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Abstract

The paper estimates macroeconomic effects and decomposes transmission channels of quantitative easing in the United States using 15-variable Bayesian vector autoregressive model with stochastic search variable selection prior, distinguishing between Treasury bond purchases, mortgage-backed securities purchases and Operation Twist. A positive quantitative easing shock has a strong, negative impact on unemployment and no impact on prices, with Treasury purchases and Operation Twist found to be more effective than purchases of mortgage-backed securities. Opposite to the assumptions usually made in the literature, quantitative easing transmits to the real economy mostly via the stock market instead of long-term rates. Among numerous extensions to the baseline model, spillbacks are found to account for 40% of the impact of Treasury purchases on unemployment and commercial paper purchases have similar effects on the economy as purchases of Treasury bonds and mortgage-backed securities. However, baseline estimates are not found to be very robust, and thus substantial uncertainty regarding the macroeconomic effects of QE persists.

Keywords: unconventional monetary policy, large-scale asset purchases, QE, GDP, unemployment, United States, stochastic search variable selection, transmission channels, spillbacks, commercial paper.

JEL: E52, E58.

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1. Introduction

Following the outbreak of the COVID-19 pandemic, large-scale asset purchases, commonly referred to as quantitative easing (QE), became the instrument of choice for central banks across the globe. Amid a secular downward trend in interest rates and given the magnitude of the pandemic shock, conventional interest rate cuts did not provide enough policy accommodation in advanced and some emerging market economies. Facing the zero lower bound (ZLB) and seemingly encouraged by the previous experience of major central banks, central banks of those economies turned to QE. Several emerging market central banks well away from the ZLB also launched asset purchases, aiming at supporting conditions in bond markets and helping governments finance unprecedented anti-crisis fiscal measures. As a result, while only 5 central banks utilised QE at some point before the pandemic, as many as 40 launched asset purchases after its outbreak (Fratto et al. 2021).

Given the above, it would seem that empirical evidence on the effectiveness of QE must be very strong. This is not entirely true, however - while the literature on the topic is very rich, its conclusions are not fully definite. The evidence on the financial market impact of QE is based primarily on event studies of major QE announcements, which show that QE reduces bond yields, increases stock prices and depreciates the exchange rate (i.a. Gagnon et al. 2011, Joyce et al. 2011, Krishnamurthy and Vissing-Jorgensen 2011). However, when other QE-related announcements are included as well, their cumulative impact turns out to be largely neutral (Greenlaw et al. 2018). It is also not entirely clear whether these on impact, financial market responses persist over a longer period of time.

The macroeconomic impact of QE is studied primarily with vector autoregressive (VAR) models. The baseline results of the majority of these studies indicate that asset purchases raise GDP and inflation in the medium run, while reducing bond yields and increasing stock prices (i.a. Weale and Wieladek 2016, Hesse et al. 2018, Kim et al. 2020). However, these results are based on small-scale VAR models that are prone to omitted variable bias; QE shocks are often identified with sign restrictions that impose negative effect on bond yields, while alternative identification schemes point to smaller or even neutral effects.

This paper contributes to the above literature by studying macroeconomic effects of QE in the United States using a larger, mid-sized Bayesian VAR model that includes 15 variables in its baseline version. Literature has demonstrated that mid-sized models forecast better than small models, while the benefits from increasing the model size further are small at best (Bańbura et al. 2010, Koop 2013). The use of a larger model reduces concerns of a potential omitted variable bias, while allowing to study purchases of various assets (Treasuries and mortgage-backed securities) as well as transmission channels of QE within a single model. In line with the latter and as an important contribution to the literature, the macroeconomic effects of QE are decomposed between various financial variables that can be partially mapped to the transmission channels discussed in the literature.

Importantly, I let the data speak to a largest extent possible. While using a larger model calls for parameter shrinkage and thus informative priors, instead of a standard and somewhat arbitrary Minnesota prior I opt for a data-based, "automatic" stochastic search variable selection (SSVS) prior. Similarly, monetary policy shocks are identified using simple Cholesky factorisation. I thus refrain from "assuming" financial market effects of QE via sign restrictions. Having said that, other priors and identification schemes, including recently popular high-frequency identification, are considered in robustness exercises.

Unlike most of the literature, the sample goes beyond the post-global financial crisis QE period, which allows for robust estimation of model parameters unrelated to QE and a comparison of how QE fares relative to conventional monetary policy. Finally, QE is measured relative to the total stock of a purchased asset, which captures the developments of the QE size over time better than measures previously used in the literature.

The baseline results indicate that QE has a strong negative impact on unemployment – 300 bln USD of Treasury bond purchases during QE1 reduced unemployment by as much as 0.7 pp. The effects on GDP are not statistically significant[2], but the median posterior effect is positive in the case of Treasury bond purchases and Operation Twist. At the same time, QE is estimated to have no effect on prices. Treasury purchases are found to be more effective than mortgage-backed securities (MBS) purchases, while Operation Twist is at least as effective as outright purchases of government bonds. Importantly, QE is found to be transmitted into the real economy mostly via an increase in stock prices and a reduction in stock market volatility, which contradicts the theoretical literature that focuses on the role of long-term rates. The exchange rate and bank lending also do not play excessively important roles in the transmission of QE.

Several extensions to the baseline specification are considered. Most importantly, QE spillovers and spillbacks are studied – the latter has not been done in the literature before. The median posterior impulse responses indicate that the effects of Treasury purchases and Operation Twist spill over to global GDP and long-term government bonds. In turn, these global effects spill back to the US, accounting for about 40% of the total impact of Treasury purchases on unemployment.

The effects of commercial paper purchases, conducted by the Fed during the global financial crisis and more recently during the pandemic, are also studied in one of the extensions. This is a novelty in the literature, as their macroeconomic effects have not been studied before. Similarly to QE, commercial paper purchases are found to be an effective tool that reduces unemployment and increases stock prices.

On top of that, the effects of QE are studied across the yield curve and for various assets, signalling and price channels are disentangled, and the effects on the housing sector and

[2] Throughout the paper, I call "statistically significant" relationships in which the 90% Bayesian credible sets of the posterior impulse responses do not contain 0 at some horizon.

various components of GDP are investigated. Contrary to the majority of the literature, the effect of QE on Treasury yields does not increase with maturity, with signalling channel playing a more important role than the price channel. Counterintuitively, MBS purchases are not found to have a stronger impact on the housing sector than Treasury purchases. Finally, QE is found to affect investment more than consumption, with no effect on government spending and net exports.

The robustness of the above-described results is checked in numerous ways. Models with fewer and more variables, as well as fewer and more lags, are considered; alternative measures of QE (purchase-based), identification of shocks (high-frequency) and priors (Minnesota-type) are used; the model is estimated on monthly rather than quarterly data and model equations are estimated one-by-one in order to account for ZLB and QE periods; finally, it is tested whether variable order and the inclusion of a structural break in the deterministic trend have any impact on the results.

In general, the baseline results with respect to unconventional monetary policy are not found to be very robust. In several alternative specifications, especially when more variables or lags are added, the impact of QE and Operation Twist on unemployment and GDP is found to be significantly smaller. At the same time, the effects of a conventional interest rate hike are robust and consistently contractionary. Thus, the effects of QE are subject to larger uncertainty than those of conventional monetary policy.

The remainder of the paper is structured as follows. Section 2 discusses the definition of QE, its history in the United States and theoretical transmission channels as well as reviews empirical literature on the topic in more detail. Section 3 describes the empirical framework and the data. Section 4 presents baseline results, including macroeconomic effects of various "types" of QE and their transmission channels. Section 5 discusses various model extensions, while Section 6 covers robustness checks. Finally, Section 7 concludes.

2. QE: definition, US history, transmission channels, empirical literature

2.1 Definition

It is worth defining quantitative easing since this term is not clearly characterised in the literature. QE is defined here as large-scale outright purchases of domestic currency-denominated long-term securities by a central bank for reasons other than steering short-term interest rates (Hertel et al. 2021). These purchases should increase the central bank's balance sheet.

Therefore, not all so-called balance sheet policies are included in the definition; in particular, credit easing policies such as ECB's TLTRO or Bank of England's Term Funding Scheme are

not. Purchases of short-term securities such as commercial paper are also excluded. While these purchases often accompany purchases of long-term securities, they are aimed at improving market liquidity rather than influencing long-term yields, which is considered the main transmission channel of QE in the literature. At the same time, purchases of long-term private securities, such as mortgage-backed securities (MBS), covered bonds, corporate bonds or stock market ETFs are included. Finally, only purchases that increase the balance sheet are covered by this definition. Therefore, the Fed's Maturity Extension Program, commonly referred to as Operation Twist, under which the Fed sold short-term and bought long-term securities, is not included. Having said that, this program is controlled for and studied in the paper alongside QE.

2.2 History in the US

QE, referred to by the Fed as large-scale asset purchases (LSAP), was first announced in the US at the peak of the global financial crisis on 25 November 2008, when the Fed decided to purchase 600 bln USD of agency-backed MBS and agency debt in order to support the housing market. The first round of QE, dubbed QE1, was expanded in March 2009 in both size and composition, as longer-term Treasury securities were included in order to support private credit markets. Following an improvement in financial and economic conditions, these purchases had ended by March 2010; in total, 1.25 trn USD of MBS, 175 bln USD of agency debt and 300 bln of Treasury bonds were purchased.

The second round of QE, QE2, was launched in November 2010, following a lacklustre pace of economic recovery over the course of the previous several months. This round consisted of 600 bln USD of Treasury bonds alone and had been completed by June 2011. In September 2011, following further disappointments in the pace of recovery and the intensification of the Eurozone sovereign debt crisis, the Fed launched the Maturity Extension Program (MEP), dubbed Operation Twist after a similar program conducted in the 1960s. Purchases of longer-term Treasury securities (with remaining maturity of over 6 years) were financed by the sales of shorter-term securities (with remaining maturity of less than 3 years), thus the program did not increase the Fed's balance sheet. Operation Twist was extended in June 2012 and had ended by the end of 2012, totalling 667 bln USD.

Finally, QE3 was announced in September 2012 following further disappointments in the pace of labour market recovery and continued headwinds from the euro area. Initially it consisted of MBS purchases as the Operation Twist was still ongoing; in December 2012 it was extended to cover Treasury bonds as well. Unlike the previous programmes, QE3 was open-ended, i.e. only the monthly scale of purchases was announced (40 bln USD for MBS and 45 bln for Treasuries) without an end date or the cumulative sum. Seeing continued improvement in economic conditions, Fed chair Ben Bernanke said in June 2013 that the Fed was likely to start reducing (tapering) purchases in September and end them by mid-2014.

These statements caused financial market turmoil around the world, with bond yields increasing, stock markets falling and capital flowing out of the emerging markets. As a result, the Fed postponed tapering from September to December. The scale of purchases was gradually reduced each month until QE3 was terminated in October 2014.

Initially, the Fed did not reinvest principal payments from MBS and agency debt holdings and thus net purchases of these securities were effectively lower than the announced gross purchases; when QE1 ended, these holdings began to dwindle. In August 2010, the Fed decided to keep its securities holdings constant and thus started reinvesting MBS and agency debt principal payments, initially into Treasury securities, and from September 2011 into MBS. When the Fed funds rate was raised from the ZLB in December 2015, it was announced that the reinvestment of principal payments would continue "until normalization of the level of the federal funds rate is well under way".

The balance sheet normalisation was eventually announced in September 2017. Principal payments were not reinvested as long as they did not exceed a gradually rising monthly cap that peaked at 30 bln USD for Treasury bonds and 20 bln USD for MBS. In March 2019, the pace of balance sheet normalisation was reduced – the cap for Treasury bonds was reduced to 15 bln USD - and the normalisation was scheduled to end altogether by the end of September. Eventually, balance sheet reduction was terminated earlier, in July 2019.

QE was restarted on a large scale with the outbreak of the COVID-19 pandemic in March 2020. Since this paper does not cover the pandemic-related measures, they are not discussed here in detail.

2.3 Transmission channels

The literature discusses numerous transmission channels of QE. When it comes to the impact on financial markets, 4 major channels can be singled out:

- **Price channel.** QE creates additional demand for purchased assets (flow effect) and limits their market supply (stock effect; D'Amico and King 2013). Under market segmentation, when some agents prefer or have access only to certain assets, and/or under imperfect substitutability of assets, changes in relative demand and supply affect asset prices (Harrison 2012, Vayanos and Vila 2021). Thus, prices of purchased assets increase.
- **Portfolio rebalancing channel**. As expected returns on purchased assets decrease, investors rebalance their portfolios towards other, imperfectly substitutable assets, whose prices also increase (e.g. Joyce et al. 2011).
- **Signalling channel.** Asset purchases signal the central bank's commitment to maintaining loose monetary policy (keeping interest rates at the ZLB). By acting as a

form of forward guidance, they lower expected future short-term interest rates, and thus long-term interest rates (e.g. Christensen and Rudebusch 2012).

- **Bank lending channel.** As prices of purchased assets and the amount of central bank reserves in bank assets increase, banks' net worth and liquidity rises, which may prompt them to extend more loans to the real economy (Joyce and Spaltro 2014, Rodnyansky and Darmouni 2017).

These are not the only channels discussed in the literature. It is also worth mentioning that QE could improve market liquidity and thus lower liquidity premium, especially in times of market stress (Christensen and Gillan 2019). This seemed to be an important rationale for launching asset purchases for many central banks during the COVID-19 pandemic. The central bank's presence in the market could also potentially reduce market volatility and uncertainty about future economic conditions and monetary policy (Weale and Wieladek 2016).

Via financial markets QE affects the real economy. Lower corporate bond yields, higher stock prices and better access to bank financing decrease financing costs for businesses and increase Tobin's q, raising business investment. Similarly, lower mortgage rates and easier access to bank credit raise residential investment. Lower mortgage payments raise disposable income, while higher stock prices increase consumer wealth, having a positive impact on consumption. Lower government bond yields and thus lower debt servicing costs might induce – or enable – government to loosen fiscal policy. Due to lower expected future short-term rates, the exchange rate depreciates, raising the competitiveness of domestic producers and thus boosting net exports; depreciation also has a direct impact on inflation as import prices increase.

Through the above-mentioned channels, QE increases GDP, which in turn raises inflation.

2.4 Empirical literature

The rich empirical literature assessing the effectiveness of QE mostly shows that asset purchases improve financial conditions and have a positive impact on economic activity and inflation (Hertel et al. 2021). However, the estimates tend to be highly uncertain and dependent on the method, assumptions, sample, economic conditions and country.

In the first years of QE, when time series remained relatively short, the studies of QE investigated mostly the response of asset prices within a short time window around the QE announcement, utilising the event study method. First studies of this kind indicated that QE was effective, i.e. bond yields fell, exchange rate depreciated and stock prices increased following QE-related announcements (Gagnon et al. 2011, Joyce et al. 2011, Krishnamurthy and Vissing-Jorgensen 2011, Lam 2011, Meaning and Zhu 2011, Christensen and Rudebusch 2012, Joyce and Tong 2012, Rosa 2012, Ueda 2012, Bauer and Rudebusch 2014, Rogers et al.

2014, Altavilla et al. 2015, Fukunaga et al. 2015, Andrade et al. 2016, Urbschat and Watzka 2020). However, these results were driven by the first QE announcements made at the height of the global financial crisis. The following announcements are found to have had smaller impact on asset prices, perhaps because they were to a large extent expected. Some studies even indicate that if the effects of all monetary policy announcements made during the QE period are summed, the effect of QE on bond yields is close to zero (Greenlaw et al. 2018).

Given short time series, the effects of QE on GDP and inflation were initially studied using either two-step approaches, in which shocks to long-term interest rates estimated with event studies are inputted into structural or VAR models (Chung et al. 2012, Kapetanios et al. 2012, Baumeister and Benati 2013, Engen et al. 2015, Churm et al. 2018, Liu et al. 2019), or dynamic stochastic general equilibrium (DSGE) models (Chen et al. 2012, Gertler and Karadi 2013, Falagiarda 2014, Andrade et al. 2016, Sahuc 2016, Hohberger et al. 2019). The former approach points to moderately positive impact on economic activity and inflation – unemployment in the US was about 1.5 pp lower and inflation 0.7-1 pp higher thanks to QE (Chung et al. 2012, Baumeister and Benati 2013, Engen et al. 2015). However, asset purchases are assumed to affect economic activity only via long-term rates, whose response to QE is estimated outside of the model, and the model is estimated using only the pre-crisis data. At the same time, the effects of asset purchases obtained from DSGE models range from small (0.1-0.3% rise in GDP following sizeable QE programmes; Chen et al. 2012, Sahuc 2016, Hohberger et al. 2019) to sizeable (1% rise in GDP following US QE2 alone; Gertler and Karadi 2013) depending on the mechanism via which QE affects long-term interest rates and the method of model estimation/calibration.

As time series got longer, the attention of the literature turned to VAR models with QE shocks identified inside the model (Schenkelberg and Watzka 2013, Garcia Pascual and Wieladek 2016, Haldane et al. 2016, Weale and Wieladek 2016, Hesse et al. 2018, Hayashi and Koeda 2019, Kim et al. 2020, Breitenlechner et al. 2021a). Kim et al. (2020) find very large impact of QE on economic activity in the US (QE2 raising industrial production by 2%) using high-frequency identification. Estimates obtained with sign restrictions are more moderate (QE2 raises GDP by about 0.5%), with the results for the UK very similar to those for the US (Weale and Wieladek 2016, Hesse et al. 2018)[3]. Estimates for the euro area and Japan using analogous methods are about twice as small (Garcia Pascual and Wieladek 2016, Haldane et al. 2016). The impact on the price level is of a very similar magnitude to the impact on GDP. There is also some evidence that the effects of QE decline over the following rounds of asset purchases and/or with improving financial conditions (Haldane et al. 2016, Hesse et al. 2018).

However, in all these studies QE shocks are identified by assuming that they lower bond yields and raise stock prices. These studies are also estimated on small samples of monthly

[3] The baseline estimates of Weale and Wieladek (2016) for the US are much larger; they are however obtained taking into account only close-ended Treasury purchases, which artificially inflates the results. When MBS purchases and open-ended QE3 are also included in the measure of QE, the estimates decline substantially and are similar to the ones of Hesse et al. (2018).

data with 5-6 variables and few lags, which makes them prone to omitted variable bias. When shocks are identified with Cholesky decomposition, estimated effects on GDP, inflation, bond yields and stock prices are smaller or even neutral (Garcia Pascual and Wieladek 2016, Haldane et al. 2016, Weale and Wieladek 2016). Schenkelberg and Watzka (2013) identify QE shocks in Japan using sign restrictions, but do not restrict responses of long-term interest rates, obtaining negative impact of QE on industrial production.

Virtually all of the above-mentioned studies lump all the QE announcements together and do not investigate whether purchases of different assets have varying financial and macroeconomic effects. The rare exceptions are Gertler and Karadi (2013) and Sahuc (2016) who within their DSGE frameworks show that purchases of private assets are more effective than purchases of government bonds. In a VAR study, only Matsuki et al. (2015) distinguish between different asset classes when investigating QE in Japan[4]. Having said that, numerous other studies look at the impact of either MBS, corporate bond, covered bond or ETF purchases, especially on financial markets, but do not compare these effects directly with those of other forms of QE (e.g. Hancock and Passmore 2011, Stroebel and Taylor 2012, Szczerbowicz 2015, Barbon and Gianinazzi 2019, Grosse-Rueschkamp et al. 2019, Bartocci et al. 2020, Di Maggio et al. 2020, Todorov 2020, Arce et al. 2021, Charoenwong et al. 2021, De Santis and Zaghini 2021).

In contrast, QE transmission channels are thoroughly studied. Gagnon et al. (2011) and Joyce et al. (2011) argue that the effect on bond yields is mostly due to the price channel, while Christensen and Rudebusch (2012) and Bauer and Rudebusch (2014) indicate that signalling channel dominates. A series of studies documents that supply and maturity structure of government debt affect prices of individual government bond series (Meaning and Zhu 2011, D'Amico et al. 2012, Joyce and Tong 2012, D'Amico and King 2013, McLaren et al. 2014, Fukunaga et al. 2015) or the yield curve as a whole (Hamilton and Wu 2012, Li and Wei 2013, Greenwood and Vayanos 2014, Eser et al. 2019, Blattner and Joyce 2020), further supporting the presence of the price channel. Furthermore, numerous studies show that QE affects other assets, especially corporate bonds, but often also stock prices and exchange rates, documenting the functioning of the portfolio rebalancing channel (Gagnon et al. 2011, Joyce et al. 2011, Krishnamurthy and Vissing-Jorgensen 2011, Lam 2011, Rosa 2012, Ueda 2012, Rogers et al. 2014, Altavilla et al. 2015, Neely 2015). Finally, Joyce and Spaltro (2014), Bowman et al. (2015a), Rodnyansky and Darmouni (2017) and Paludkiewicz (2021) show that the bank lending channel is also present, as QE leads to an increase in credit supply, though the size of this effect is rather small.

However, the vast majority of the above-mentioned papers stops at investigating the transmission of QE to financial markets and does not discuss the transmission of QE to

[4] They find that purchases of long-term government bonds and ETFs have a positive impact on output, while purchases of short-term government bonds and REITs are ineffective. However, their model is estimated on daily data and the impact of QE on output is estimated to last only for several days.

macroeconomic aggregates. This also includes VAR studies, some of which investigate transmission channels (Garcia Pascual and Wieladek 2016, Weale and Wieladek 2016, Kim et al. 2020), but do not discuss their relative importance for GDP and inflation.

Alongside QE, I also study Operation Twist, i.e. purchases of long-term government bonds financed by the sale of short-term government securities. Most studies of QE include Operation Twist-related announcements in the measures of QE, not distinguishing between the two. This makes some sense since from the theoretical viewpoint, the effects of Operation Twist should not vary much from the effects of QE as at the ZLB, purchases financed by issuing reserves are largely equivalent to purchases financed with short-term securities (e.g. Ehlers 2012). Thus, the functioning of the price, signalling and portfolio rebalancing channels should be broadly similar. However, as reserves do not increase, the bank lending channel could be impaired. Studies that look at Operation Twist separately are rare – Swanson (2011) investigates the original Operation Twist conducted in 1960s, while Ehlers (2012) looks at the modern Maturity Extension Program. Both find that Operation Twist is effective in depressing government bond yields.

3. Empirical framework and data

3.1 BVAR with SSVS prior

The following VAR model with exogenous variables is estimated on quarterly data:

$$Y_t = \delta_0 + \sum_{k=1}^{4} A_k Y_{t-k} + \delta_1 t + \delta_2 post\_crisis_t + \delta_3 post\_crisis_t * t + \varepsilon_t,\ \varepsilon_t \sim N(0, \Sigma) \quad (1)$$

where Y_t is a vector of M endogenous variables at time t, $post\_crisis_t$ is a dummy variable equal to 1 from the outbreak of the global financial crisis in 2008Q3 onwards, and ε_t is a vector of residuals, which is assumed to be normally distributed with variance-covariance matrix Σ. A_k are matrices of coefficients associated with lag k, δ_0 is a vector of constants and δ_1 to δ_3 are vectors of parameters associated with the piecewise linear time trend.

The above model is estimated using Bayesian methods. Literature has demonstrated that using prior information improves forecasting properties of a model, especially when the number of parameters to be estimated is large relative to the time series dimension (e.g. Litterman 1986). The most popular prior is the Minnesota (Litterman) prior, which models time series as random walks (though the prior on AR(1) coefficient can be changed) and sets tighter priors (shrinks parameters more towards zero) on more distant lags and lags of other variables compared to own lags. With sufficiently tight priors, even very large models can be successfully estimated (Bańbura et al. 2010).

However, in structural analysis there is risk that tight priors could dominate the information coming from the data. Moreover, the Minnesota prior assumes that time series are generated by a certain stochastic process and requires a researcher to set prior hyperparameters (prior

tightness) in a somewhat arbitrary fashion. For these reasons, the previous literature on macroeconomic effects of quantitative easing has mostly used non-informative priors (Weale and Wieladek 2016, Hesse et al. 2018) that effectively give little gain from Bayesian relative to classical methods. Thus, given small samples models had to be kept small (usually 5-6 variables and 2 lags), which increased the risk of omitted variable bias and precluded more detailed analysis of transmission channels.

To deal with the above-mentioned issues, I use stochastic search variable selection (SSVS) prior (George et al. 2008). This procedure requires minimal input from the researcher, is data-based and provides sufficient shrinkage so that a mid-sized model (15 variables with 4 lags with a little over 200 observations in the baseline specification) can be estimated successfully[5]. The idea behind SSVS is simple – if the initial parameter estimate is close to 0, the prior is tight, effectively restricting the parameter to 0; if the initial estimate is far from zero, prior is non-informative, and thus the parameter is estimated freely.

Hence, SSVS is a hierarchical prior such that:

$$\alpha_i|\gamma_i \sim (1-\gamma_i)N(0,\tau_1) + \gamma_i N(0,\tau_2) \tag{2}$$

$$\gamma_i \sim Bernoulli(\pi) \tag{3}$$

where α_i is an element of a vector of model parameters $\alpha = [\delta_0^1, \dots, \delta_0^M, A_1^{1,1}, \dots, A_4^{M,M}, \delta_1^1, \dots, \delta_2^1, \dots, \delta_3^1, \dots]$.

3 hyperparameters (τ_1, τ_2 and π) need to be set. τ_1 takes a low value, effectively restricting the parameter estimate to 0. τ_2 is high, letting the parameter be estimated freely. π is the parameter of the Bernoulli density which sets how often the parameter is allowed to be estimated freely. τ_1 is set to 0.1 times the standard deviation of the ordinary least squares (OLS) parameter estimate, τ_2 to 10 times that standard deviation, and π is set to the non-informative 0.5.

A very similar SSVS prior is set for the variance-covariance matrix Σ. An upper triangular matrix Ψ satisfying $\Sigma^{-1} = \Psi'\Psi$ is considered. The prior for the upper diagonal elements of matrix Ψ grouped in the vector η is analogous to the prior for parameters α:

$$\eta_{ij}|\omega_{ij} \sim \big(1-\omega_{ij}\big)N(0,\kappa_1) + \omega_{ij}N(0,\kappa_2) \tag{4}$$

$$\omega_{ij} \sim Bernoulli(q) \tag{5}$$

where η_{ij} is the element of vector η corresponding to i-th row and j-th column of matrix Ψ.

Diagonal elements of matrix Ψ grouped in the vector ψ take the Gamma prior:

$$\psi_{ii}^2 \sim Gamma(\beta_1, \beta_2) \tag{6}$$

[5] Koop (2013) shows that SSVS fares relatively well in a forecasting exercise for a model and a sample of a similar size.

Hyperparameters κ_1, κ_2 and q are set to 0.1, 6 and 0.5, respectively. Gamma density hyperparameters β_1 and β_2 are both set to the default non-informative value of 0.01.

The joint posterior of a model with the SSVS prior is not of a known form, thus Gibbs sampling is required. For conditional posteriors and the Gibbs sampling setup, see George et al. (2008) or Korobilis (2008). The results are obtained using Matlab codes provided by Koop and Korobilis (2010) and are based on 2000 iterations of the Gibbs sampler with 1000 burn-in. Given the size of the model and its numerous extensions, a significantly larger number of iterations would be very time-consuming. However, when the baseline model is estimated with 60000 iterations (and 10000 burn-in), the differences in results are negligible, suggesting that convergence is achieved quickly (results not reported).

Structural shocks are identified using Cholesky decomposition, i.e. a given variable is assumed to contemporaneously affect only variables ordered afterwards (the order of variables is presented in the data subsection). This is the most agnostic way of identifying shocks - there are no assumptions about the signs of responses, unlike with sign restrictions when bond yields are usually assumed to fall and stock prices to rise following a positive QE shock (Weale and Wieladek 2016, Hesse et al. 2018). The recently popular high-frequency identification of Gertler and Karadi (2015) also implicitly assumes the signs of financial market reaction to QE shocks. Moreover, sign restrictions are difficult to implement in larger models, while high-frequency identification effectively prohibits from distinguishing among various assets (MBS vs Treasuries) and instruments (Operation Twist vs QE). Nevertheless, a simplified version of high-frequency identification is used in one of the robustness checks (subsection 6.5).

3.2 Data

The model is estimated on the data for the United States. The US has a relatively long history of QE (second only to Japan), which exclusively includes a period of "balance sheet normalisation", i.e. QE unwinding. Moreover, the construction of the US QE has been relatively simple, i.e. it consisted of 2 assets (MBS and Treasuries) as opposed to as many as 4 in Japan and the euro area, which simplifies the analysis. On top of that, QE has clearly been considered a primary unconventional monetary policy tool in the US (though other measures were also used in the initial phase of the crisis), while in other jurisdictions – especially the euro area – credit easing policies often played an equally important role and would have to be controlled for. Finally, US has the best macroeconomic and financial data coverage, allowing the researcher to estimate a relatively large model on a relatively long sample.

The model is estimated on quarterly data, covering the period from 1966Q1 to 2019Q4. Quarterly data is chosen as the key variable – GDP – is available in official sources only on quarterly basis. While this variable could be interpolated, monthly data would likely provide little added value – the sample would have to be shortened due to the lack of availability of

monthly data in earlier periods and the lag length would have to be increased from 4 to 12, losing extra degrees of freedom. Finally, monthly data tends to be more noisy. Nevertheless, the model is estimated on monthly data in one of the robustness checks (subsection 6.6).

The sample extends well beyond the QE period of 2008-2014. This provides additional degrees of freedom to estimate parameters unrelated to QE with more precision. Moreover, the effects of QE can be compared to those of conventional monetary policy. To account for potential structural shifts around the outbreak of the global financial crisis, a piecewise linear time trend is added to the model, with the structural break in 2008Q3. At the same time, the sample ends before the outbreak of the coronavirus pandemic – while the Fed's reaction to the pandemic provides another great natural experiment for the study of QE effects, more time needs to pass before the macroeconomic reaction to this episode can be reliably studied within the VAR framework.

In a standard fashion for quarterly data, the lag length is set to 4. Robustness of the results to this choice is checked in subsection 6.3.

15 variables are included in the baseline specification. These variables can be divided into 4 categories:

- 3 key macroeconomic variables: GDP, PCE deflator, unemployment.
- 4 monetary policy variables: Fed Funds rate, Treasury purchases, MBS purchases, Operation Twist.
- 5 transmission channel variables: 10Y Treasury yield, NEER, S&P 500, bank credit, stock market volatility.
- 3 control variables: import prices, housing starts, primary surplus.

Detailed information on the variable construction is provided in Table 1.

Price level is measured with PCE deflator, the Fed's preferred measure of inflation. Conclusions do not change if other measures of inflation (CPI, core CPI, core PCE, GDP deflator) are used instead (results not reported for brevity). Conventional monetary policy is measured with the Fed funds rate. If, similar to Gertler and Karadi (2015), 1-year Treasury yield is used in order to account for forward guidance, the results do not change significantly (not reported for brevity).

Measures of unconventional monetary policy are forward-looking and relative to the stock of purchased assets. Q1, Q2 and Operation Twist were close-ended, i.e. the Fed announced the expected total size of these programmes. As expected sizes of purchases are more likely to drive financial market prices than actual purchases, these announced sizes of purchases are included in the measures of QE and Operation Twist. In contrast, QE3 and balance sheet normalisation were open-ended, i.e. the Fed announced only a monthly scale of purchases (or balance sheet reduction) without an end date or expected total. Therefore, similar to Hesse et al. (2018) and Kim et al. (2020), expectations about the future size of the Fed balance

sheet (SOMA portfolio) from the NY Fed Survey of Primary Dealers are used as a measure of Treasury and MBS purchases from the beginning of QE3 onwards[6], with the exception of Fed announcements that ended QE3 and balance sheet normalisation.

Table 1. Variables in the baseline specification

Variable	Construction	Source
Unemployment	U-3 unemployment rate, per cent	FRED
GDP	log real GDP	FRED
Import prices	log imports of goods and services deflator	FRED
PCE deflator	log PCE chain-type price index	FRED
Bank credit	Bank credit to GDP, per cent	FRED, own calculations
Housing starts	New privately-owned housing units started, millions of units	FRED
Primary surplus	Government net lending/borrowing + government interest payments, corrected for BP compensation payment, to GDP, per cent	FRED, own calculations
Stock market volatility	Mean daily min-max spread of S&P 500 index, per cent	Stooq.pl, own calculations
Fed Funds rate	Effective Federal Funds rate, per cent	FRED
MBS purchases	Announced/expected cumulative Fed purchases of MBS and agency debt securities to agency-backed mortgage pools, per cent	Fed press releases, Survey of Primary Dealers, FRED, own calculations
Treasury purchases	Announced/expected Fed cumulative Treasury purchases to public debt, per cent	Fed press releases, Survey of Primary Dealers, FRED, own calculations
Operation Twist	Announced cumulative size of Operation Twist to public debt, per cent	Fed press releases, FRED, own calculations
10Y Treasury yield	10Y Treasury constant maturity rate, per cent	FRED
NEER	log NEER, narrow index	BIS
S&P 500	log S&P 500 index	Bloomberg

As a novelty relative to the previous literature, unconventional monetary policy measures are scaled relative to the proxy of the total stock of purchased assets, i.e. Treasury purchases and Operation Twist are scaled to public debt, while MBS purchases are scaled to agency-backed mortgage pools[7]. From a theoretical perspective, QE can affect prices of assets by

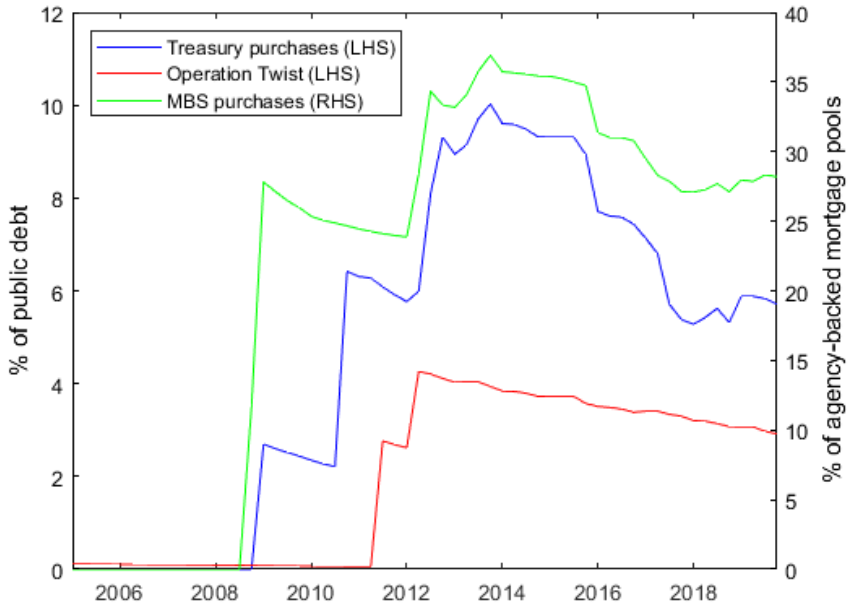
[6] Questions regarding asset purchases varied from survey to survey. If several questions regarding purchases and SOMA portfolio were asked, the one providing the most detailed answers is used. If expected SOMA portfolio was given over several points in time in the future, the timeframe with highest/lowest expected amount (during QE3/balance sheet normalisation) is picked. Answers are rescaled taking into account only SOMA portfolio expansion since the beginning of QE, i.e. discarding SOMA holdings from before December 2008, and differences in the Fed announcements regarding QE1 and QE2 and the actual SOMA portfolio expansion. If a range was provided as an answer, midpoint of that range is used. The last survey from a given quarter is used, unless no questions regarding SOMA portfolio were asked – then the previous survey is used, if such questions were asked; if not, then observations from the previous quarter are used.

[7] Agency-backed mortgage pools are calculated as a cumulative sum of flows rather than directly using the level statistic in order to correct for large jumps in the level statistic stemming i.a. from changes in accounting rules.

changing their relative supply (Harrison 2012). Therefore, a measure of QE scaled by the supply of assets should capture QE effects better than unscaled measures or measures scaled to GDP that have been previously used in the literature.

Unconventional policy measures are presented in Figure 1.

Figure 1. Unconventional monetary policy measures



As mentioned earlier, QE and Operation Twist were not the only unconventional monetary programmes conducted by the Fed during and after the global financial crisis. Among others, the Fed also purchased a sizable amount of commercial paper as a part of its Commercial Paper Funding Facility (CPFF). The effects of this programme are investigated in one of the model extensions (subsection 5.5).

The transmission of QE to the real economy is captured with 3 key financial variables: 10-year Treasury bond yield, stock prices and effective exchange rate, as well as bank credit and stock market volatility. While the inclusion of these variables does not always allow to clearly distinguish across transmission channels discussed in the literature (as e.g. the response of 10-year yield reflects both the price and signalling channels), the response of key financial variables to QE is interesting on its own. The bank lending channel is investigated via the inclusion of the bank credit variable, which is a novelty relative to other studies of QE that use VAR models. In addition to the channels most often mentioned in the literature, I also test the hypothesis that QE can stabilise market conditions during periods of market stress, which is proxied by the stock market volatility variable[8].

[8] The stock market volatility is computed as mean daily min-max spread of the S&P500 index as standard measures of volatility or uncertainty (such as VIX or Economic Policy Uncertainty index) are not available over a large part of the sample.

Numerous other variables could be included in the model to study the transmission channels of QE in more detail – Treasury yields of different maturities, corporate bond yields, mortgage rates or total mortgage stock. Due to high collinearity with variables already present in the model, these variables are excluded from the baseline specification, but are studied in the extension section where they are added one-by-one, replacing the collinear variable. The 10-year yield could also be decomposed into expected short-term rate and term premium in order to distinguish between signalling and price channels, which is also done in the extension section (subsection 5.2).

Import prices, housing starts and general government primary surplus are included as control variables. Import prices have a significant impact on inflation; as the US economy plays a crucial role in the global economy, affecting i.a. commodity prices, import prices are treated as an endogenous rather than exogenous variable[9]. Housing starts are included as the housing sector played a key role around the global financial crisis. It is also interesting to check whether MBS purchases have a stronger impact on the housing sector than Treasury purchases. The choice of the housing sector proxy (alternatively housing permits, new home sales, house prices) has little impact on the results (not reported for brevity). Finally, fiscal policy, proxied by primary surplus, is also included as fiscal expansion and consolidation played an important role during and after the financial crisis and may potentially influence the estimates of QE effects.

Numerous other control variables have been considered, but ultimately have not been included in the baseline specification as they are found to provide little additional information, i.e. it turns out they have virtually no impact on GDP or inflation. These are i.a. oil, global food and global energy prices, consumer inflation expectations, corporate profits, GDP, inflation and long-term interest rates abroad. Nevertheless, a large-sized model that includes i.a. those variables is considered in one of the robustness checks (subsection 6.2).

The order of variables in Cholesky decomposition is presented in Table 1. This is largely a standard ordering where economic activity goes first, inflation second, followed by other slow-moving variables, monetary policy variables and financial, fast-moving variables. Unemployment is ordered first, before GDP, as employment is a factor of production contributing directly to GDP, which tends to react to demand shocks with a lag. Import prices follow economic activity as they react to global – and thus US – demand conditions, but precede inflation, as they can be transmitted to domestic prices relatively quickly. Bank credit is ordered fifth as it is influenced by overall macroeconomic conditions, but before housing starts that may depend on the availability of mortgage credit. At the same time, housing starts go after economic activity as residential investment enters GDP only when houses are sold. Fiscal policy is the last of the slow-moving variables as it can be contemporaneously influenced by all the preceding variables.

[9] Block exogeneity Wald test confirms this hypothesis – the null hypothesis which states that import prices are exogenous is rejected at any conventional significance level.

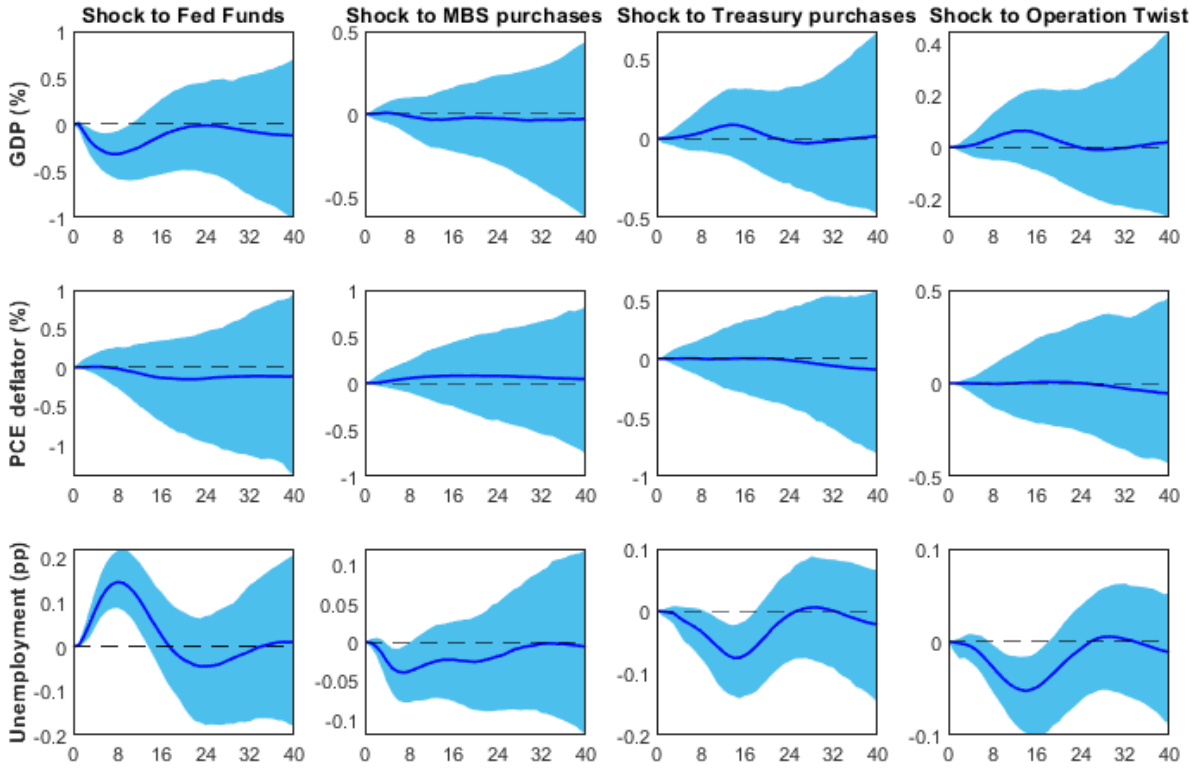
Among monetary policy variables, the order reflects the timing of announcements (MBS purchases were announced before Treasury purchases etc.). Treasury yield goes first after monetary policy variables, followed by the exchange rate that is directly influenced by expected future short-term rates embodied in bond yields. Stock prices are last, as they can be affected both by expected short-term rates and the exchange rate. Importantly, stock market volatility is ordered before monetary policy variables as monetary policy tends to react quickly to market disruptions.

4. Baseline results

4.1 Macroeconomic effects

The responses of GDP, prices and unemployment to one standard deviation QE, Operation Twist and conventional monetary policy shocks are presented in Figure 2.

Figure 2. Response of main macroeconomic aggregates to one standard deviation monetary policy shocks: baseline specification



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. One standard deviation of shocks: 0.69 pp for fed funds rate, 0.88% of total mortgages for MBS purchases, 0.29% of public debt for Treasury purchases and 0.09% of public debt for Operation Twist. On horizontal axis: quarters since the shock.

An unexpected increase in MBS and Treasury purchases has a statistically significant negative effect on unemployment, and so does a positive shock to Operation Twist. Quantitatively, if entirely unexpected, MBS purchases announced as a part of QE1 (1.45 trn USD) would decrease unemployment by 1.25 pp after 7 quarters, while Treasury purchases

announced as a part of the same programme (300 bln USD) would reduce unemployment by 0.7 pp after 14 quarters. Dollar for dollar, Treasury purchases are thus estimated to have longer-lasting and almost three times as strong effects as MBS purchases. Interestingly, Operation Twist is estimated to be even more effective, with the first round of the Maturity Extension Program (MEP1) alone, worth 400 bln USD, reducing unemployment by as much as 1.5 pp after 14 quarters.

Relative to conventional monetary policy, Treasury purchases take longer to be transmitted into the economy (14 vs 8 quarters for unemployment). At the same time, they are powerful – to reduce unemployment by as much as QE1 Treasury purchases, Fed funds rate would have had to be cut by 3.4 pp. Having said that, the effects of QE are less precisely estimated than those of conventional monetary policy, which is however understandable given shorter time series.

Despite the size of impact on unemployment, QE and Operation Twist have no statistically significant effects on GDP. Nevertheless, median posterior estimates for Treasury purchases and Operation Twist remain positive. There are two potential explanations why these effects are not statistically significant. Firstly, the model might not capture well the post-crisis slowdown in potential growth, even though the structural break in linear trend is included in the model specification. Secondly, unconventional monetary policy may have contributed to the slowdown in labour productivity growth by increasing the prevalence of "zombie" firms (Banerjee and Hofmann 2018, McGowan et al. 2018). If the latter were true, conventional monetary policy should have a similar effect, but impulse response functions do not support this view. Therefore, the former hypothesis seems more likely.

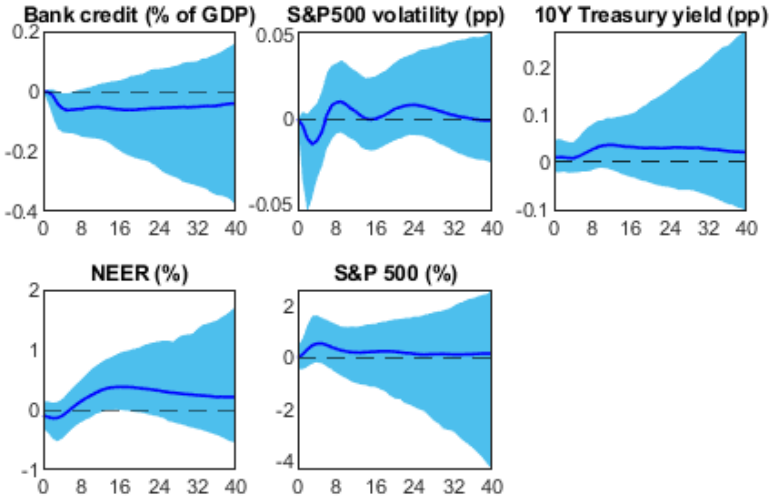
If median estimates were to be trusted, a shock to Treasury purchases equal to 1% of public debt increases GDP by 0.3% after 14 quarters. This result is roughly in line with the rest of the literature – e.g. Hesse et al. (2018) find that a QE shock equal to 1% of GDP raises GDP by about 0.2%, though the transmission is estimated to be somewhat faster.

Finally, both conventional and unconventional monetary policy are estimated to have no impact on prices. While in contrast to the most of the monetary VAR literature, this result lines up well with the literature on the Phillips curve flattening, i.e. the weakening relationship between economic activity and inflation (i.a. Kuttner and Robinson 2010, Blanchard 2016, Leduc and Wilson 2017, Gali and Gambetti 2019).

4.2 Transmission channels

The impulse responses of the transmission channel variables to QE and Operation Twist shocks are presented in Figures 3-5.

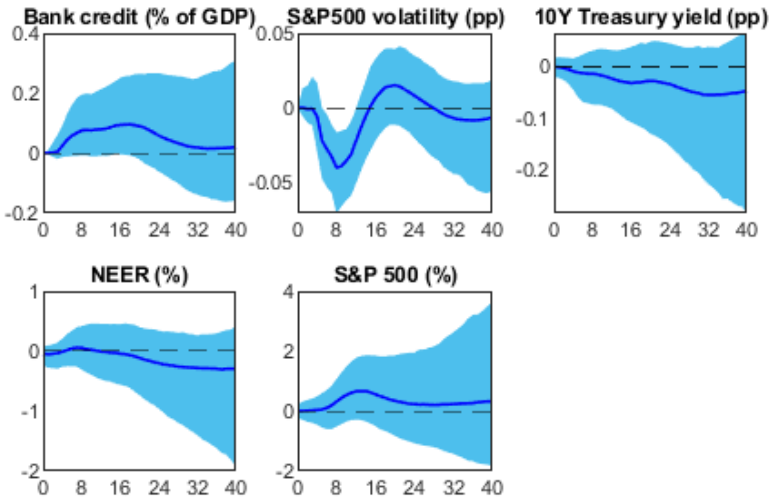
Figure 3. Response of transmission channel variables to a one standard deviation shock in MBS purchases: baseline specification



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets.
One standard deviation of the shock is equal to 0.88% of total mortgages.
On horizontal axis: quarters since the shock.

The responses to MBS purchases (Figure 3) are somewhat surprising. Firstly, MBS purchases reduce bank credit. This could be, however, due to an increase in MBS issuance – when mortgages are securitised, bank credit decreases. This hypothesis is investigated in subsection 5.3. At the same time, the exchange rate appreciates. The effects on Treasury yields and the stock market are not statistically significant, though MBS purchases seem to decrease market volatility and raise stock prices, as one would expect, but increase bond yields. The effects on mortgage rates, which should theoretically be more closely related to MBS purchases, are studied in subsection 5.3.

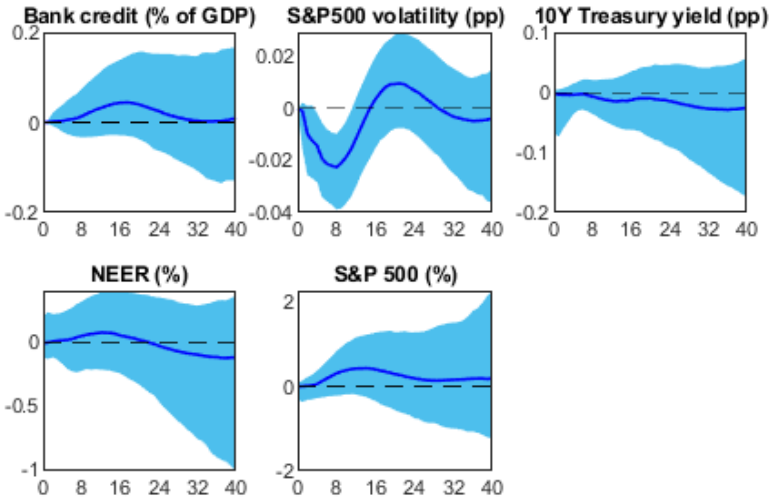
Figure 4. Response of transmission channel variables to a one standard deviation shock in Treasury purchases: baseline specification



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets.
One standard deviation of the shock is equal to 0.29% of public debt.
On horizontal axis: quarters since the shock.

The responses to Treasury purchases (Figure 4) are much better aligned with economic intuition. Treasury purchases increase bank credit, suggesting that the bank lending channel is in operation, and decrease stock market volatility. The uncertainty channel of QE, while not underlined in the theoretical literature, has been found to be important in some of the previous VAR studies (Weale and Wieladek 2016). The effects on other variables are not statistically significant, but median estimates are in line with the intuition – bond yields decrease, exchange rate depreciates (though with a large lag) and stock prices increase.

Figure 5. Response of transmission channel variables to a one standard deviation shock in Operation Twist: baseline specification



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets.
One standard deviation of the shock is equal to 0.09% of public debt.
On horizontal axis: quarters since the shock.

The responses to Operation Twist (Figure 5) are very similar to those of Treasury purchases, but somewhat less precisely estimated, further confirming that Operation Twist can be regarded as a close substitute of outright Treasury purchases.

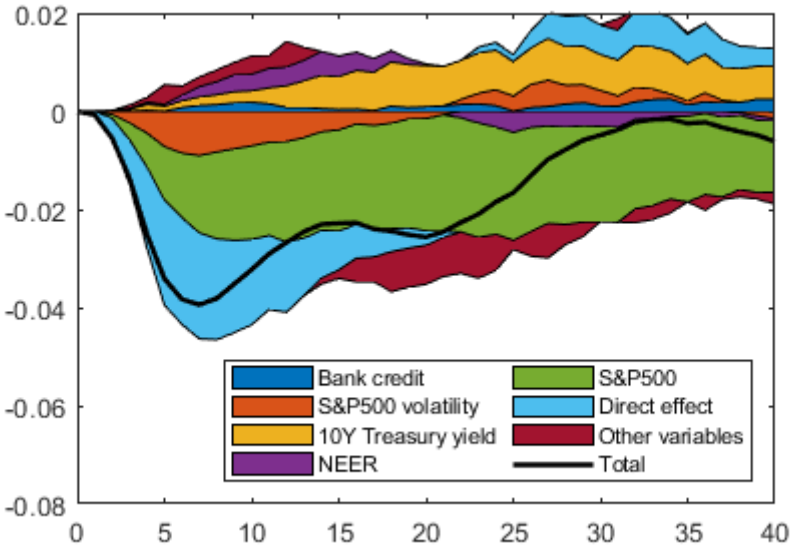
Statistical significance does not always translate into economic relevance, however. Thus, to further study transmission channels of QE and Operation Twist, the decomposition of the impulse responses per the variable of transmission is conducted. The contribution of a given variable to an impulse response is calculated as a difference between the baseline impulse response and the impulse response obtained when the direct impact of monetary policy on a given variable is switched off[10]. Similar approaches have been used in the literature to conduct counterfactual analysis in VAR models (e.g. Uribe and Yue 2006, Akinci 2013, Carriere-Swallow and Cespedes 2013, Caballero et al. 2019, Vicondoa 2019, Degasperi et al. 2021). Importantly, I switch off only the direct impact of monetary policy on a given variable,

[10] Coefficients on estimated lagged monetary policy variables and the covariance with monetary policy shocks in the Cholesky-decomposed variance-covariance matrix are set to zero for a given equation.

which can therefore be indirectly affected by monetary policy shocks via other variables of the model, similar to Uribe and Yue (2006), Akinci (2013) and Caballero et al. (2019)[11].

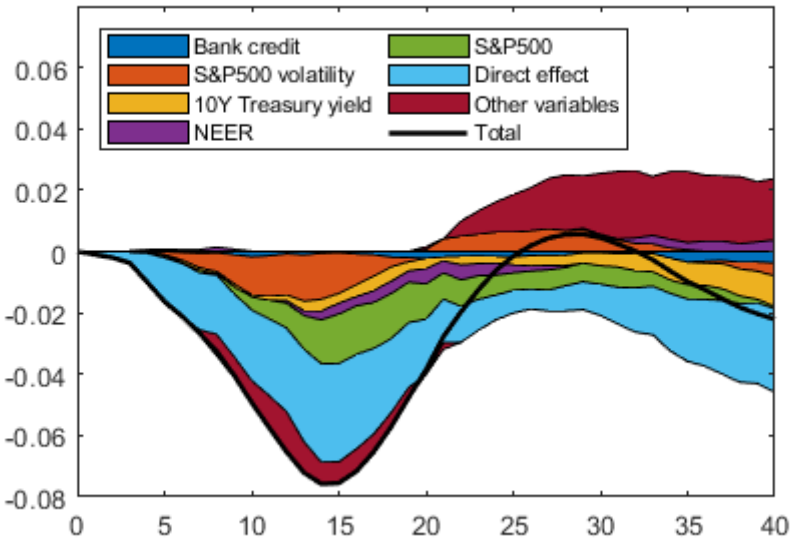
The decomposition of responses of unemployment to QE and Operation Twist shocks is presented in Figures 6-8.

Figure 6. Response of unemployment to a one standard deviation shock in MBS purchases: decomposition per variable of transmission (pp)



One standard deviation of the shock is equal to 0.88% of total mortgages. On horizontal axis: quarters since the shock.

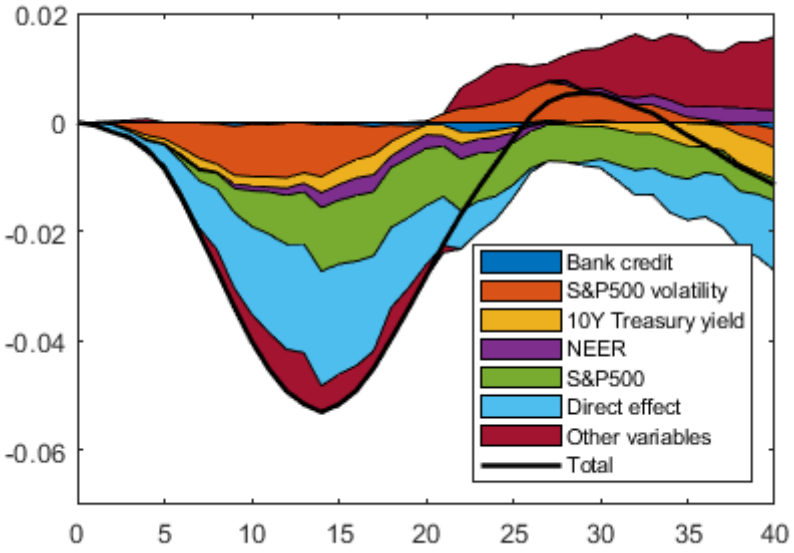
Figure 7. Response of unemployment to a one standard deviation shock in Treasury purchases: decomposition per variable of transmission (pp)



One standard deviation of the shock is equal to 0.29% of public debt. On horizontal axis: quarters since the shock.

[11] An alternative approach to conduct counterfactual analysis would be to use structural scenario analysis, under which chosen VAR shocks offset the impact of a given shock on a given variable (Antolin-Diaz et al. 2021). However, in such a case the response of the given variable to the given shock would be set to zero, and thus both direct and indirect channels of impact would be switched off.

Figure 8. Response of unemployment to a one standard deviation shock in Operation Twist: decomposition per variable of transmission (pp)



One standard deviation of the shock is equal to 0.09% of public debt. On horizontal axis: quarters since the shock.

For all of the unconventional monetary policy shocks, the most important channels of transmission are stock market volatility and stock market prices, while Treasury yields play little role. Prices of risky assets thus matter much more than prices of "risk-free" assets. This contradicts the assumptions made in both the theoretical and empirical literature on QE, which focuses on the impact of QE on government bond yields. Mapping these results to the transmission channels discussed in the literature, price channel that affects Treasury yields is found to be of little importance, while portfolio rebalancing and uncertainty channels matter much more[12].

The exchange rate also has little importance for the transmission of QE, which one would expect for a large and relatively closed economy such as the US. The bank lending channel, even though Treasury purchases have a statistically significant impact on bank credit, plays a negligible role. Finally, Treasury purchases and Operation Twist have a large direct impact on unemployment, suggesting that some important transmission channels are not accounted for in the model.

5. Extensions

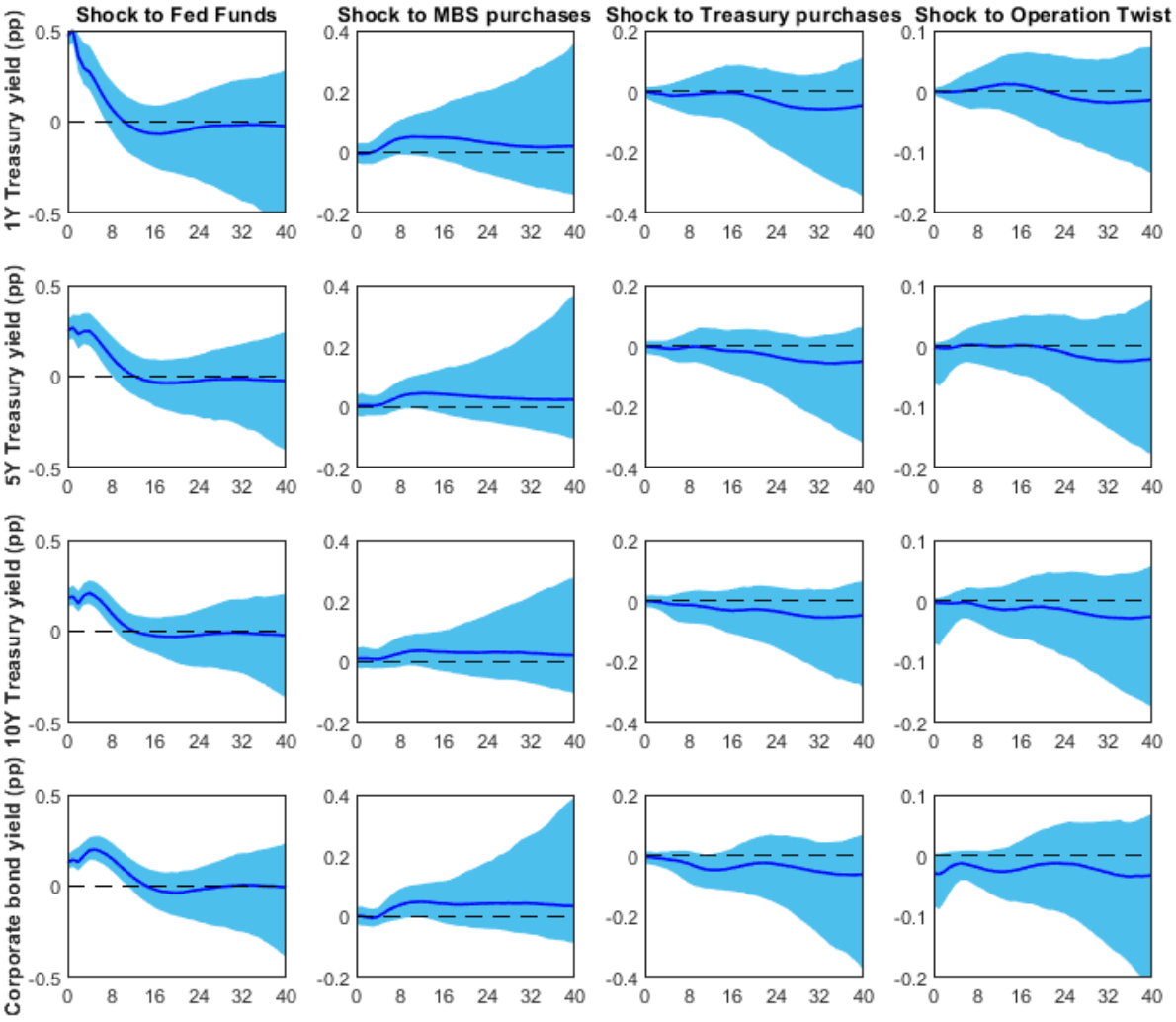
Several extensions of the baseline model, in which one or more variables are added or replaced, are considered.

[12] It is difficult to judge the importance of the signalling channel, which may potentially affect not only government bond yields, but also stock prices and the exchange rate.

5.1 Impact across the yield curve

As a first extension, the impact of QE and Operation Twist on shorter-term (1Y and 5Y) Treasury yields and Baa corporate bond yield is investigated[13]. Due to collinearity, this is done one-by-one, each variable replacing the 10Y Treasury yield in the baseline specification. The results are presented in Figure 9.

Figure 9. Response of Treasury yields and corporate bond yields to one standard deviation monetary policy shocks



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. One standard deviation of shocks: 0.69 pp for fed funds rate, 0.88% of total mortgages for MBS purchases, 0.29% of public debt for Treasury purchases and 0.09% of public debt for Operation Twist. On horizontal axis: quarters since the shock.

The impact of QE and Operation Twist on shorter-term Treasury yields and corporate bond yields is not statistically significant, same as in the case of 10Y Treasury yield. Median posterior estimates are very similar across the yield curve for QE and tend to increase with maturity for Operation Twist. This contrasts somewhat with the majority of the literature

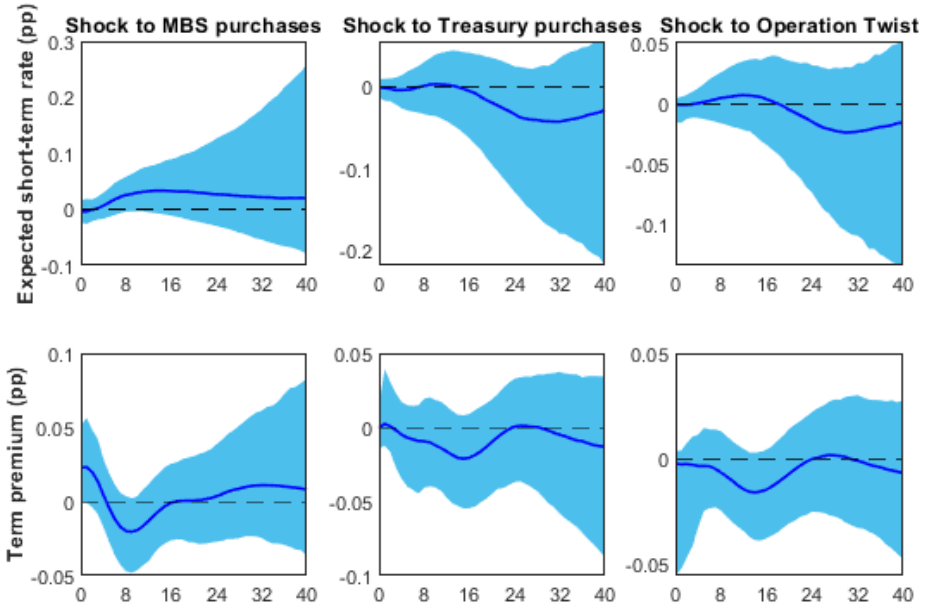
[13] The data comes from FRED (1Y Treasury constant maturity rate, 5Y Treasury constant maturity rate and Moody's seasoned Baa corporate bond yield series).

which finds that the effects of QE increase substantially with maturity (e.g. Gagnon et al. 2011). The median impact on corporate bond yields is similar to that on 10Y Treasury bonds. For conventional policy, the impact on bond yields decreases with maturity, as one would expect.

5.2 Price and signalling channels

As a further extension, the response of 10Y Treasury yields is disentangled between the price and signalling channels. In the literature, this is done either by looking at overnight index swap (OIS) rates as a proxy for expected future short-term rates (e.g. Joyce et al. 2011) or model-based decompositions between expected future short-term rates and the term premium (e.g. Gagnon et al. 2011, Christensen and Rudebusch 2012). I opt for the latter approach, utilising the decomposition of Adrian et al. (2013)[14]. The responses of expected future short-term rates and the term premium to unconventional monetary policy shocks are presented in Figure 10.

Figure 10. Response of expected short-term rates and term premium to one standard deviation unconventional monetary policy shocks



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. One standard deviation of shocks: 0.87% of total mortgages for MBS purchases, 0.29% of public debt for Treasury purchases and 0.09% of public debt for Operation Twist. On horizontal axis: quarters since the shock.

The responses of expected future short-term rates and term premium are statistically insignificant, similar to the responses of 10Y Treasury yield in the baseline specification. For Treasury purchases and Operation Twist, median estimates are larger for expected short-term rates (though with a large lag), suggesting that the signalling channel seems to play a

[14] The data comes from Bloomberg. Expected future short-term rates are ordered before term premium in the Cholesky decomposition.

more important role than the price channel. It should be noted that the response of expected short-term rates does not capture the whole effect of the signalling channel, as it may influence the real economy also via stock prices and the exchange rate. The opposite is true for the price channel, further supporting the view that the signalling channel is of more importance.

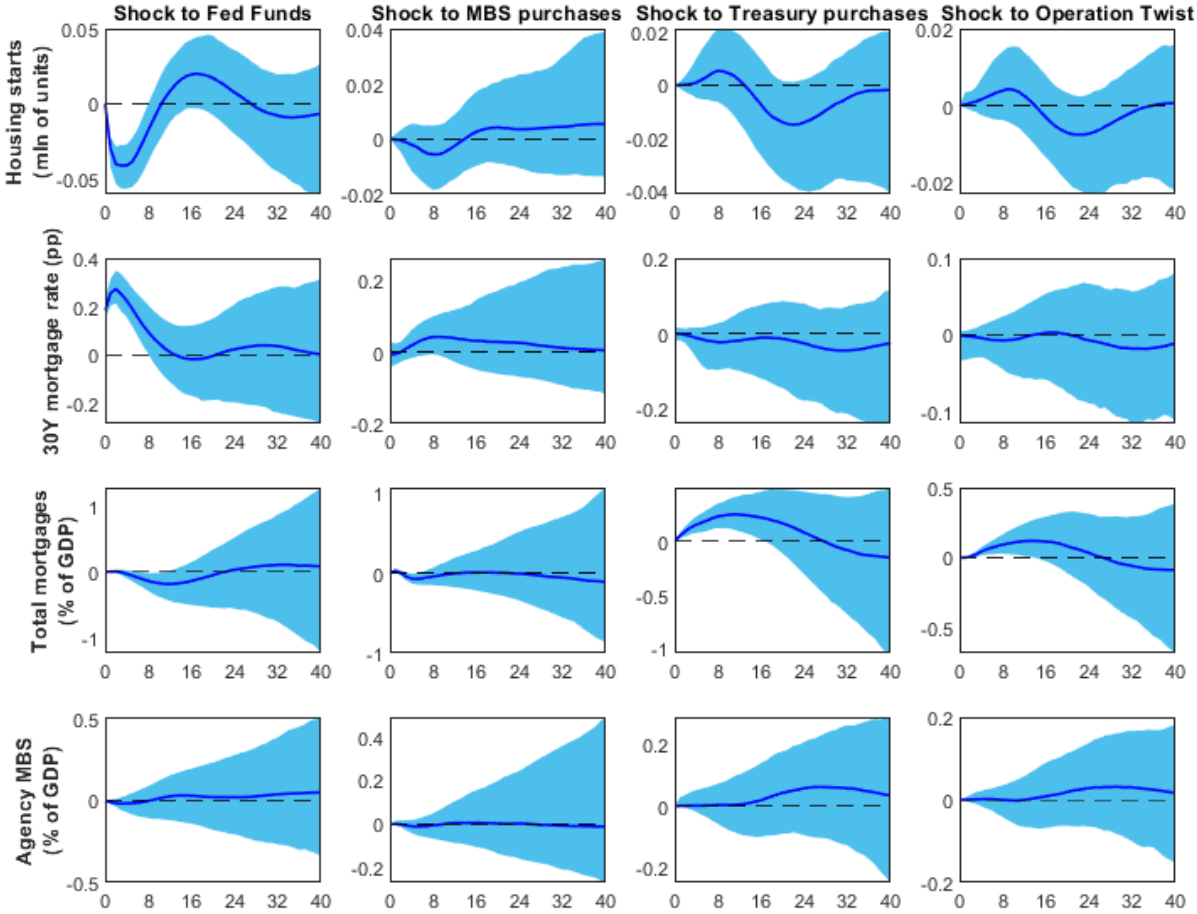
5.3 Housing market

In the baseline specification, MBS purchases are less effective than Treasury purchases. It can be argued, however, that the baseline specification omits important transmission channels of MBS purchases. MBS purchases may make securitisation more attractive, increasing the issuance of agency MBS, which may lower mortgage rates and improve access to mortgage loans, increasing mortgage origination and having a positive impact on the activity in the housing market. To investigate whether this is indeed the case, three additional versions of the model are estimated: with 30Y mortgage rate replacing 10Y Treasury yield and either total mortgage stock or agency-backed mortgage pools added to the specification[15]. The impulse responses of these variables, alongside housing starts from the baseline specification, to monetary policy shocks are presented in Figure 11.

MBS purchases are estimated to have no substantial effects on the housing market. There is no effect on MBS issuance, the response of housing starts is also statistically insignificant. If anything, mortgage rates increase and the mortgage stock decreases slightly, against expectations. In contrast, Treasury purchases and Operation Twist have a statistically significant positive impact on the mortgage stock, which however does not translate into an increase in housing starts. Nevertheless, there is no evidence that MBS purchases have a stronger effect on the housing sector than Treasury purchases; if anything, the opposite is true.

[15] 30Y mortgage rate is the 30Y fixed-rate mortgage average series from FRED. The sample for this specification is shorter, starting in 1971Q2. Total mortgage stock is the cumulated sum of the All sectors; Total mortgages; Asset, Flow series from FRED, relative to GDP. Similarly, agency-backed mortgage pools is the cumulated sum of the Agency-and GSE-backed mortgage pools; Total mortgages; Asset, Flow series from FRED, relative to GDP. This variable is supposed to capture the total stock of agency MBS. Due to the presence of large structural breaks in the level series as a result of i.a. regulatory changes, the cumulated flow series are used instead of the level series. Total mortgage stock and agency-backed mortgage pools are ordered 6th in the Cholesky decomposition, i.e. after bank credit and before housing starts.

Figure 11. Response of housing market variables to one standard deviation monetary policy shocks



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. One standard deviation of shocks: 0.69 pp for fed funds rate, 0.88% of total mortgages for MBS purchases, 0.29% of public debt for Treasury purchases and 0.09% of public debt for Operation Twist. On horizontal axis: quarters since the shock.

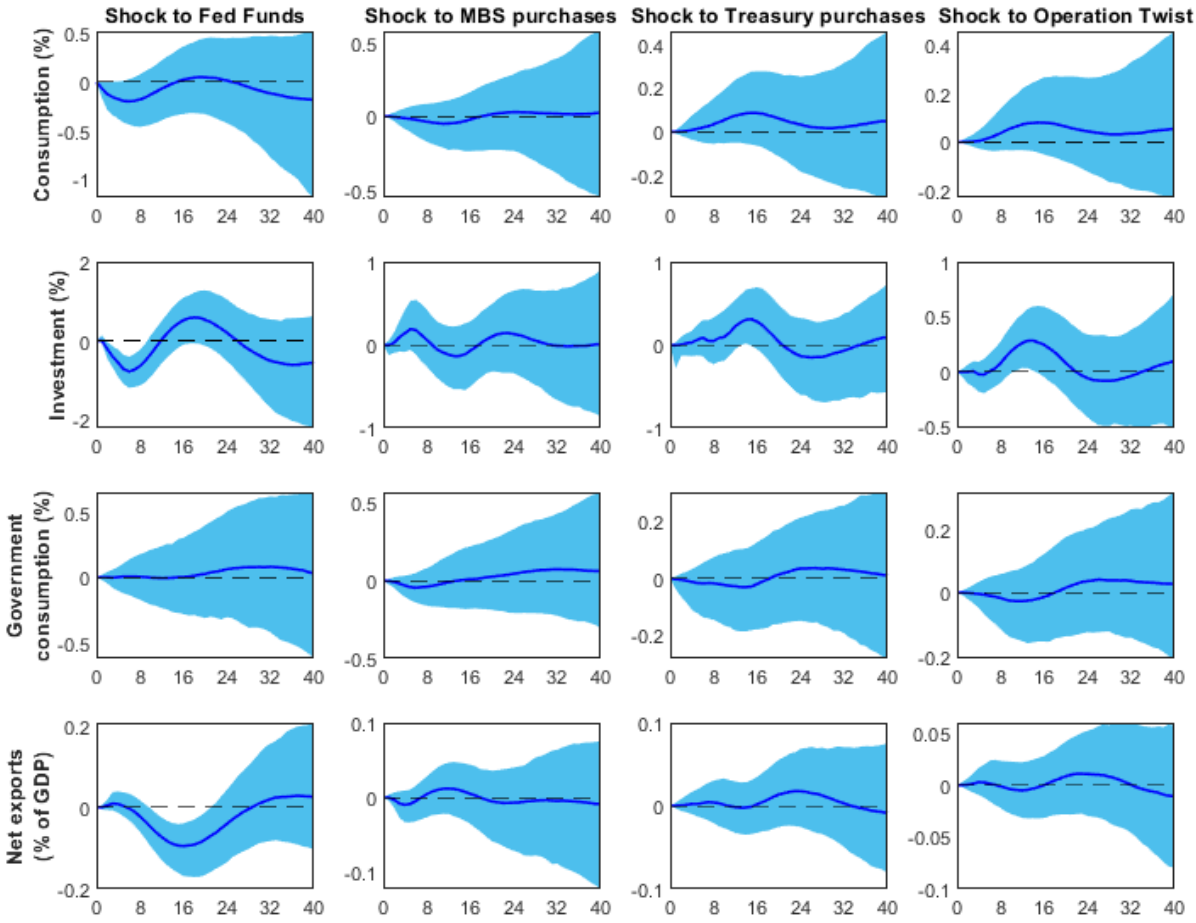
5.4 GDP components

To further our understanding of macroeconomic effects of QE and its transmission channels, it seems worthwhile to study the responses of GDP components to QE shocks. Surprisingly, none of the VAR studies cited in Section 2 does that. This paper fills this gap.

GDP is replaced in the specification by its four main components: consumption, investment, government consumption and net exports[16]. The responses of these variables to monetary policy shocks are presented in Figure 12.

[16] Real personal consumption expenditures, real gross private domestic investment, real government consumption expenditures and gross investment, all in logs, and net exports of goods and services, relative to GDP, all from FRED.

Figure 12. Response of GDP components to one standard deviation monetary policy shocks



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. One standard deviation of shocks: 0.69 pp for fed funds rate, 0.88% of total mortgages for MBS purchases, 0.29% of public debt for Treasury purchases and 0.09% of public debt for Operation Twist. On horizontal axis: quarters since the shock.

Treasury purchases and Operation Twist have a statistically significant positive impact on investment. While the response of consumption is not statistically significant, median estimates are visibly positive. The reaction of investment is almost four times as large as the reaction of consumption, in line with the higher volatility of investment in the business cycle and responses to conventional monetary policy shocks. MBS purchases, on the other hand, have no visible impact on consumption and investment, in line with the insignificant reaction of GDP to MBS purchases in the baseline specification.

Government consumption does not react to QE and Operation Twist (as well as conventional interest rate adjustments), suggesting that lower debt financing costs do not encourage the government to spend more (though for QE the decline in Treasury yields is found not to be statistically significant, as shown in subsection 4.2). Net exports do not react as well, suggesting that the positive impact on the domestic economy and thus imports may be offset by positive spillovers to other economies and hence an increase in foreign demand. This contrasts somewhat with the negative reaction of net exports to a conventional interest rate hike, which may reflect stronger international spillovers. These international spillovers are investigated in subsection 5.6.

As demonstrated in subsection 4.2, QE affects the real economy mostly via the stock market. Treasury purchases, by increasing stock prices, thus seem to encourage business investment via higher Tobin's q and easier access to financing in capital markets. Furthermore, higher stock prices increase household wealth, boosting consumption. At the same time, the lack of the reaction of government consumption confirms that the fiscal policy channel of QE does not play an important role in the US.

5.5 Commercial paper

As mentioned earlier, Treasury bonds and MBS were not the only securities purchased by the Fed before the pandemic. On 7 October 2008, i.e. before MBS and Treasury purchases were launched, the Fed announced the creation of the Commercial Paper Funding Facility (CPFF) that purchased three-month unsecured and asset-backed commercial paper[17]. At peak in January 2009, the Fed owned 350 bln USD of commercial paper, about 20% of its total stock. CPFF was thus comparable in size to QE1 Treasury purchases (300 bln USD). Over the following months, purchases were gradually decreasing, until the facility expired in February 2010. Similar to Treasury and MBS purchases, CPFF was relaunched during the COVID-19 pandemic, hence it remains in the Fed's toolkit.

Studies of the CPFF are rare and mostly descriptory (Anderson and Gascon 2009, Adrian et al. 2011). Duca (2013) argues that CPFF prevented a meltdown of the commercial paper market, while Li (2015) shows that it increased bank lending. Thus, this is the first study that investigates the macroeconomic effects of commercial paper purchases.

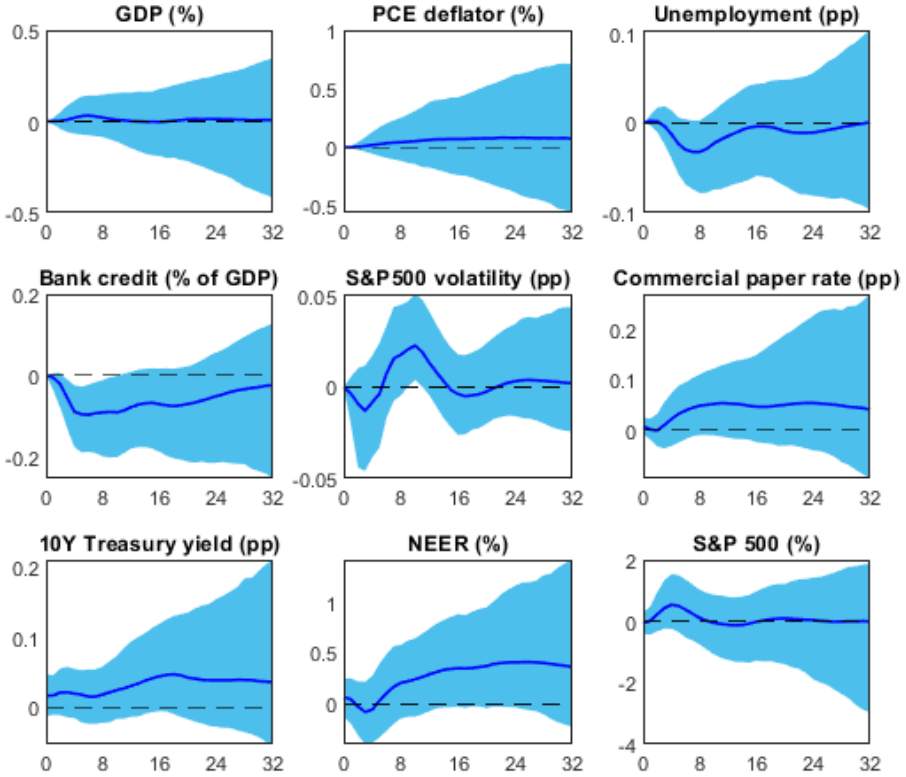
In order to do so, the baseline specification is augmented with two variables: Fed commercial paper purchases as a percentage of commercial paper outstanding, and 3-month commercial paper rate[18]. As CPFF was announced earlier than other unconventional policies, it is ordered directly after the Fed funds rate, while due to its short-term nature, commercial paper rate is placed just after monetary policy variables. The responses of the main macroeconomic aggregates and transmission channel variables to the CPFF shock are shown in Figure 13.

Commercial paper purchases are found to have no impact on GDP or inflation. However, they decrease unemployment, suggesting that they do have a positive impact on economic activity. If CPFF purchases were fully unanticipated, they would have decreased unemployment by as much as 1 pp after 7 quarters. Hence, their impact on the labour market is of a similar magnitude to those of QE1 MBS purchases, QE1 Treasury purchases or the first round of Operation Twist.

[17] See Adrian et al. (2011) for the details on the commercial paper market and the CPFF.

[18] The data comes from FRED. Commercial paper purchases are defined as net portfolio holdings of Commercial Paper Funding Facility LLC divided by commercial paper outstanding, in per cent. 3-month commercial paper is composed of three series that cover different time periods: 3-month AA financial commercial paper rate, 3-month commercial paper rate and commercial paper rates for New York.

Figure 13. Response of main macroeconomic aggregates and transmission channel variables to one standard deviation shock to commercial paper purchases



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. One standard deviation of a shock to commercial paper purchase is equal to 0.61% of commercial paper outstanding. On horizontal axis: quarters since the shock.

Similar to other unconventional policies, this impact seems to materialise mostly via an increase in stock prices, which is not statistically significant, but relatively large. At the same time, CPFF does not seem to reduce commercial paper rates[19] or Treasury yields. The responses of bank credit and the exchange rate are contractionary, but these channels have a relatively weak impact on economic activity.

Overall, it seems that commercial paper purchases played a role in stabilising economic activity during the global financial crisis. One should remember, however, that CPFF time series are very short, even relative to other unconventional measures studied here, and thus the above results should be interpreted with caution.

5.6 Spillovers and spillbacks

Another interesting issue is how and to what extent US unconventional monetary policy spills over to the rest of the world. This topic has received much attention in the public debate and the literature following the 'taper tantrum' episode, which strongly affected some emerging markets, and the formation of the 'dilemma' hypothesis, which claims that due to

[19] Admittedly, quarterly frequency is not ideal to study the response of commercial paper rates. Moreover, at the end of 2008 the commercial paper market effectively froze, and thus often interest rates were not even noted.

the presence of the global financial cycle, driven by US monetary policy, independent monetary policy in small open economies is not possible under free capital mobility (Rey 2015).

However, this strand of literature has focused on capital flow and financial market spillovers of QE (e.g. Ahmed and Zlate 2014, Bowman et al. 2015b, Fratzscher et al. 2018), with fewer studies investigating the effects on economic activity and inflation. Among those, Bhattarai et al. (2021) find that while US QE affects bond yields, exchange rates and stock prices in emerging markets (EMs), it has no significant impact on output and inflation. In contrast, Chen et al. (2016) find that the effect of US QE on output tends to be positive in both advanced and emerging market economies, with Tillmann (2016) coming to a similar conclusion for EMs and Haldane et al. (2016) for major economies (UK, Japan and the euro area). On top of that, Alpanda and Kabaca (2020) and Kolasa and Wesołowski (2020) study international spillovers of QE in DSGE settings, arriving at opposite conclusions when it comes to the impact of QE on economic activity in either the rest of the world or small open economy.

Thus, there seems to be no consensus in the literature on how QE affects economic activity abroad. Moreover, the empirical studies use models with few variables, which are prone to omitted variable bias. Therefore, it seems worth investigating this question within a mid-sized framework utilised in this paper.

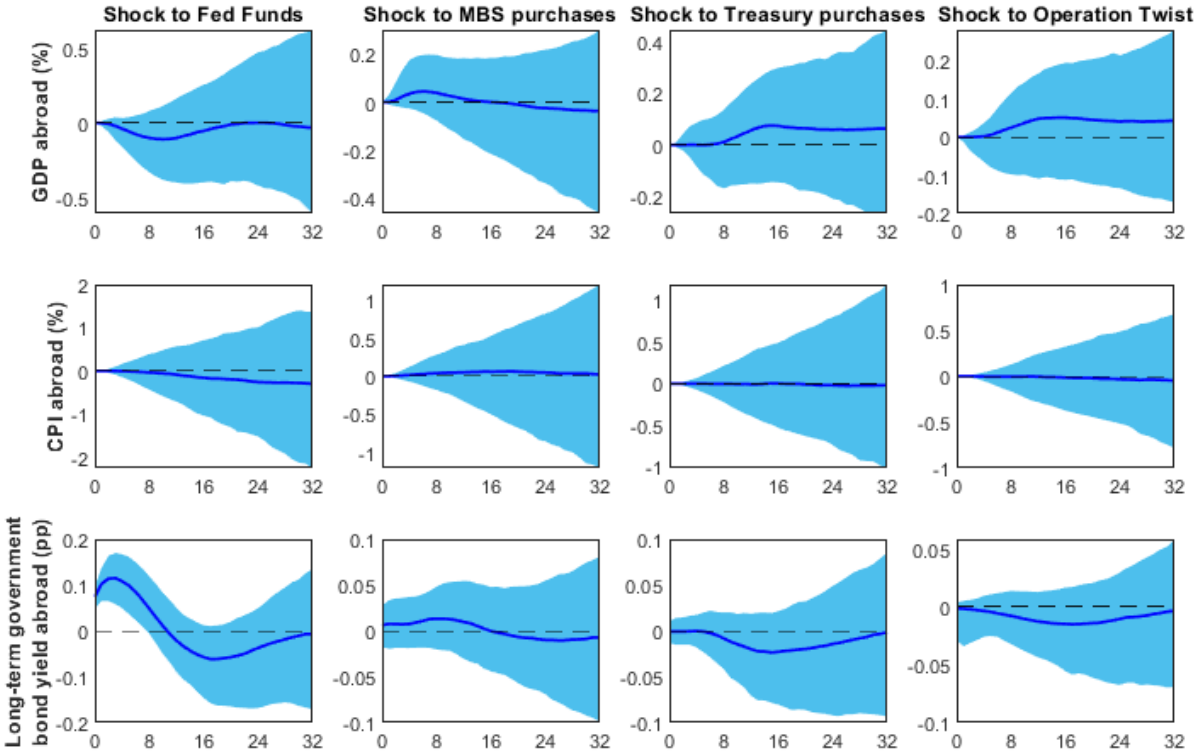
In order to do so, the baseline specification is augmented with three variables: export-weighted real GDP abroad, import-weighted CPI abroad, and public debt-weighted long-term government bond yield abroad[20]. The rest-of-the-world variables are placed directly after the corresponding domestic variables, reflecting the assumption that the US economy is more likely to contemporaneously affect the rest of the world than the rest of the world is to affect the US. The responses of the rest-of-the-world variables to the US monetary policy shocks are presented in Figure 14.

The responses of GDP, CPI and government bond yields abroad to QE and Operation Twist shocks are not statistically significant, which is not surprising given that the responses of domestic GDP, prices and bond yields are not statistically significant as well. However, median estimates indicate that Treasury purchases and Operation Twist tend to increase GDP and lower government bond yields abroad. Quantitatively, the peak responses of GDP abroad are only a bit smaller than those of domestic GDP, suggesting that US unconventional monetary policy has about the same effect on the export-weighted rest of the world as on the US economy. At the same time, the effects on government bond yields

[20] The data on real GDP, CPI, long-term government bond yields and general government gross debt comes from OECD, Eurostat and Bloomberg, while the data on US exports and imports is from the US Census Bureau. GDP abroad and CPI abroad cover the countries that had at least 1% share in US exports and imports, respectively, in 2018, while the data on long-term government bond yields covers OECD countries. GDP abroad and CPI abroad indices are constructed from appropriately weighted seasonally adjusted QoQ growth rates.

abroad are about twice as small as the impact on Treasury yields (though they arrive sooner), suggesting that financial market spillovers are weaker than the real economy ones.

Figure 14. Response of rest-of-the-world variables to one standard deviation monetary policy shocks



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. One standard deviation of shocks: 0.69 pp for fed funds rate, 0.90% of total mortgages for MBS purchases, 0.29% of public debt for Treasury purchases and 0.09% of public debt for Operation Twist. On horizontal axis: quarters since the shock.

If the US monetary policy indeed drives the global financial cycle and the Fed plays the role of a global central bank, global welfare could be improved if the Fed took international spillovers of its policy into account. However, if these spillovers lead to spillbacks, i.e. they spill over back to the US economy, the Fed is likely to already take them into account and the potential global welfare gains from adjusting the Fed's mandate might be limited.

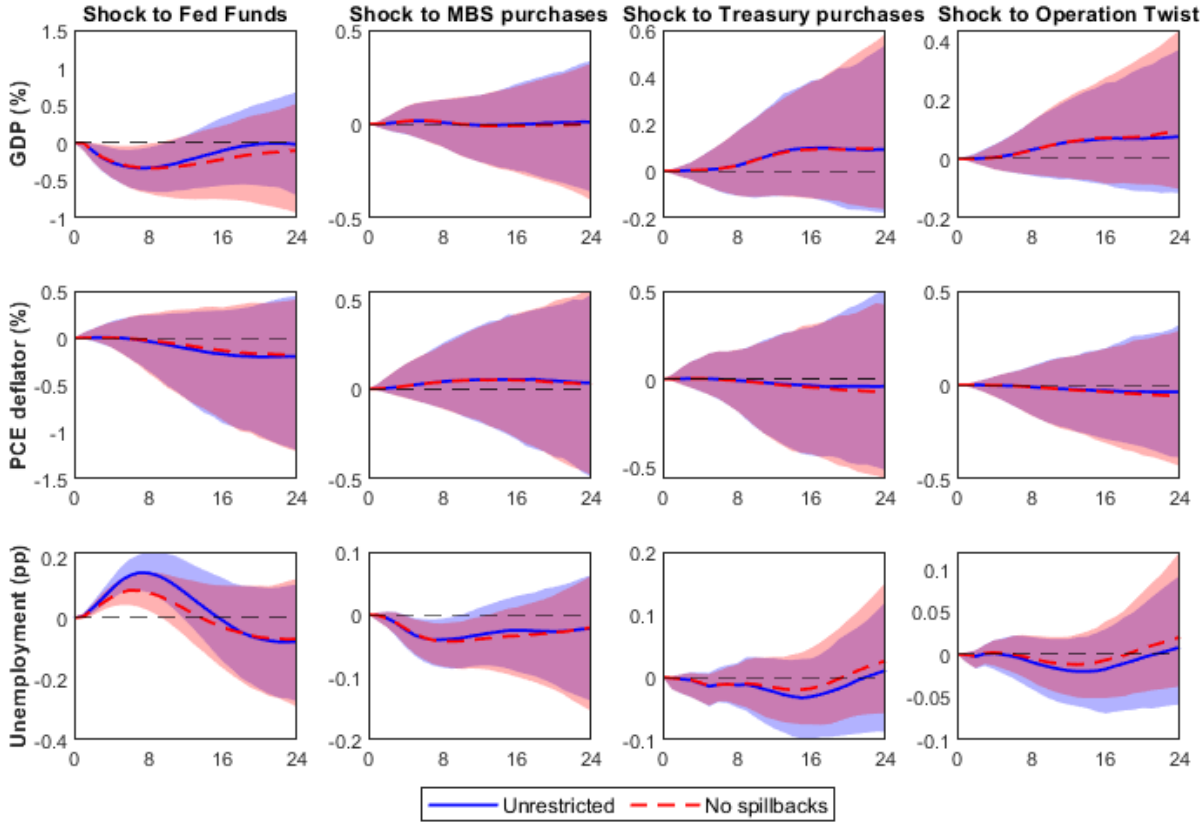
Against this background, some policymakers have called for major central banks to internalise spillovers (Rajan 2016, Carney 2019), while others claimed that the Fed already takes spillbacks into account (Fischer 2014, Yellen 2019). Despite the importance of this topic for policymakers, spillbacks have so far received very little attention in the literature. Only recently, Breitenlechner et al. (2021b) have found that spillbacks account for as much as half of the effects of conventional monetary policy on economic activity in the US. No study has investigated the spillbacks of unconventional monetary policy. This paper fills this gap.

The same model specification is used to study spillbacks as to study spillovers, i.e. the baseline specification is augmented with GDP abroad, CPI abroad and long-term government bond yields abroad. Following Breitenlechner et al. (2021b), spillbacks are defined as a difference between unrestricted impulse responses and impulse responses obtained from the counterfactual in which spillovers to the rest of the world of a studied

policy are assumed to equal zero – with spillovers zeroed-out, there should be no spillbacks. The counterfactual is computed using structural scenario analysis (SSA), under which structural parameters of the model remain unchanged and spillovers of a given policy are offset by a chosen set of shocks – in this case, the rest-of-the-world shocks, i.e. shocks to GDP abroad, CPI abroad and long-term government bond yields. Offsetting the response of a given variable with shocks to this variable is not only intuitive, but this is also the approach most often used in the SSA literature (Bernanke et al. 1997, Kilian and Lewis 2011, Bachmann and Sims 2012, Wong 2015, Epstein et al. 2019, Breitenlechner et al. 2021b). For the technical details on structural scenario analysis, see Antolin-Diaz et al. (2021) or Appendix C of Breitenlechner et al. (2021b).

Figure 15 presents the unrestricted and counterfactual responses of the main macroeconomic aggregates to monetary policy shocks, while Figure 16 shows the posterior distributions of spillbacks for the same variables and shocks.

Figure 15. Unrestricted and counterfactual responses of main macroeconomic aggregates to one standard deviation monetary policy shocks

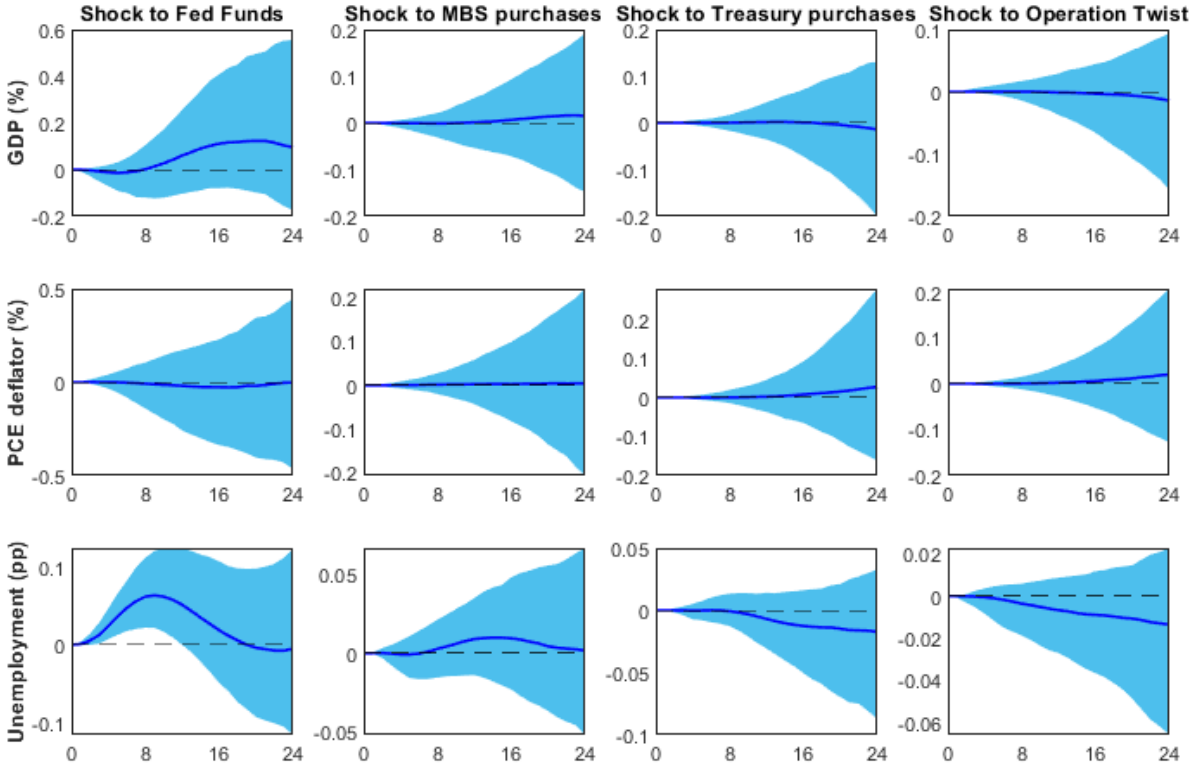


Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. One standard deviation of shocks: 0.69 pp for fed funds rate, 0.90% of total mortgages for MBS purchases, 0.29% of public debt for Treasury purchases and 0.09% of public debt for Operation Twist. On horizontal axis: quarters since the shock.

GDP and PCE deflator responses to QE and Operation Twist shocks hardly differ between the unrestricted model and the counterfactual, both in terms of median estimates and 90% credible sets, suggesting that there are essentially no spillbacks from unconventional monetary policies to these variables in the US. The case is somewhat different for the

response of unemployment to Treasury purchases and Operation Twist, however. Even though the estimates of spillbacks are not significantly different from zero, unemployment falls by visibly less in the counterfactual – for both Treasury purchases and Operation Twist, spillbacks account for about 40% of the peak decline in unemployment[21].

Figure 16. Spillbacks to main macroeconomic aggregates from one standard deviation monetary policy shocks



Lines indicate median estimates, shaded areas represent 90% Bayesian credible sets. One standard deviation of shocks: 0.69 pp for fed funds rate, 0.90% of total mortgages for MBS purchases, 0.29% of public debt for Treasury purchases and 0.09% of public debt for Operation Twist. On horizontal axis: quarters since the shock.

Given that only Breitenlechner et al. (2021b) study spillbacks of conventional monetary policy, it is also worth taking a closer look at the responses to Fed funds shocks. The conclusions here are similar to the ones for unconventional policy - spillbacks to GDP and prices are not statistically significant (though they seem to increase GDP in the medium run following a contractionary shock), but those to unemployment are shock-amplifying and account for about 40% of the peak response. My results thus differ somewhat from those of Breitenlechner et al. (2021b) who find large shock-amplifying spillbacks to industrial production, consumption and investment.

In any case, conventional and unconventional monetary policy spillbacks seem to be of a very similar nature. However, it is rather difficult to come up with a plausible hypothesis why spillbacks are present for unemployment, but not GDP.

[21] It should be noted, however, that in the specification augmented with the rest-of-the-world variables the reaction of unemployment to Treasury purchases and Operation Twist is much smaller than in the baseline specification and not statistically significant.

6. Robustness checks

Numerous robustness checks have been conducted. Below the checks with respect to the number of variables, priors, the number of lags, measures of QE, shock identification, frequency of data, treatment of the ZLB period, break in the time trend, and variable order are discussed. For brevity, I do not report the results of the robustness exercises involving alternative measures of conventional monetary policy, price level, credit or the housing sector, as well as checks with respect to the prior hyperparameters. For the same reason, only the responses of the main macroeconomic aggregates are reported, without analysing the transmission channels.

In general, the results with respect to unconventional monetary policy are found not to be very robust. In several alternative specifications, the impact of QE and Operation Twist on unemployment and GDP is significantly smaller than in the baseline specification. The impact of Treasury purchases on unemployment is found to be close to zero or neutral when more variables or lags are added or the Bańbura et al. (2010) prior is used. The effects of MBS purchases are somewhat more robust, but they also decrease when the structural break is eliminated from the deterministic trend or MBS purchases are ordered after Treasury purchases.

6.1 Number of variables

Two alternative model specifications are considered: small, with 6 variables, and large, with 27 variables. The 6-variable specification resembles that used in other studies (Weale and Wieladek 2016, Hesse et al. 2018) with an addition of conventional monetary policy, i.e. comprises of GDP, PCE deflator, Fed funds rate, QE (announced/expected MBS and Treasury purchases combined), 10Y Treasury yield and the S&P 500 stock index. The large specification adds to the baseline specification 12 control and transmission channel variables that are not very similar to and do not overlap with the baseline variables; many of these variables are used in the extensions discussed in Section 5. These additional variables are listed in **Error! Reference source not found.**. The sample of the large specification is shorter, beginning in 1978Q1. Due to a larger number of variables and a shorter sample, 2 lags are used instead of 4.

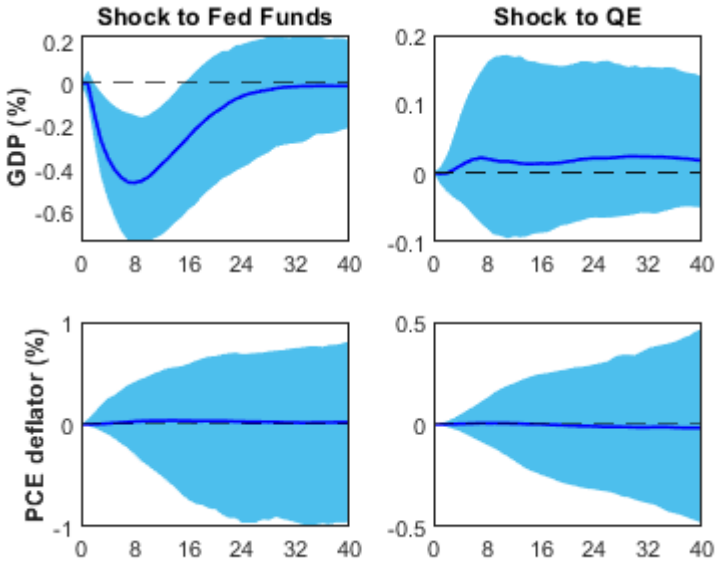
The responses of GDP and prices to Fed funds rate and QE from the small specification are presented in Figure 17. Prices still do not react to QE, while the response of GDP is also insignificant, with median posterior only slightly positive. The QE measure is now a sum of MBS and Treasury purchases. Since in the baseline specification the median response of GDP to MBS purchases is slightly negative, while for Treasury purchases positive, the results from the small specification are consistent with the baseline. Having said that, there is a clear

informational gain from including unemployment and distinguishing between MBS and Treasury purchases in the specification.

Table 2. Additional variables in the large specification

Variable	Order	Construction	Source
Capacity utilisation	2	Capacity utilisation in total industry, per cent	FRED
GDP abroad	4	log export-weighted GDP abroad	OECD, Eurostat, Bloomberg, US Census Bureau, own calculations
Inflation expectations	6	median expected price change next 12 months, University of Michigan Surveys of Consumers, per cent	FRED
Corporate profits	8	log corporate profits after tax (without inventory valuation and capital consumption adjustments)	FRED
Public debt	9	Total public debt to GDP, per cent	FRED, own calculations
Agency MBS	11	Agency- and GSE-backed mortgage pools to GDP, per cent	FRED, own calculations
House prices	12	log nominal residential property prices	BIS
Commercial paper purchases	17	net portfolio holdings of Commercial Paper Funding Facility to commercial paper outstanding, per cent	FRED, own calculations
Commercial paper rate	21	3-month AA financial commercial paper rate (1997Q1-2019Q4) and 3-month commercial paper rate (1971Q2-1996Q4), per cent	FRED
Long-term government bond yield abroad	23	Public debt-weighted long-term government bond yield in OECD countries, per cent	OECD, Eurostat, Bloomberg, own calculations
Corporate bond yield	25	Moody's seasoned Baa corporate bond yield, per cent	FRED
Mortgage rate	27	30Y fixed rate mortgage average, per cent	FRED

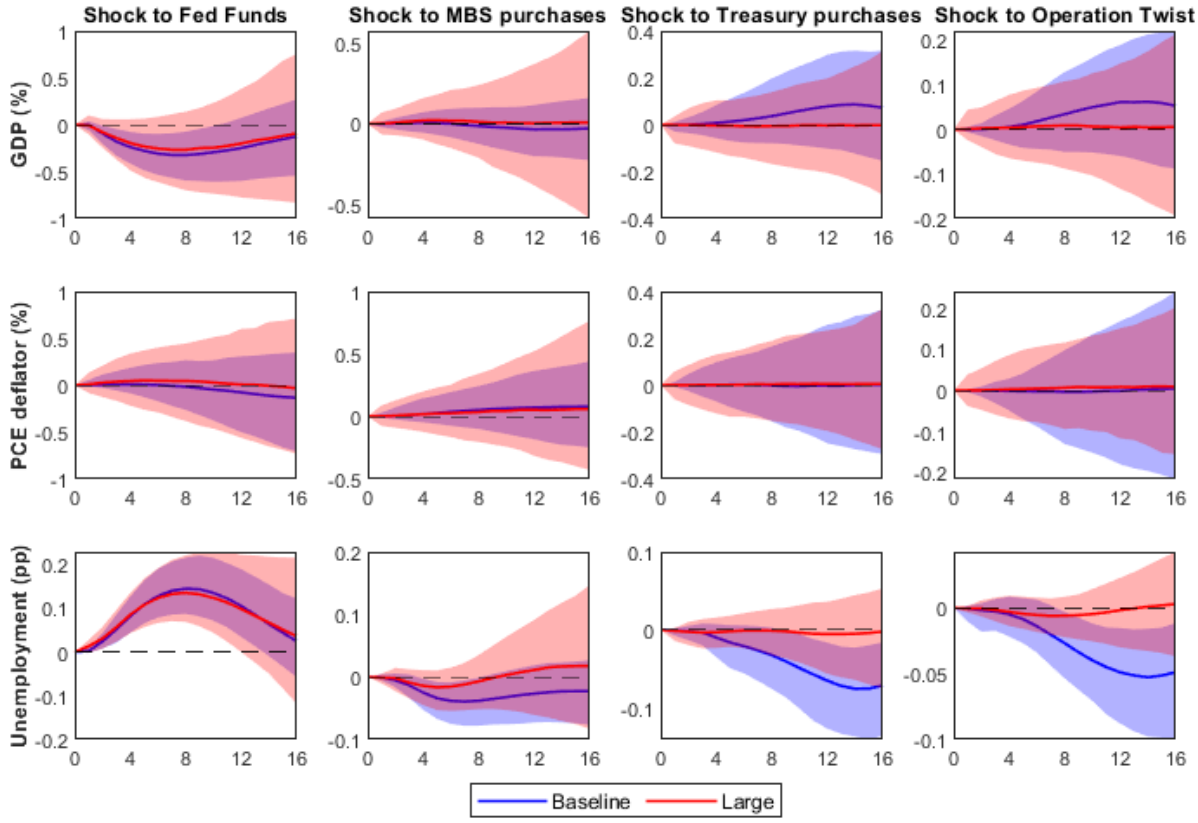
Figure 17. Responses of GDP and prices to one standard deviation monetary policy shocks: small specification



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. One standard deviation of shocks: 0.80 pp for fed funds rate, 0.76% of public debt for QE. On horizontal axis: quarters since the shock.

The responses of the main macroeconomic aggregates to monetary policy shocks obtained from the large specification are presented in Figure 18. With the inclusion of additional variables, the macroeconomic effects of unconventional monetary policy decrease significantly. The impact on unemployment is no longer statistically significant and the peak effect is multiple times smaller for MBS purchases and Operation Twist and close to zero for Treasury purchases. Similarly, the median posterior effects on GDP are very close to zero. In contrast, the effects of conventional monetary policy continue to be statistically significant and of similar size.

Figure 18. Responses of main macroeconomic aggregates to one standard deviation monetary policy shocks: baseline vs large specification



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. One standard deviation of shocks: 0.69 pp for fed funds rate, 0.88% of total mortgages for MBS purchases, 0.29% of public debt for Treasury purchases and 0.09% of public debt for Operation Twist. The impulse responses from the large specification are rescaled so that the sizes of shocks are equal across specifications. On horizontal axis: quarters since the shock.

It should be noted, however, that even under informative SSVS prior, credible sets widen significantly in the large specification relative to the baseline (especially over longer horizons, which are not reported for legibility) due to declining degrees of freedom and an increasing degree of collinearity. Computational time also increases significantly. The SSVS prior is therefore not suitable for large models and the above discussed results should not be overly trusted. To effectively estimate large models, one needs to use relatively simple priors and Theil's mixed estimation, as shown by Bańbura et al. (2010). Robustness of the baseline results to this approach is investigated in the next subsection.

6.2 Bańbura et al. (2010) priors

To investigate the robustness of the results to the prior used, the 15-variable specification is estimated using the method of Bańbura et al. (2010). They use a type of a Minnesota prior, which was originally developed by Litterman (1986) and later adjusted by Kadiyala and Karlsson (1997). The basic principle of the Minnesota prior is that all the equations are centred around the random walk, i.e. coefficients on own first lags are shrunk towards 1 (though the prior on AR(1) coefficients can be changed), and all the other coefficients are shrunk towards zero. In addition, more distant lags are assumed to provide less information

than more recent lags, and thus tighter priors are set on the coefficients associated with them, while the priors on the intercepts are diffuse. The prior for the covariance matrix of the residuals is centred around a diagonal matrix estimated from a series of autoregressive models with p lags (AR(p) models).

This type of a Minnesota prior takes the form of a normal-inverse-Wishart prior:

$$\alpha|\Psi \sim N(\alpha_0, \Psi \otimes \Omega_0) \tag{7}$$

$$\Psi \sim iW(S_0, v_0) \tag{8}$$

where the prior parameters α_0, Ω_0, S_0 and v_0 are chosen such that:

$$E\big((A_k)_{ij}\big) = \begin{cases} \delta_i, & k = 1, j = i \\ 0, & otherwise \end{cases} \tag{9}$$

$$V\big((A_k)_{ij}\big) = \frac{\lambda^2}{k^2}\frac{\sigma_i^2}{\sigma_j^2} \tag{10}$$

and the expectation of Ψ is equal to the diagonal covariance $\Sigma = diag(\sigma_1^2, \dots, \sigma_n^2)$, with the diagonal elements estimated from AR(p) models for each of the variables. For details, see Kadiyala and Karlsson (1997).

On top of that, Bańbura et al. (2010) consider setting an additional prior on the sum of the coefficients, originally proposed by Doan et al. (1984). This prior shrinks the sum of $\big(I_n - A_1 - \cdots - A_p\big)$ towards zero, which rules out cointegration, with the tightness of this prior regulated by the hyperparameter τ. Since Bańbura et al. (2010) find the sum of the coefficients prior to significantly improve forecasting performance, it is included in the specification.

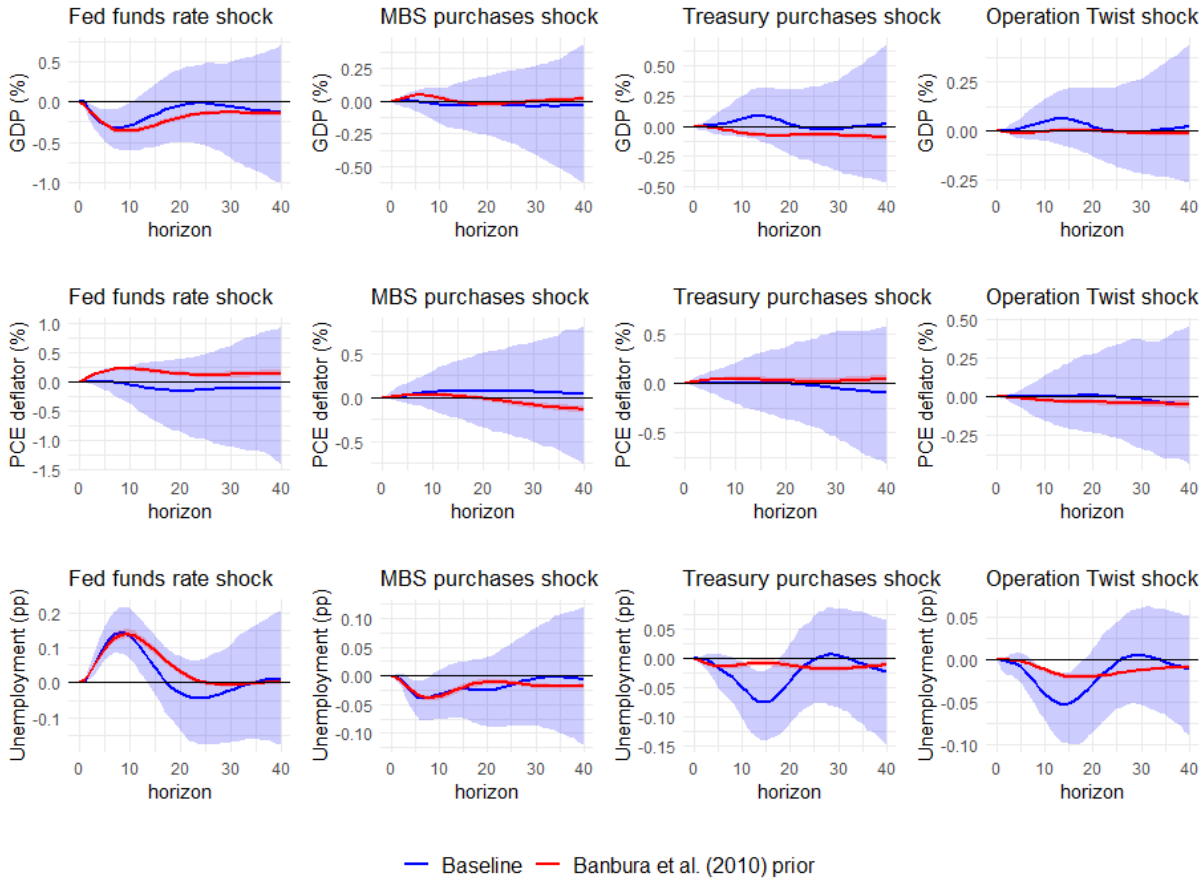
Bańbura et al. (2010) estimate their models using Theil's mixed estimation, i.e. instead of treating prior and likelihood as two distinct elements that combined give the posterior, prior and likelihood are mixed together by adding to the data dummy observations generated from the prior. The OLS estimate obtained from this staked data is equal to the posterior. This procedure allows to effectively estimate large models, even when the number of coefficients exceeds the number of observations. For details, see Bańbura et al. (2010).

The prior for AR(1) coefficients δ_i is set to 1 for the variables in log-levels and QE and Operation Twist measures and 0.9 for all the other variables (since they are all relatively persistent) with the exception of less persistent stock market volatility that gets the prior of 0.5. Overall tightness λ is set to 0.23 following the λ-fitting exercise of Bańbura et al. (2010)[22]. The prior for the sum of the coefficients τ is relatively loose and equal to 10λ, following Bańbura et al. (2010). The model is estimated in R using lbvar package.

[22] The hyperparameter λ value is set such that the model fit is equal to that of a 3-variable model consisting of GDP, PCE deflator and the Fed funds rate estimated with OLS.

The comparison of the impulse responses obtained from the 15-variable specification using the SSVS prior and the Bańbura et al. (2010) prior is presented in Figure 19.

Figure 19. Responses of main macroeconomic aggregates to one standard deviation monetary policy shocks: baseline vs Bańbura et al. (2010) prior



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. One standard deviation of shocks: 0.69 pp for fed funds rate, 0.88% of total mortgages for MBS purchases, 0.29% of public debt for Treasury purchases and 0.09% of public debt for Operation Twist. The impulse responses from the alternative specification are rescaled so that the sizes of shocks are equal across specifications. On horizontal axis: quarters since the shock.

The most striking result is how narrow the credible sets obtained using the Bańbura et al. (2010) method are relative to the SSVS prior, making virtually all the results statistically significant. Looking at posterior medians, QE and Operation Twist continue to reduce unemployment. However, while the effect of MBS purchases is very similar to the one obtained using the SSVS prior, the estimates for Operation Twist and Treasury purchases are much smaller, with the latter not very far from zero.

The effects on GDP and prices are either positive or negative, with no clear patterns. Thus, the results obtained using Bańbura et al. (2010) method seem somewhat less economically plausible than the baseline results, even though credible sets are much narrower. At the same time, the baseline estimates of QE effects prove not to be very robust, somewhat in contrast to the effects of conventional monetary policy that remain broadly similar across specifications.

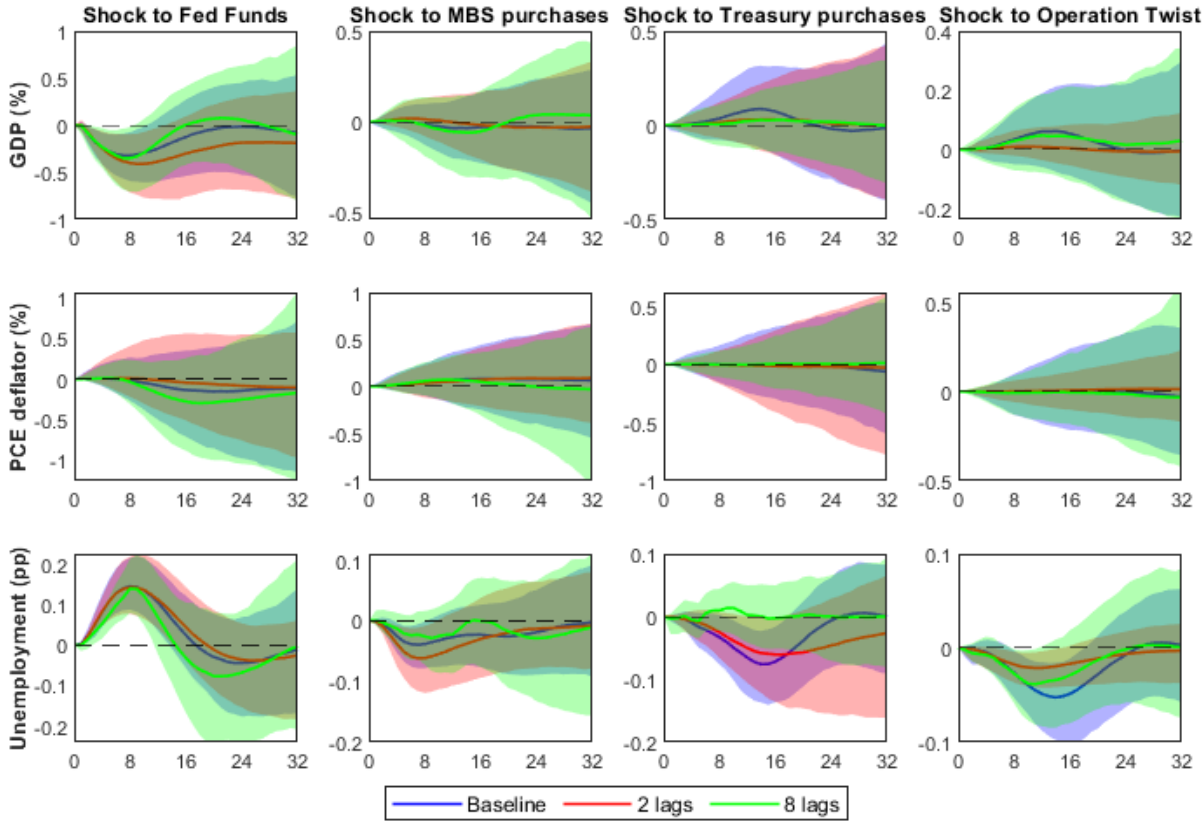
Since the Bańbura et al. (2010) method is designed for estimating large models, I also investigate whether the results obtained using this method are robust to increasing model size. This exercise is described in detail in Appendix A. In general, the addition of more variables has a significant effect on the results, with the estimates of impulse responses shrinking towards zero, similar as under the SSVS prior with more variables. This suggests there might still be significant omitted variable bias in the baseline specification. Having said that, QE and Operation Twist continue to reduce unemployment in all specifications.

6.3 Number of lags

The robustness to the baseline results to the choice of the number of lags is investigated by estimating two alternative models, with either 2 or 8 lags, instead of the baseline 4. The impulse responses of the main macroeconomic aggregates to monetary policy shocks for the baseline and two alternative specifications are compared in Figure 20.

The choice of the number of lags does have an impact on the results. With fewer lags, the effects of unconventional monetary policy on unemployment remain statistically significant and of similar magnitude as in the baseline specification (with the exception of Operation Twist), but the median posterior impact of Treasury purchases and Operation Twist on GDP is smaller and very close to zero. With more lags, Treasury purchases have no impact on unemployment and GDP, while the impact of MBS purchases on unemployment is no longer statistically significant. At the same time, the effects of conventional monetary policy remain broadly similar across specifications.

Figure 20. Responses of main macroeconomic aggregates to one standard deviation monetary policy shocks: robustness with respect to the number of lags



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. One standard deviation of shocks: 0.69 pp for fed funds rate, 0.88% of total mortgages for MBS purchases, 0.29% of public debt for Treasury purchases and 0.09% of public debt for Operation Twist. The impulse responses from the alternative specification are rescaled so that the sizes of shocks are equal across specifications. On horizontal axis: quarters since the shock.

6.4 Purchase-based measures of QE

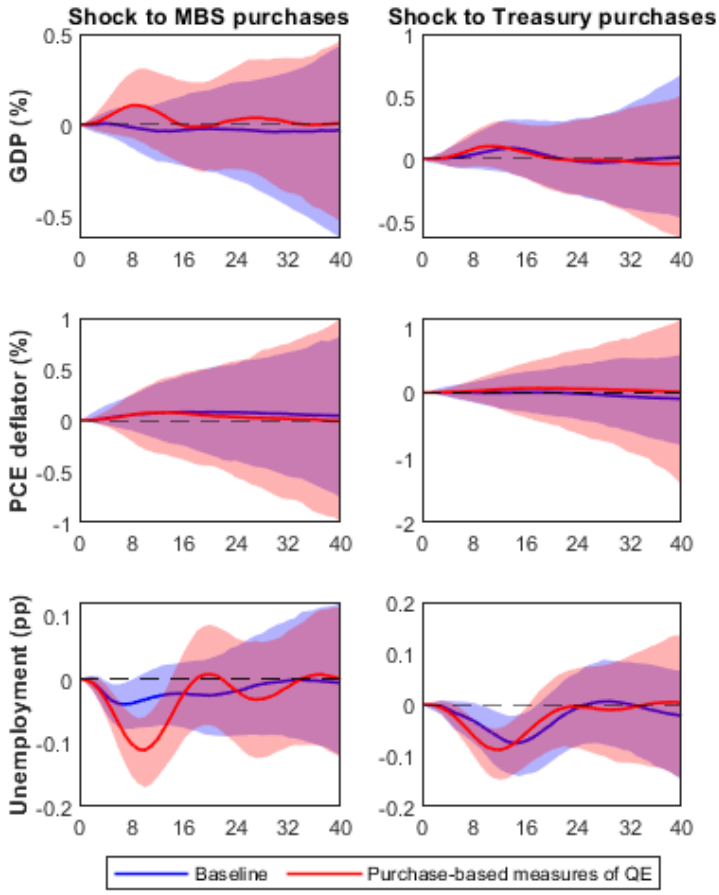
To test whether the construction of the QE variables matters for the results, the measures of MBS and Treasury purchases that take into account actual purchases, rather than announcements, are used in an alternative model specification[23]. These measures continue to be scaled relative to the proxies of security stocks (agency-backed mortgage pools and public debt, respectively). Operation Twist is dropped from the specification as it is not straightforward to construct a purchase-based measure of this policy[24].

The responses of the main macroeconomic aggregates to QE shocks for the baseline and the alternative specification are compared in Figure 21.

[23] Data comes from the FRED series "Assets: Securities Held Outright: U.S. Treasury Securities" and" Assets: Securities Held Outright: Mortgage-Backed Securities".

[24] Holdings of longer-term (maturing in over 5 years) Treasury securities could be used, but they would have to be cleaned from QE Treasury purchases, which is not straightforward.

Figure 21. Responses of main macroeconomic aggregates to one standard deviation QE shocks: robustness with respect to the measure of QE



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. One standard deviation of shocks: 0.88% of total mortgages for MBS purchases and 0.29% of public debt for Treasury purchases. The impulse responses from the alternative specification are rescaled so that the sizes of shocks are equal across specifications. On horizontal axis: quarters since the shock.

The results are qualitatively robust to the choice of the QE variables. The impulse responses of Treasury purchases are very similar across specifications, while MBS purchases have a somewhat stronger impact on unemployment and GDP in the alternative specification.

6.5 High-frequency identification of shocks

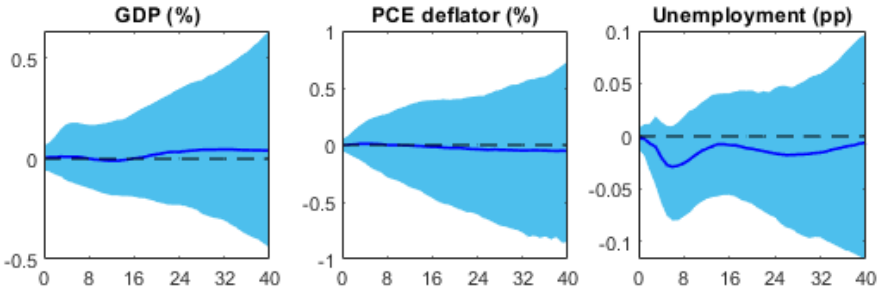
The Cholesky decomposition identification of monetary policy shocks has been criticised on the grounds that zero restrictions of this kind do not emerge from DSGE models (Canova and Pina 1999). Moreover, in a model which includes financial variables the assumption that monetary policy does not respond contemporaneously to financial conditions is questionable[25]. Therefore, alternative identification schemes have been developed – Uhlig (2005) imposes sign restrictions on the impulse responses, while Gertler and Karadi (2015)

[25] In the baseline specification, this problem is alleviated by ordering stock market volatility before the monetary policy variables.

obtain monetary policy shocks by instrumenting reduced-form residuals with the event-study responses of financial asset prices to monetary policy announcements.

To test the robustness of the baseline results to the method of shock identification, the high-frequency of identification of Gertler and Karadi (2015) is conducted in a simplified manner. The "LSAP factor" estimated by Swanson (2021) is used as a high-frequency measure of financial asset price responses to QE-related announcements[26]. Instead of using this variable as an instrument for reduced-form residuals in line with the proxy SVAR literature, I treat it as a direct measure of QE shocks that is included as one of the variables in the VAR model[27]. At the same time, the baseline measures of QE (MBS and Treasury purchases) and Operation Twist are dropped from the specification. Since the LSAP factor is supposed to be exogenous, it is ordered first in the Cholesky decomposition. The responses of the main macroeconomic aggregates to this shock are presented in Figure 22.

Figure 22. Responses of main macroeconomic aggregates to one standard deviation Swanson (2021) QE shocks



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. On horizontal axis: quarters since the shock.

The LSAP factor has no impact on GDP and prices. The response of unemployment is not statistically significant as well, but the median posterior is negative in the short run. Even though the results cannot be directly compared with the baseline as one standard deviation of the QE shock can no longer be interpreted in dollar terms and there is only one measure of unconventional monetary policy instead of three, the peak median posterior effect on unemployment is smaller than for any of the baseline unconventional monetary policy measures.

[26] Swanson (2021) calculates responses of various financial asset prices (Fed funds and Eurodollar futures, Treasury bond yields, stock prices and exchange rates) to monetary policy announcements over 30-minute windows and summarises them into 3 principal components that are interpreted as shocks to Fed funds rate, forward guidance and QE.

[27] The LSAP factor series provided by Swanson (2021) is available at daily frequency beginning in July 1991. To obtain a quarterly measure of shocks, following Kolasa and Wesołowski (2021), the daily series is first cumulated, and then quarterly averages are calculated and differenced. In such a way, a shock that appears late in a quarter is effectively split between the current and the upcoming quarter. Prior to 1991Q1, the series is assumed to equal 0, so that the model can be estimated on the baseline sample.

6.6 Monthly data

Since the majority of the data used in the baseline specification is available at monthly frequency, the model could be estimated on monthly rather than quarterly data. Monthly data provides more observations, but at the same time tends to be more noisy and requires the inclusion of more lags in the specification.

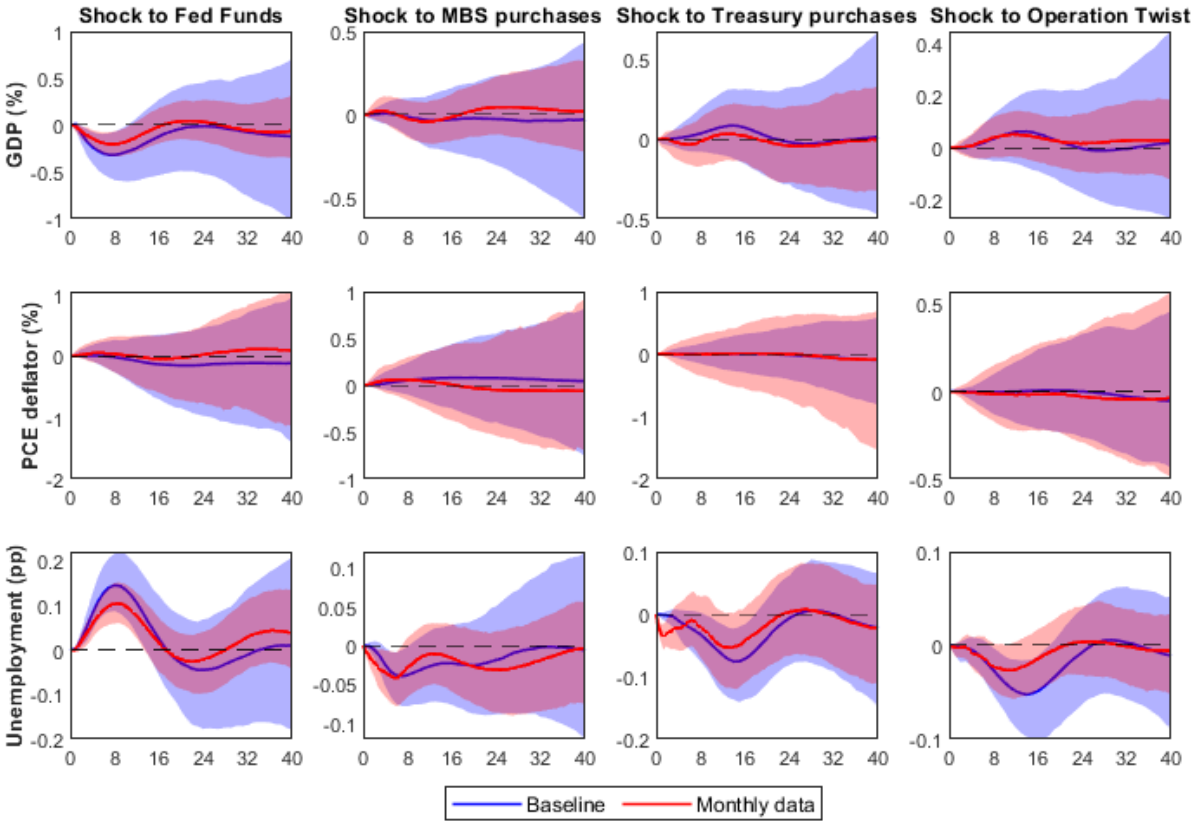
The majority of monthly data comes from the same sources and is constructed in the same way as quarterly data[28]. The exceptions are data on GDP, import prices and primary surplus; the latter two series are eventually dropped from the specification. Monthly estimates of GDP are available since 1992 from IHS Markit Macroeconomic Advisers. Before 1992, GDP data is interpolated from a simple model which explains log GDP with log real personal consumption expenditures, capacity utilisation in total industry, log non-farm employment, unemployment, housing starts and time trend, estimated on quarterly data between 1967Q1 and 1991Q4 with OLS. In the case of import prices and primary surplus, the data series used in the baseline specification are not available in monthly frequency. Data on commodity import prices and federal government deficit could be used as substitutes, but it is available over a significantly shorter time frame (since late 1988 and late 1980, respectively) and in the case of government deficit, it is very noisy. Therefore, these variables are not used and the specification is reduced to 13 variables.

The sample starts in 1967M1, thus the starting point is very similar to the baseline specification (1966Q1). 12 lags are included, in line with 4 quarterly lags in the baseline. The impulse responses of the main macroeconomic aggregates to monetary policy shocks from the specifications using quarterly and monthly data are compared in Figure 23.

The baseline results are largely robust to the use of monthly data. The only clearly visible difference is the peak response of unemployment to Operation Twist, which is about twice as small under monthly data as in the baseline. The impact of conventional monetary policy on GDP and unemployment is also somewhat smaller. Qualitative conclusions remain unchanged, however.

[28] In the case of data scaled by GDP or agency-backed mortgage pools, 3-month moving average of quarterly GDP and agency-backed mortgage pools is used.

Figure 23. Responses of main macroeconomic aggregates to one standard deviation monetary policy shocks: quarterly vs monthly data



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. One standard deviation of shocks: 0.69 pp for fed funds rate, 0.88% of total mortgages for MBS purchases, 0.29% of public debt for Treasury purchases and 0.09% of public debt for Operation Twist. The impulse responses from the alternative specification are rescaled so that the sizes of shocks are equal across specifications. On horizontal axis: quarters since the shock.

6.7 Treatment of the ZLB and QE periods

A potential problem with the baseline specification is the treatment of the QE and ZLB periods. QE either did not exist or was not taken into consideration by the Fed before the global financial crisis. However, in a baseline linear model, QE shocks continue to be estimated for the pre-2008 period and have an impact on the economy. At the same time, as the full sample is used to estimate the systematic response of QE policy to economic conditions, this response is likely to be underestimated, and thus QE shocks are likely to be overestimated – at least in the later period, when QE became a well-established policy. Similarly, (negative) conventional monetary policy shocks continue to be estimated when the Fed funds rate is at the zero lower bound.

To deal with this problem, I follow Kim et al. (2020) and estimate the model equation-by-equation, with the equations for non-monetary policy variables estimated on the full sample, the equation for the Fed funds rate estimated over the non-ZLB period (1966Q1-2008Q4,

2015Q1-2019Q4[29]) and equations for MBS purchases, Treasury purchases and Operation Twist estimated over the QE period, i.e. the time when QE was a part of the Fed's toolkit, purchases/balance sheet reduction undergoing or not (2008Q4-2019Q4). The variance-covariance matrix is estimated using the residuals from the QE period, with the Fed funds rate residuals assumed to equal zero in the ZLB period.

To mimic the baseline specification as much as possible, each equation is estimated using Bayesian methods under the SSVS prior and the same hyperparameters as in the baseline[30]. However, this equation-by-equation SSVS is not equivalent to the baseline method, as the variance-covariance matrix is not estimated simultaneously with the model coefficients. For this reason, the results for the equation-by-equation SSVS estimated on an unrestricted sample are reported alongside the baseline and alternative specification results in order to investigate to what extent the differences in impulse responses stem from the treatment of ZLB and QE periods, and to what extent from methodological differences.

The responses of the main macroeconomic aggregates to monetary policy shocks across the baseline specification, the unrestricted equation-by-equation SSVS specification and the equation-by-equation SSVS accounting for the ZLB and QE periods are compared in Figure 24.

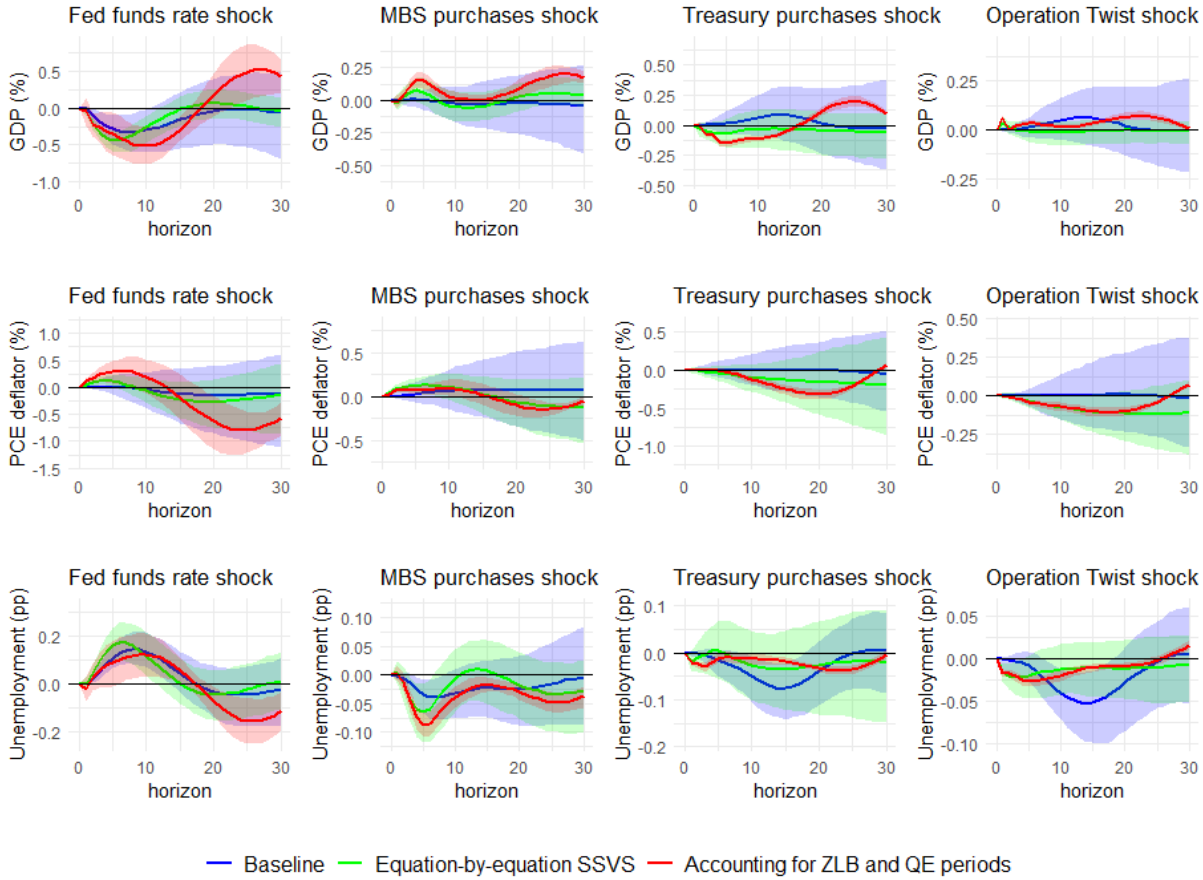
It is first worth noting that the results are largely robust to the treatment of the ZLB and QE periods as the impulse responses obtained from the unrestricted specification (green) and the restricted specification that accounts for the ZLB and QE periods (red) are quite similar, at least for unconventional monetary policy[31]. In other words, ignoring the fact that QE was not a part of the Fed's toolkit before 2008 does not have a significant impact on the results. Having said that, the results from the alternative specification do differ from the baseline (e.g. Treasury purchases have a much smaller impact on unemployment and tend to reduce prices), but this mostly reflects methodological differences (equation-by-equation vs simultaneous estimation, green vs blue). While the simultaneous estimation utilised in the baseline specification is clearly more efficient, one should not overly worry about these differences.

[29] The Fed funds rate was raised from the ZLB in 2015Q4, but serious discussions about the first rate hike began earlier, with the increase initially expected to take place in June 2015. Therefore, the non-ZLB sample restarts in 2015Q1, following the end of QE3 in 2014Q4.

[30] Alternative specifications are estimated in R using boral package.

[31] For conventional monetary policy, more significant differences can be spotted, but this is to be expected as the non-ZLB sample used to estimate the variance-covariance matrix in the restricted specification is effectively very small (2015Q1-2019Q4).

Figure 24. Responses of main macroeconomic aggregates to one standard deviation monetary policy shocks: robustness to the treatment of ZLB and QE periods



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. One standard deviation of shocks: 0.69 pp for fed funds rate, 0.88% of total mortgages for MBS purchases, 0.29% of public debt for Treasury purchases and 0.09% of public debt for Operation Twist. The impulse responses from the alternative specification are rescaled so that the sizes of shocks are equal across specifications. On horizontal axis: quarters since the shock.

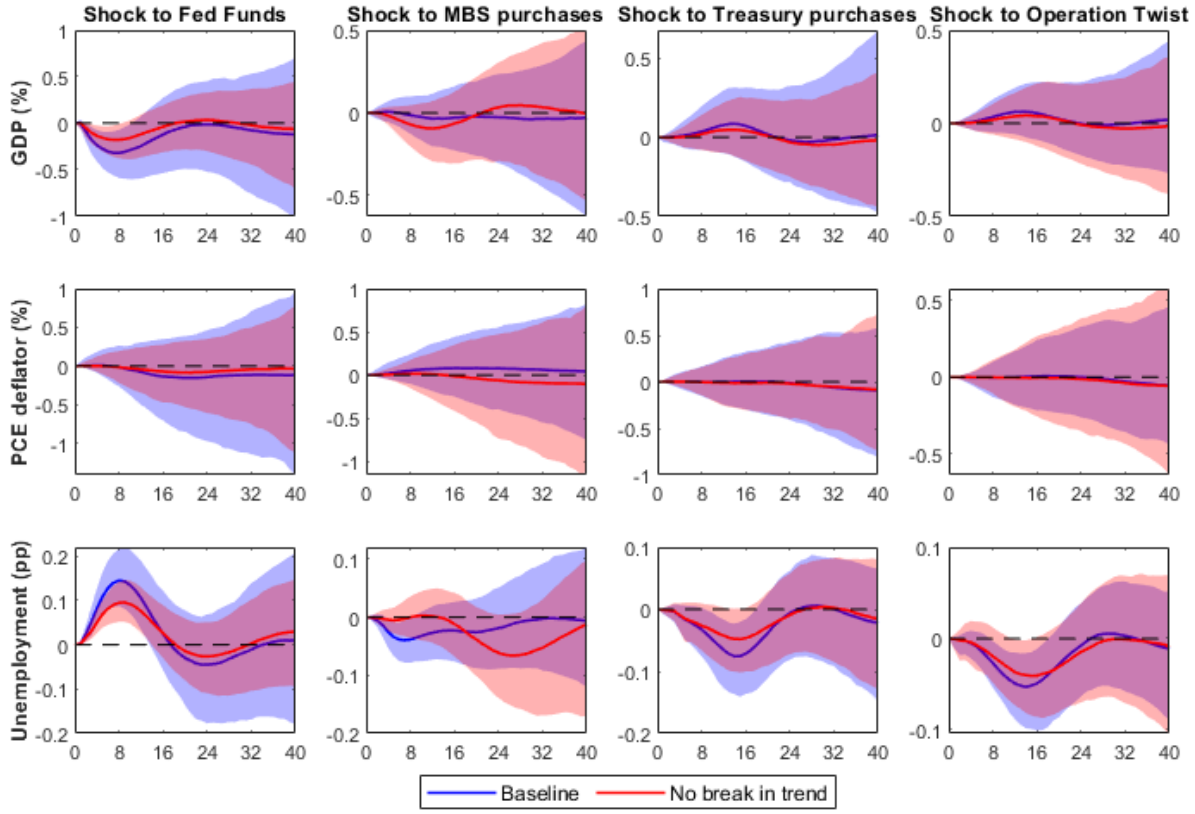
6.8 No structural break in the deterministic trend

The baseline specification includes a break in the deterministic trend at the outset of the global financial crisis in order to account for potential slowdown in potential GDP growth and other post-crisis structural breaks. In this subsection I investigate whether this specification choice has an influence on the results. In the alternative specification, the break in the time trend is eliminated, but the trend itself is retained. Figure 25 compares the responses of main macroeconomic aggregates to monetary policy shocks across the baseline and alternative specifications.

The inclusion of the structural break has some impact on the estimates of the effects of MBS purchases - without the break, an increase in MBS purchases continues to have a negative impact on unemployment, but with a much larger lag. The impulse responses to Treasury purchases and Operation Twist shocks are very similar across specifications, while the effects of conventional monetary policy shocks are estimated to be somewhat smaller without the

break. Overall, however, the results are qualitatively robust to the specification of the time trend.

Figure 25. Responses of main macroeconomic aggregates to one standard deviation monetary policy shocks: baseline vs no break in trend



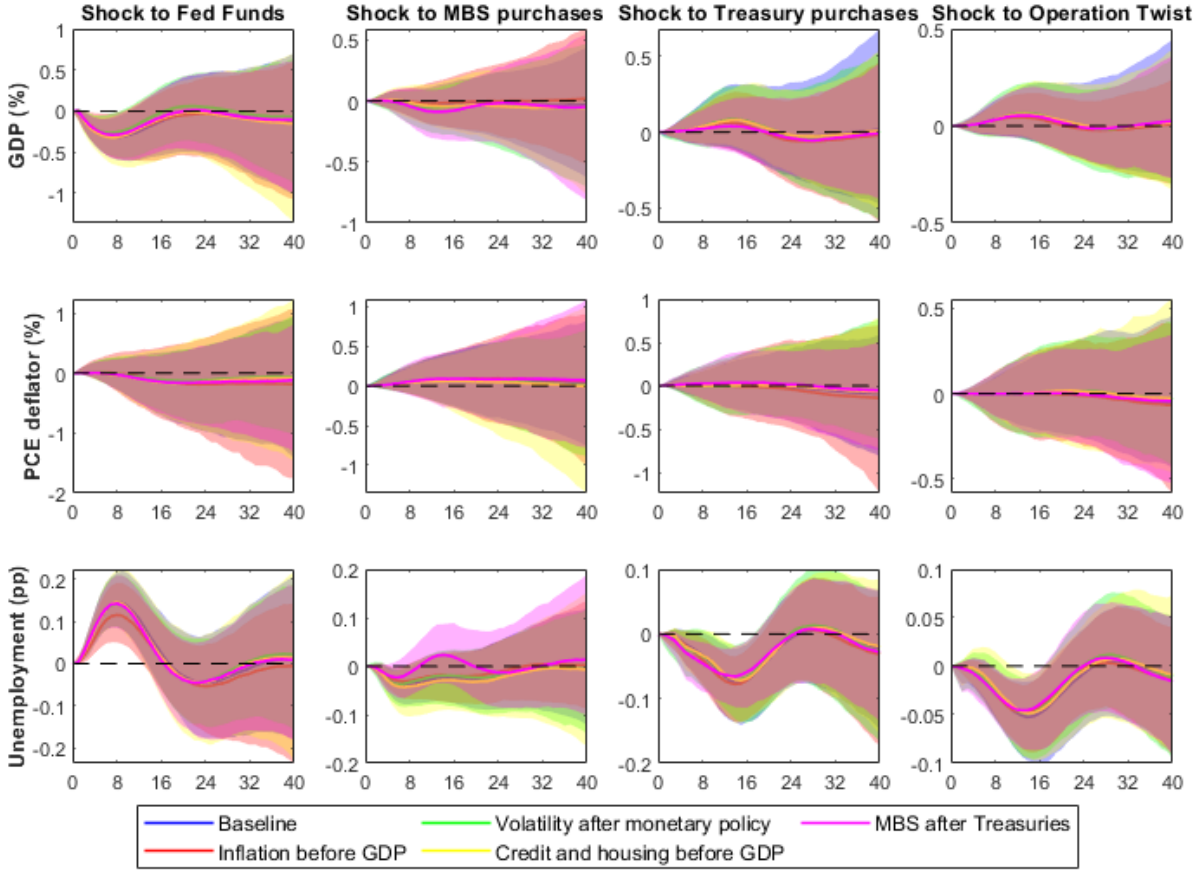
Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. One standard deviation of shocks: 0.69 pp for fed funds rate, 0.88% of total mortgages for MBS purchases, 0.29% of public debt for Treasury purchases and 0.09% of public debt for Operation Twist. The impulse responses from the alternative specification are rescaled so that the sizes of shocks are equal across specifications. On horizontal axis: quarters since the shock.

6.9 Variable order

Shocks identified using Cholesky decomposition tend to be sensitive to variable order. To investigate whether variable order has any bearing on the results, 4 alternative specifications are estimated. In the first specification, inflation-related variables (import prices and PCE deflator) are placed before economic activity variables (unemployment and GDP) to reflect the assumption that economic activity influences inflation with a lag. In the second specification, stock market volatility – as a fast-moving variable - is placed directly after monetary policy variables. In the third specification, bank credit and housing starts are placed before GDP as loans are likely to be immediately spent on consumption or investment, and thus contemporaneously affect GDP; similarly, housing starts are treated as a proxy for residential investment, which directly influences GDP. Finally, in the fourth specification, MBS purchases are placed after Treasury purchases and Operation Twist, reflecting their supporting role in QE.

The responses of main macroeconomic aggregates to monetary policy shocks across the baseline and alternative specifications are compared in Figure 26.

Figure 26. Responses of main macroeconomic aggregates to one standard deviation monetary policy shocks: different variable orderings



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. One standard deviation of shocks: 0.69 pp for fed funds rate, 0.88% of total mortgages for MBS purchases, 0.29% of public debt for Treasury purchases and 0.09% of public debt for Operation Twist. The impulse responses from the alternative specification are rescaled so that the sizes of shocks are equal across specifications. On horizontal axis: quarters since the shock.

The results are robust to the order of variables. In the vast majority of cases, the differences across specifications are negligible, both in terms of median posteriors and credible sets. Only when MBS purchases are placed after Treasury purchases and Operation Twist, their impact on unemployment is visibly smaller.

7. Discussion and conclusion

The paper finds that QE has a positive impact on economic activity as it tends to reduce unemployment. Purchases of Treasury bonds are found to be more effective than MBS purchases, while Operation Twist is at least as effective as outright purchases of government bonds. Importantly, QE is found to be transmitted into the real economy mostly via an increase in stock prices and a reduction in stock market volatility, which contradicts the theoretical literature that focuses on the role of long-term rates. Bank lending is found to

increase following Treasury purchases, but this channel plays a negligible role in the transmission of QE to the real economy.

Several extensions to the baseline specification are considered. Contrary to the majority of the literature, the effect of QE on Treasury yields does not increase with maturity, with the signalling channel playing a more important role than the price channel. Somewhat counterintuitively, MBS purchases are not found to have a stronger impact on the housing sector than Treasury purchases. Moreover, QE is found to affect investment more than consumption, with no effect on government spending and net exports. Commercial paper purchases are also studied and found to be an effective tool that reduces unemployment. Finally, the effects of Treasury purchases seem to spill over to global GDP and long-term government bonds, though these estimates are not statistically significant. In turn, these global effects spill back to the US, accounting for about 40% of the total impact of Treasury purchases on unemployment.

In the baseline specification, QE is found to be a powerful tool, which is more than capable to replace conventional monetary policy at the ZLB - QE1 Treasury purchases alone are estimated to have reduced unemployment by 0.7 pp. However, the effects of QE are not found to be very robust. In several alternative specifications, the impact of QE and Operation Twist on unemployment and GDP is found to be significantly smaller.

At the same time, the effects of conventional monetary policy are much more robust, with interest rate hikes having a consistently contractionary effect on GDP and unemployment. Therefore, the effects of QE are found to be much more uncertain than those of conventional policy. This has important implications for policymaking – while conventional policy can be relied on, the same cannot be said with full confidence about asset purchases. Hence, ZLB does constrain central banks – if not by making monetary policy impotent, then by making the effects of this policy much more uncertain.

Another important policy conclusion is the finding that MBS purchases have a smaller impact on the macroeconomy and the housing sector than Treasury purchases, even if this finding is not entirely robust. Therefore, there seems to be little rationale for conducting MBS purchases instead of Treasury purchases; at most, MBS purchases should play a supporting role to Treasury purchases. The Fed seems to have come to a similar conclusion as while in the past MBS played at least an equally important role in QE as Treasury bonds, following the COVID-19 pandemic they accounted for less than 30% of purchases.

In the robustness checks, the results are significantly affected when more variables or lags are included in the specification, suggesting that omitted variable bias is at play even in a mid-sized VAR model. This underlines the importance of a further development of methods designed to estimate large-scale models.

Importantly, the conclusion that QE transmits to the real economy mostly via the stock market means that the results presented in this paper do not necessarily generalise to other

economies. Capital markets play a much larger role in the US than virtually anywhere else in the world, including other advanced economies, which could imply that the effects of QE are stronger in the US than elsewhere. In this context, a natural further line of research would be to study the impact of QE in other jurisdictions. The pandemic QE programmes in the economies that have not previously conducted asset purchases would be of particular interest, as their macroeconomic effects have not been thoroughly studied yet.

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Appendix

A. Larger models using the Bańbura et al. (2010) method

Since the Bańbura et al. (2010) method is designed for estimating large models, I investigate whether the results obtained using this method are robust to increasing the model size. Two larger models are estimated: the 27-variable one discussed in the subsection 6.1 and the 54-variable one. The latter model additionally includes the variables considered in Section 5, additional control variables and alternative measures of economic phenomena included in the baseline specification that do, however, differ in a significant way from the variables already included in the model. Very close substitutes for the baseline variables, such as CPI and GDP deflator or alternative measures of QE, continue to be excluded from this specification. The additional variables included in the largest specification are listed in Table A. 1.

Table A. 1. Additional variables included in the 54-variable specification

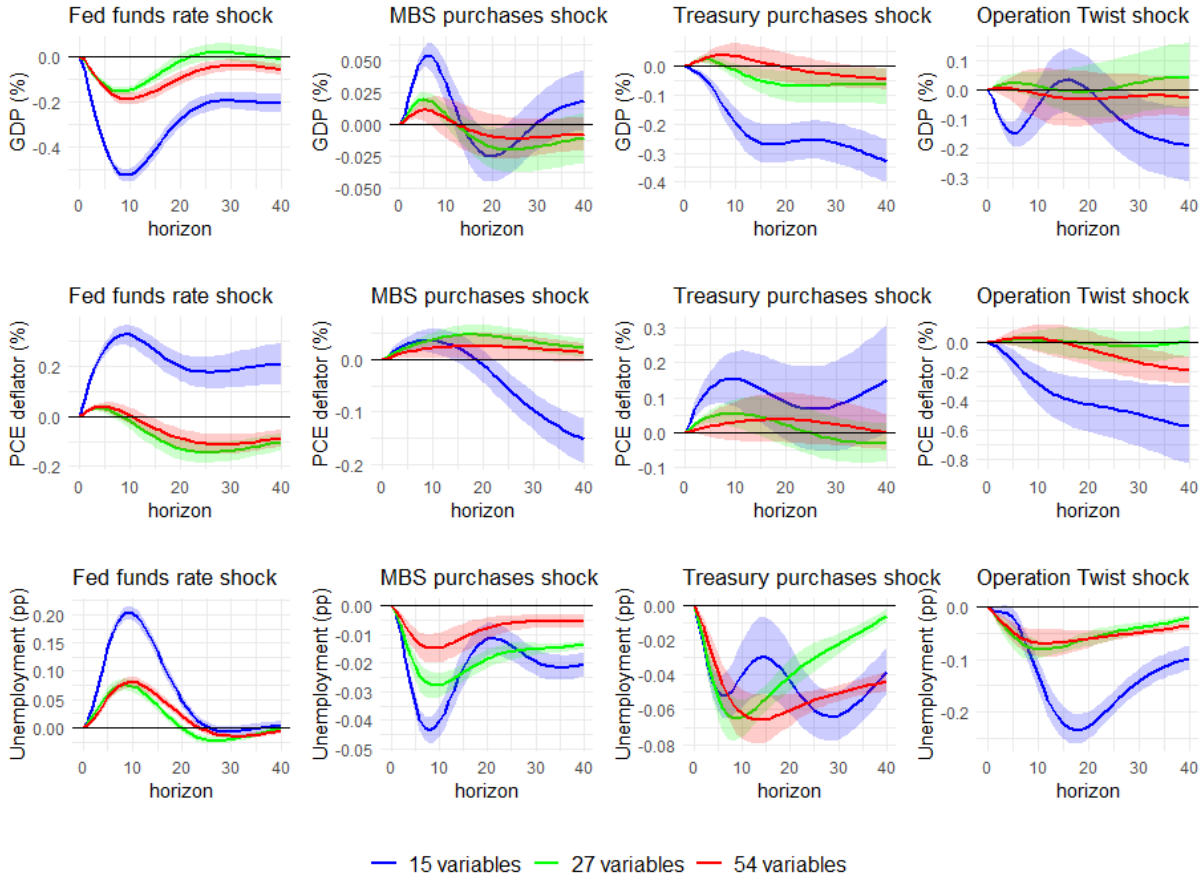
Variable	Order	Construction	Source
Employment	2	log total non-farm employees	FRED
Consumption	4	log real personal consumption expenditures	FRED
Investment	5	log real gross private domestic investment	FRED
Government consumption	6	log real government gross consumption expenditures and gross investment	FRED
Net exports	7	net exports of goods and services to GDP, per cent	FRED, own calculations
Oli prices	10	log spot crude oil price, WTI	FRED
Global energy prices	11	log global energy prices index	World Bank Commodity Price Data
Global food prices	12	log global food prices index	World Bank Commodity Price Data
Core PCE deflator	15	log PCE excluding food and energy chain-type price index	FRED
CPI abroad	17	log import-weighted CPI abroad	OECD, Bloomberg, own calculations
Total mortgages	22	all sectors total mortgages to GDP, per cent	FRED, own calculations
Household debt	23	liabilities of households and nonprofit organizations in the form of debt securities and loans to GDP, per cent	FRED, own calculations
Corporate debt	24	liabilities of nonfinancial business in the form of debt securities and loans to GDP, per cent	FRED, own calculations
Credit to non-financial sector	25	credit to private non-financial sector by banks to GDP, per cent	BIS
New home sales	27	new one family houses sold, mln of units	FRED
Housing permits	28	new privately-owned housing units authorized	FRED

		in permit-issuing places, mln of units	
1Y expected short-term rate	38	Adrian, Crump and Moench (2013) average expected future short-term rates over the next 1Y	Bloomberg
1Y term premium	39	Adrian, Crump and Moench (2013) 1Y term premium	Bloomberg
2Y expected short-term rate	40	Adrian, Crump and Moench (2013) average expected future short-term rates over the next 2Y	Bloomberg
2Y term premium	41	Adrian, Crump and Moench (2013) 2Y term premium	Bloomberg
5Y expected short-term rate	42	Adrian, Crump and Moench (2013) average expected future short-term rates over the next 5Y	Bloomberg
5Y term premium	43	Adrian, Crump and Moench (2013) 5Y term premium	Bloomberg
10Y expected short-term rate	44	Adrian, Crump and Moench (2013) average expected future short-term rates over the next 10Y	Bloomberg
10Y term premium	45	Adrian, Crump and Moench (2013) 10Y term premium	Bloomberg
1Y Treasury yield	46	1Y Treasury constant maturity rate	FRED
2Y Treasury yield	47	2Y Treasury constant maturity rate	FRED
5Y Treasury yield	48	5Y Treasury constant maturity rate	FRED

The hyperparameter λ continues to be set using the fitting method of Bańbura et al. (2010) resulting in λ declining to 0.15 and 0.10 for the 27- and 54-variable models, respectively. The impulse responses obtained from these models together with the 15-variable one, all estimated using the Bańbura et al. (2010) method, are presented in Figure A. 1.

The addition of the first 13 variables has a significant effect on the results, the addition of further 27 variables less so. In general, the estimates shrink towards zero, suggesting there might still be significant omitted variable bias in the baseline specification. Having said that, QE and Operation Twist continue to reduce unemployment. The effects on GDP and prices become more economically plausible, with slightly positive impacts of MBS and Treasury purchases and largely neutral in the case of Operation Twist. For conventional monetary policy, the prize puzzle largely disappears, but the size of the effects on GDP and unemployment declines more than twice.

Figure A. 1 Responses of main macroeconomic aggregates to 1pp monetary policy shocks: various model sizes under Bańbura et al. (2010) prior



Lines indicate median impulse responses, shaded areas represent 90% Bayesian credible sets. Shock are normalised to 1, i.e. 1 pp for fed funds rate, 1% of total mortgages for MBS purchases, 1% of public debt for Treasury purchases and 1% of public debt for Operation Twist. On horizontal axis: quarters since the shock.