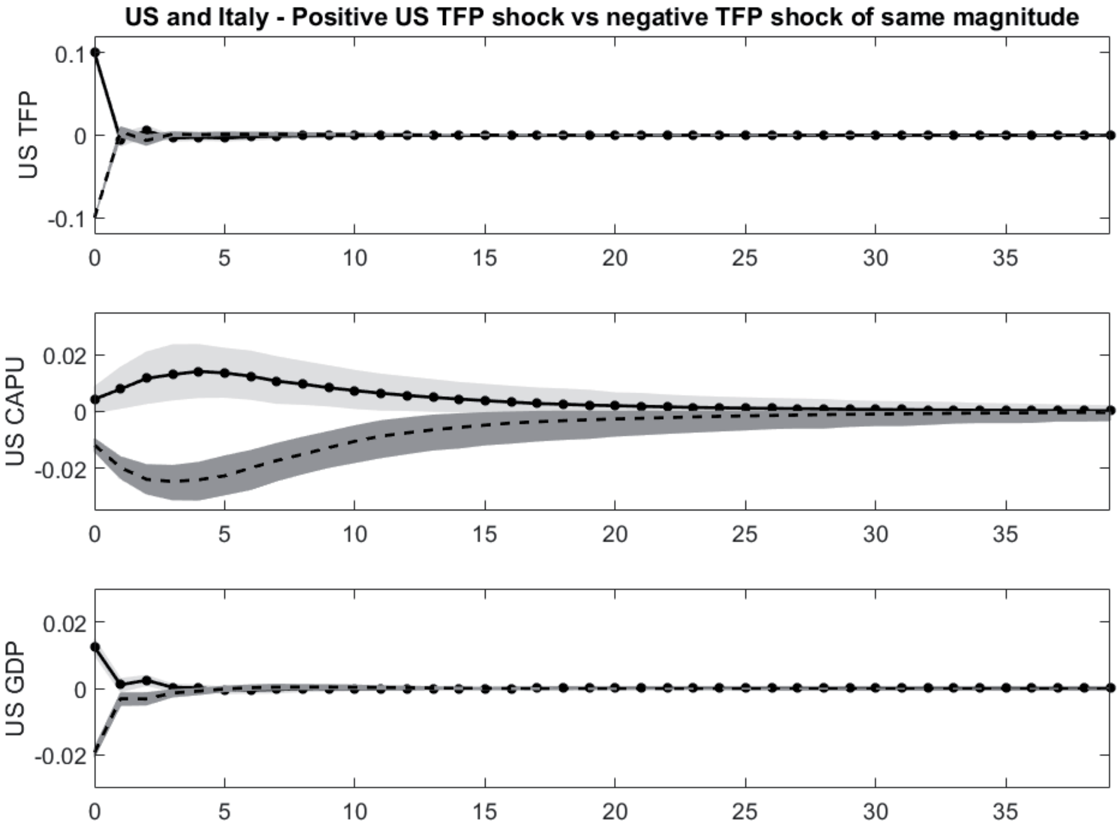
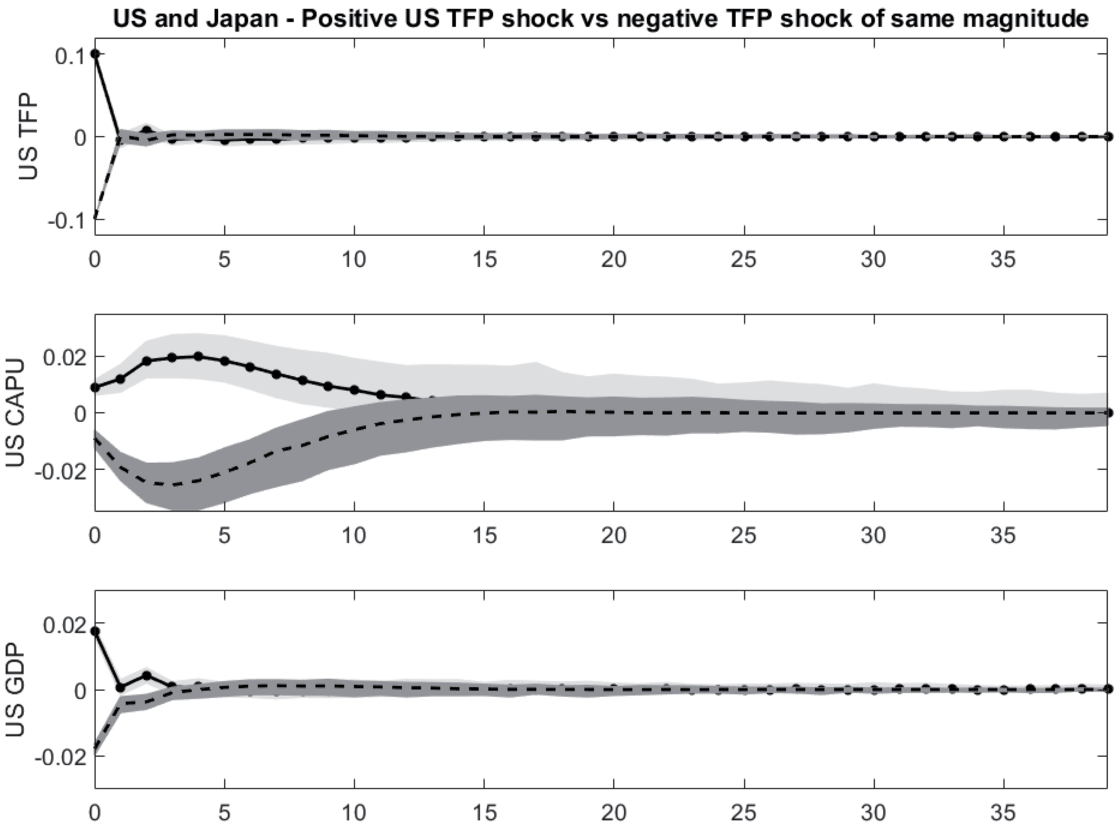


Figure 18 – US - Japan impulse response functions - Japan variables



14 Results on omitted countries

Figure 19 – US - France impulse response functions - US variables

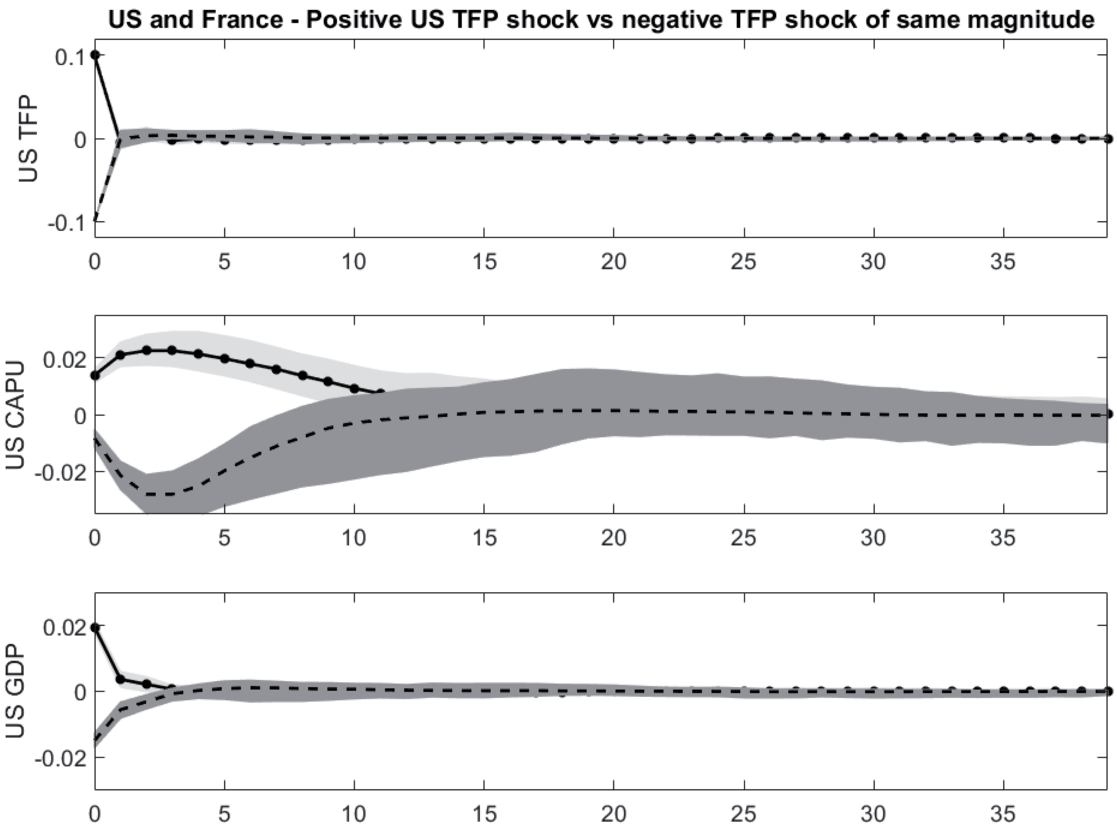


Figure 20 – US - France impulse response functions - French variables

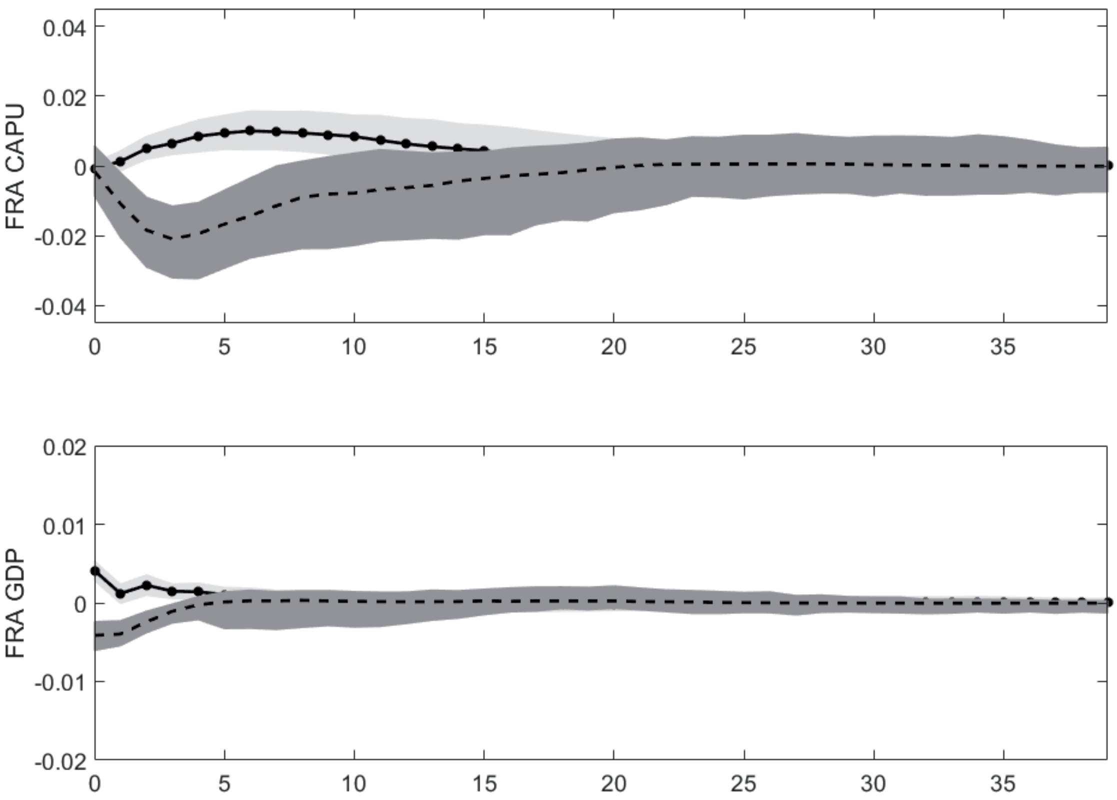


Figure 21 – US - UK impulse response functions - UK variables

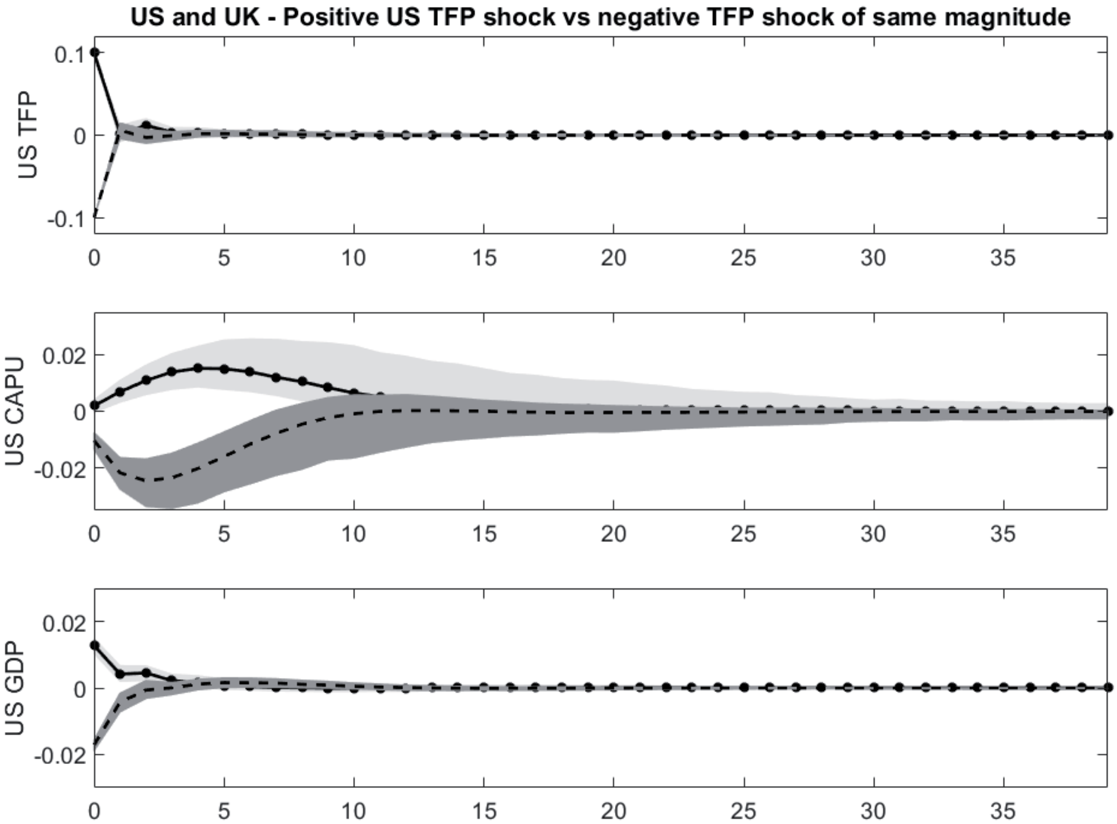
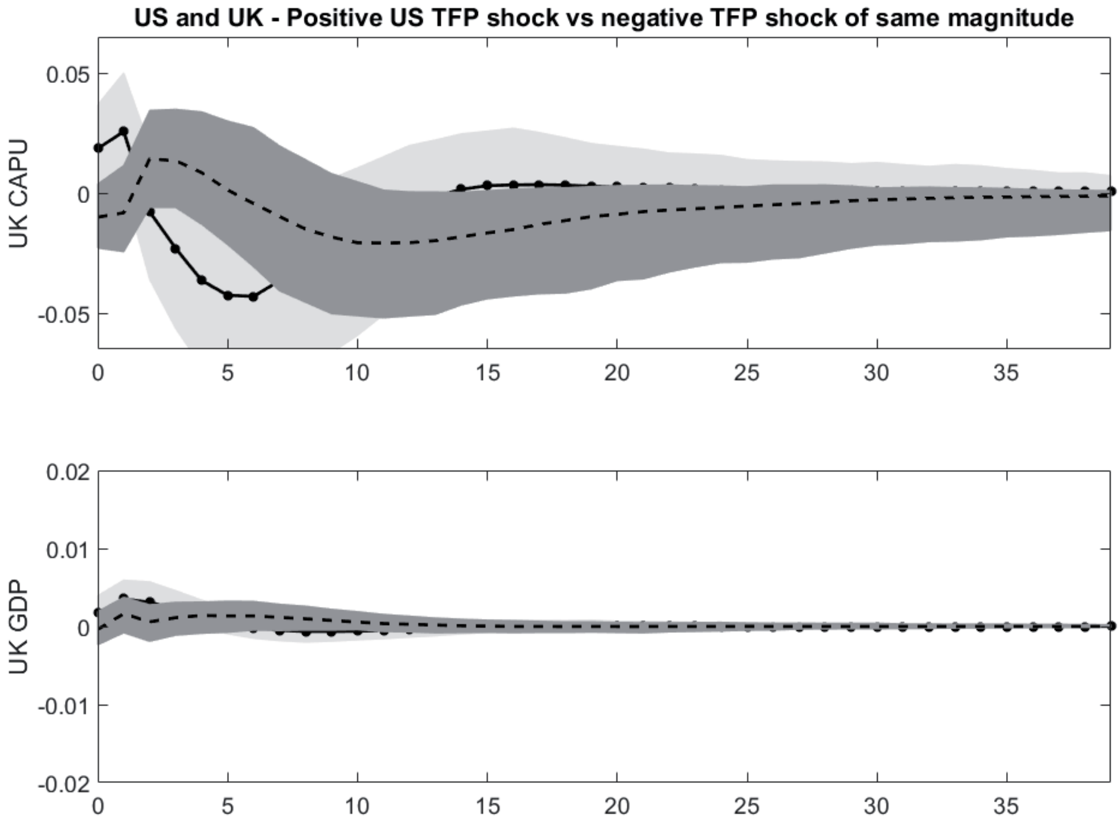


Figure 22 – US - UK impulse response functions - UK variables



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