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Macroeconomic Uncertainty and Capital-Skill Complementarity

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Macroeconomic Uncertainty and Capital-Skill Complementarity
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ABSTRACT: I examine the impact of macroeconomic uncertainty on labor market outcomes for skilled and unskilled workers and propose a new channel to improve our understanding of the underlying propagation mechanisms. I find that uncertainty shocks are recessionary with the unskilled experiencing a steeper fall in employment. To rationalize these findings, I build a New Keynesian DSGE model with skill heterogeneity and wage rigidities, which, coupled with precautionary labor supply, significantly amplify contractionary effects of uncertainty on the real economy.

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I. INTRODUCTION

Since the Great Recession persuasive empirical evidence has demonstrated that uncertainty is an important force driving business cycles, adversely affecting economic activity and labor market dynamics. However, while labor market segmentation resulting from differences in skills is widespread, its role in the transmission of uncertainty has been overlooked.[1] This paper contributes to the debate by studying the effects of aggregate uncertainty on employment and wages of skilled and unskilled workers, shedding light on the underlying propagation channels. A better understanding of these mechanisms could inform policies responsible for providing insurance against and insulating from such shocks.

Figure 1 provides preliminary suggestive evidence on the relationship between macroeconomic uncertainty, the relative employment rate and the skill premium.[2] I use the CPS MORG data to plot the annual averages of the cyclical components of the relative employment rate and the skill premium between 1979 to 2018.[3] First, Figure 1 highlights a strong positive correlation between the uncertainty measure and the relative employment rate (correlation coefficient is 0.38), while there is no significant relation between the uncertainty measure and the skill premium (correlation coefficient is -0.1). Second, during the recent recessions macroeconomic uncertainty soared to the unusually high levels. These periods were also characterized by increasing relative employment rate and declining wage premium. In addition, labor market indicators differ substantially depending on skill. In particular, the unskilled unemployment rate is greater and more volatile than that of the skilled, whereas skilled wages are relatively more stable than unskilled wages. While this evidence does not imply any causality in one direction or the other, below I show empirically that macroeconomic uncertainty shocks lead to increases in relative employment rate, but do not significantly affect the skill premium in the US economy.

I start the analysis by estimating a structural vector autoregression (SVAR) model of quarterly macroeconomic and labor market variables, and the macroeconomic uncertainty index of Jurado, Ludvigson, and Ng (2015) for the United States, using data from the Current Population Survey Merged Outgoing Rotation Groups (CPS MORG) to construct quarterly measures of wage and employment rates for college educated and non-college educated workers for the sample period 1979Q1–2018Q4. I find that macroeconomic uncertainty shocks increase the employment rate gap between skilled and unskilled workers

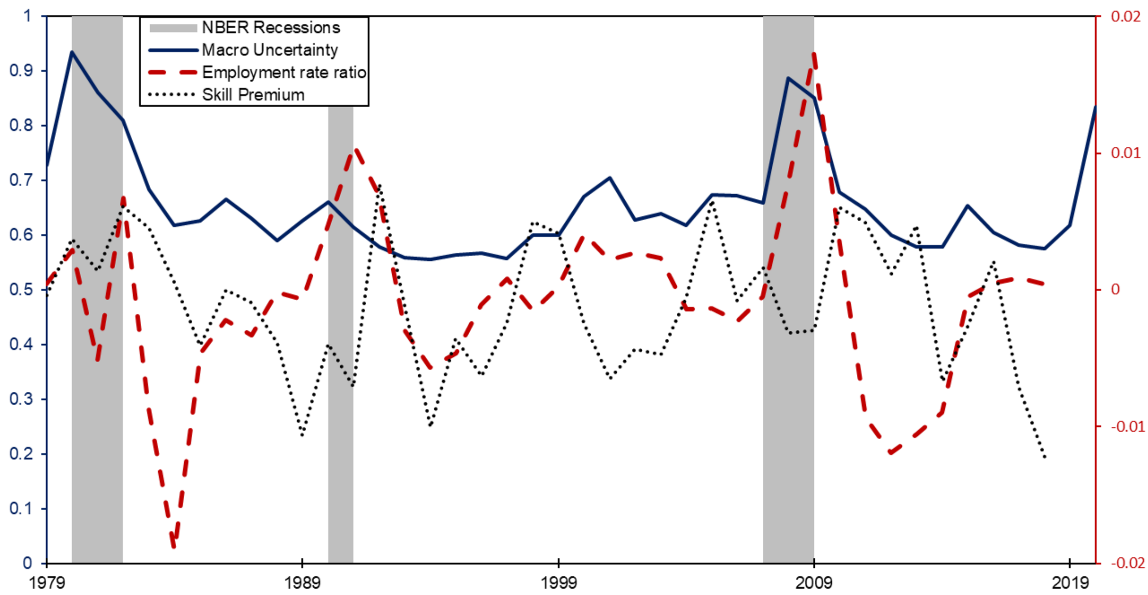
[1] Part of this literature studies the impact of uncertainty on unemployment, but considering aggregate labor market (Caggiano and Groshenny (2014), Choi and Loungani (2015), Schaal (2017), Leduc and Liu (2016), Cacciatore and Ravenna (2020), Guglielminetti (2016), and Leduc and Liu (2016)).

[2] The skill premium is defined as the ratio of a skilled wage to an unskilled wage.

[3] Construction of the data is described in Section II.

(the relative employment), while the response of the skilled-to-unskilled wage ratio (the skill premium) is negligible.

Figure 1. Macro Uncertainty and Skill Premium



Note: The solid blue line represents the macro uncertainty measure from Jurado, Ludvigson, and Ng (2015). I use the annual average of their monthly series with $h = 1$ (i.e., 1-month-ahead uncertainty). The dotted black line and the dashed red line represent the annual averages of the cyclical components of quarterly relative employment rate and skilled-to-unskilled wage premium respectively. The left-hand-side axis is related to uncertainty, and right-hand-side axis is related to the relative employment rate and the skill premium.

To rationalize these findings, I build a New-Keynesian Dynamic Stochastic General Equilibrium (DSGE) model featuring two types of households (skilled and unskilled), capital-skill complementarity and asymmetric wage rigidity. First, capital-skill complementarity in production generates interactions between skill composition of labor and capital demand. The relevance of capital-skill complementarity for the cyclical behavior of aggregate economy and the skill premium has been vastly documented in the literature (Griliches (1969), Krusell and others (2000), Lindquist (2004), Balleer and van Rens (2013), Maliar, Maliar, and Tsener (2017), Correa, Lorca, and Parro (2019)). Second, wages are "asymmetrically rigid" following empirical evidence in support of higher aggregate wage rigidity for more skilled workers due to, among other reasons, the effort of high-skilled workers being more valuable and more difficult to monitor, higher wage bargaining power of the skilled, hiring and training costs being higher for the skilled making firms more reluctant to cut their wages.[4] Uncertainty shocks are specified as shocks to the time-varying volatility of technology following Fernandez-Villaverde and others (2011). The model is calibrated to US data and solved using third-order perturbation and pruning.

In the model, an increase in uncertainty affects employment and wage gaps between skilled and unskilled workers through the interaction of capital-skill complementarity and households' precautionary labor supply, and generates responses of output, consumption, investment, employment and wages qualitatively in line with the empirical evidence. As uncertainty increases, the relative prices of capital equipment and labor fall, discouraging investment and employment. In general equilibrium, as firms adjust capital slower than labor, the capital-to-skilled labor ratio increases. With skilled labor complementary to capital, the increase in the capital-to-skilled labor ratio dampens the decline in the marginal product of skilled labor, thus attenuating the decrease in skilled labor demand and resulting in a higher relative labor ratio. Given skilled wage is more rigid, the response of the relative wage ratio is negligible. In addition, relatively smaller decline in the skilled wage implies a commensurately smaller increase in the skilled wage markup relative to the unskilled one than if wage rigidity was symmetric, amplifying the increase in the relative labor ratio.

This paper contributes to the literature that studies the role of uncertainty as a driving force of business cycles through complex transmission channels.[5] This literature has mainly focused on the behavior of firms in capital and product markets. The key transmission channels are (i) the aggregate demand channel (Basu and Bundick (2017a)) consisting in that in response to an increase in uncertainty, households lower consumption, increase savings and hours worked, resulting in lower output due to nominal price rigidities; (ii) the real option-value channel (Bernanke (1983) and Bloom (2009)) relying on investment irreversibility, for example due to non-convex adjustment costs, which induces firms to pause investment and hiring and "wait-and-see" until uncertainty is resolved.

Part of this literature, which considers the implications of uncertainty on labor market is more scarce. Empirically work (see Caggiano and Groshenny (2014), Choi and Loungani (2015), Leduc and Liu (2016)) shows that a rise in aggregate uncertainty increases unemployment. Theoretical literature has shown that labor market frictions amplify the effects of uncertainty similar to investment irreversibility through the real option-value channel in the labor market. Guglielminetti (2016) and Leduc and Liu (2016) show in a model with

[4] See, for instance for the US – Shapiro and Stiglitz (1984), Akerlof (1982) and Akerlof and Yellen (1990), Campbell and Kamlani (1997), for Europe – Cahuc, Postel-Vinay, and Robin (2006), Du Caju, Fuss, and Wintr (2009) and Babecký and others (2010).

[5] With the exception of a few papers that find no significant effect of uncertainty shocks (Bachmann and Bayer (2013)) or consider different channels of uncertainty propagation (see discussion in Bloom (2009)).

labor search-and-matching frictions that unemployment significantly increases as a result of an uncertainty shock. This paper differs in several respects. First, existing works do not consider neither investment irreversibility nor different types of labor employed in production. While previous studies focus on the effects of macroeconomic uncertainty on the aggregate employment and wages, I am interested in understanding the transmission of uncertainty on the dynamics of employment and wages of skilled and unskilled workers.

This paper also relates to the academic work on capital-skill complementarity. The hypothesis of capital-skill complementarity is not new and was first formalized by Griliches (1969)[6]. This strand of literature mostly focused on income inequality (Griliches (1969), Krusell and others (2000), Angelopoulos, Asimakopoulos, and Malley (2014), Lindquist (2004)). Krusell and others (2000) show that capital-skill complementarity is critical to explain the skill premium in the US economy. The capital-skill complementarity hypothesis has been adopted recently to study the implications of monetary and fiscal policies (Dolado, Motyovszki, and Pappa (2021), Angelopoulos, Asimakopoulos, and Malley (2014), Angelopoulos, Jiang, and Malley (2017)). In a study closest to this paper due to a similar modelling approach, Dolado, Motyovszki, and Pappa (2021) focus on the distributional effects of monetary policy. Dolado, Motyovszki, and Pappa (2021) study expansionary monetary policy shocks, which they find, as other favorable aggregate demand shocks, increase labor earnings inequality as the skill premium, the relative employment and relative labor income share increase. I consider a different nature of the shock and find that uncertainty shocks have no significant effect on the skill premium, but raise the relative employment and relative labor income share similar to expansionary monetary policy shocks. In the aggregate uncertainty literature the role of capital-skill complementarity is muted: the elasticity of substitution between labor and different types of labor is identical.

This paper bridges the aforementioned strands of literature by studying an asymmetric impact of uncertainty on skilled and unskilled labor. On the empirical side, I document the effects of macroeconomic uncertainty shocks on relative skilled employment and on the wage gap between the skilled and unskilled. The theoretical model developed in this paper rationalizes the empirical evidence and explains the propagation mechanisms.

The results indicate that policy makers should consider the increased impact of uncertainty on labor market, which depends on skill composition of labor force. Negative impact is larger on employment of the less skilled and educated, and more skilled (educated)

[6]Griliches (1969) was the first to formalize and test the capital-skill complementarity hypothesis, which he initially called "capital-schooling" complementarity. This hypothesis states that workers depending on their "skill" or "education" have different roles in production: skilled labor is more complementary with physical capital than unskilled or "raw" labor, which implies that skilled workers have a lower elasticity of substitution with capital than low-skilled workers do.

are more likely to weather economic crisis and shocks better. Policy initiatives and instruments could partly alleviate contraction. Stimulus measures of monetary policy can cushion the impact of higher uncertainty on aggregate employment. Targeted policy interventions, such as targeted vacancy subsidies could help preserve employment of unskilled workers. Maintaining or increasing government spending on education, training, including on-the-job-learning programs, can potentially improve the productivity of employed unskilled workers and increase their complementarity with technical capital. Tax policy could play an important role, for example through a reduction in capital income taxes coupled with an increase in labor income taxes. The reduction in capital taxes raises the stock of capital and, with capital-skill complementarity, the relative supply of and the relative marginal product of skilled labor. Lower capital taxes would thus encourage skill accumulation and, depending on the degree of wage stickiness lower the skill premium. In contrast, higher labor income taxes lower the benefit of skill accumulation since skilled labor income is taxed at a higher rate. However, if combined with a reduction in capital income taxes, higher labor income taxes reduce only part of the cost to accumulate skilled labor. The net effect would depend on country-specific circumstances. In addition, the unprecedented nature of the Covid pandemic highlighted the importance to invest in digital skills and technology, subsidizing internet access or low-cost computers for the more vulnerable groups. As the results show, there could be potential distributional consequences of high uncertainty at business-cycle frequencies. For a more complete picture further analyses and different models are needed.

The rest of the paper is organized as follows. In Section II I motivate further analysis by estimating the dynamic effects of uncertainty shocks on the macroeconomy in an SVAR model. Section III presents the setup of the theoretical model. Section IV provides underlying intuitions of the transmission mechanisms of macroeconomic uncertainty in the model. Section V describes the parametrization and solution method. Results and sensitivity analysis are presented and discussed in Section VI. The final section provides concluding remarks.

II. Empirical Evidence

In this section, I examine empirical effects of macroeconomic uncertainty shocks on aggregate economic dynamics and relative employment rates and relative wages in an SVAR model. SVAR estimates are based on United States data of quarterly frequency from 1979Q1 to 2018Q4. Recent studies argue that macroeconomic uncertainty is exogenous when evaluating its effects on the US macroeconomy (see Carriero, Clark, and Marcellino (2018), Piffer and Podstawski (2018), Angelini and others (2019), and Angelini and Fanelli (2019)).

Based on this evidence, I consider macroeconomic uncertainty as exogenous to the business cycle.[7]

A. Data

As a measure of uncertainty, I use the macroeconomic uncertainty index estimated by Jurado, Ludvigson, and Ng (2015) (JLN),[8] which is a broad measure of macroeconomic uncertainty. An advantage of using Jurado, Ludvigson, and Ng (2015) index is that its sample period is the longest among other reputable uncertainty measures.

Micro-level data on labor market come from the NBER extracts of the Current Population Survey (CPS) Merged Outgoing Rotation Groups (MORG),[9] which is a monthly household survey of employment and labor markets. I use these data to construct series of employment rates, relative employment rate ratio, real hourly wages for each worker skill type and the skill premium. Each monthly sample contains approximately 30,000 individuals associated with a person-level earnings weights, which when applied allow for nationally representative estimates of the US population. The data covers the period from 1979M1 to 2018M12. I restrict the sample to the individuals of the working age from 16 to 64 years old, discard self-employed individuals, observations with missing or negative person-level earnings weights, armed forces workers and observations with zero earnings. I also abstract from the individuals with missing labor force status from the dataset (no information on the employment status). I classify workers as skilled and unskilled based on educational attainment following an extensive literature, which studied the division of labor force between college and high school graduates and the resulting wage premium to skilled workers (see Acemoglu and Autor (2011), Goldin and Katz (2008) and Hornstein, Krusell, and Violante (2005)). The skilled group of workers encompasses individuals hav-

[7]For an extensive review on macroeconomic uncertainty and its exogeneity to the business cycle, see Castelnuovo (2019).

[8]The index of economic uncertainty developed by Jurado, Ludvigson, and Ng (2015) is the common variation in uncertainty across hundreds of economic series. Jurado, Ludvigson, and Ng (2015) measure uncertainty is based on squared forecast errors for a large panel of macroeconomic time series. Other proxies of macroeconomic uncertainty, namely the changes in VIX, i.e. an implied volatility measure derived from US S&P 500 options prices, are more likely to be affected by shocks specific to the stosck market rather than an increase in uncertainty about the aggregate economy (see for example, Bekaert, Hoerova, and Lo Duca (2013), Stock and Watson (2012), Caldara and others (2016)). I use the Jurado, Ludvigson, and Ng (2015) macroeconomic uncertainty index, available on the authors' personal websites, a quarterly average of monthly values for $h = 1$ (one month forecast horizon).

[9]Data were extracted from the NBER website: https://data.nber.org/data/morg.html.

ing an education qualification of college and above, and the unskilled group includes all other individuals having lower than a college degree.[10]

Hourly wages are computed as weekly earnings divided by usual weekly hours for weekly workers and hourly earnings (on the main job) for hourly workers. To construct real hourly wage series, the resulting hourly wages are deflated into constant, 2012 dollars using Consumer Price Index research series from the Bureau of Labor Statistics of the United States. The weighted averages for each skill group are calculated using the CPS MORG earnings sampling weights *earnwt*. I obtain the skill premium as the ratio between the weighted average of real hourly wages of skilled and the unskilled workers. Employment for skilled (unskilled) individuals in a given quarter is just the sum of skilled (unskilled) individuals, weighted by their sampling weight, who report to be employed in that period. Employment rate of the skilled (unskilled) is the share of employed skilled (unskilled) workers in the skilled (unskilled) labor force. Relative employment rate ratio is the ratio between employment rate of skilled and unskilled workers. I aggregate these monthly time series into quarterly ones by taking three months averages. The resulting quarterly time series are adjusted for seasonality using the X-13-ARIMA algorithm. I choose not to detrend variables as in Bachmann and Bayer (2013) and Jurado, Ludvigson, and Ng (2015). I conduct alternative estimations with linearly detrended data and using one-sided HP filter in the Appendix, Section A. A one-sided HP filter, instead of a standard two-sided HP-filter, preserves the temporal ordering of the data (Stock and Watson (1999)). As such, using a one-sided filter ensures that the time ordering of the data remains undisturbed and the autoregressive structure maintained, in contrast to a two-sided filter, which incorporates future information in the data estimates. A two-sided HP-filter takes future values to construct current filtered data, which contradicts the backward looking structure of the model solution. The rest of the series are retrieved from the FRED database. Output is real GDP (GDPC1). Consumption is real personal consumption expenditures (PCEC9C6). Investment is real gross private domestic investment (GPDIC1). The economy-wide measure of the hourly real wage is compensation per hour in the business sector (HCOMPBS) divided by the GDP deflator (GDPDEF). I obtained inflation from the percentage change in implicit price deflator (GDPDEF).

[10] Other studies, for example Acemoglu and Autor (2011), Angelopoulos, Jiang, and Malley (2017), Dolado, Motyovszki, and Pappa (2021), use the same definition for skilled and unskilled groups of workers.

B. SVAR Methodology

The SVAR-(p) model reads as follows:

$$Y_t = c + \sum_{p=1}^{P} B_p Y_{t-p} + \varepsilon_t$$

where p is the number of lags, c is a vector of constants, B_p is the coefficient matrix for the p^{th} lag of Y_t, ε_t is the vector of reduced form zero-mean innovations, and $Y_t = [\sigma_t^z \quad y_t \quad i_t \quad c_t \quad n_t^s \quad \left(\frac{n^s}{n^u}\right)_t \quad w_t^s \quad \left(\frac{w^s}{w^u}\right)_t \quad \pi_t]'$ is a vector comprising the following variables: σ_t^z the macroeconomic uncertainty measure – JLN index from Jurado, Ludvigson, and Ng (2015)[11], y_t – real GDP, i_t – real gross private domestic investment, c_t – real personal consumption expenditures, n_t^s – the skilled employment rate defined as the share of skilled employed workers in the skilled labor force, $\frac{n_t^s}{n_t^u}$ – the employment rate ratio[12], w_t^s – weighted average of real hourly wage of employed in the skilled category[13], $\frac{w_t^s}{w_t^u}$ – wage ratio (the skill premium), π_t – the quarterly growth rate of GDP implicit price deflator. I take logs of the uncertainty measure, to interpret the impulse response functions (IRFs) in percentage terms. Output, consumption, capital investment, and skilled wage enter the SVAR in log levels. In order to determine the lag order p, I use Akaike Information Criterion (AIC), which indicates that $p = 2$ is appropriate.

Uncertainty shock is defined as a one standard deviation increase in the JLN index of macroeconomic uncertainty. I identify the structural uncertainty shock via a recursive ordering (Cholesky decomposition), which is widely-employed in the uncertainty literature (see, for example Bloom (2009), Fernandez-Villaverde and others (2015), Leduc and Liu (2016) and Basu and Bundick (2017a)). It ensures that the uncertainty shock is orthogonal to the other stochastic elements in the SVAR. I order the uncertainty shock first since I assume that uncertainty is not contemporaneously affected by the state of the economy, and uncertainty has contemporaneous effect on all other variables with a delay of one quarter.

[11]The Jurado, Ludvigson, and Ng (2015) macro uncertainty measure is available at https://www.sydneyludvigson.com/data-and-appendixes/ and comes in monthly frequency, which I converted to quarterly using simple average.

[12]Inclusion of the wage and employment gaps in addition to the individual variables for skilled workers allows to interpret the responses of the respective variables for unskilled workers.

[13]Aggregated real hourly wage of employed in skilled category combines the usual hourly earnings for hourly workers (excluding otc), and non-hourly workers (including otc) in the usual hourly earnings.

C. Impulse Response Analysis

Figure 2 displays impulse responses to one standard deviation uncertainty shock. An exogenous increase in macroeconomic uncertainty leads to a persistent and significant decline in output. By the 4^{th} quarter output falls by 0.37%, while consumption and capital investment drop by 0.25% and 1.9% respectively. A contemporaneous fall in inflation, although not significant, suggests that the uncertainty shock acts like a demand shock in line with previous studies.[14] As for labor market responses, employment rate of skilled labor features a hump-shaped response and stays down for about 3 years, and it falls by 0.14% to the lowest level in the 5^{th} quarter. The relative employment rate ratio increases in the 5^{th} quarter by 0.2% suggesting that firms tend to adjust unskilled employment more than skilled jobs. Hence, the unskilled employment rate fall more substantially than the skilled one. On the other hand, the movement in the skilled wage and the wage ratio (skill premium) is negligible – the decline in the wage ratio is very insignificant of 0.07%. This implies the presence of rigidities such as wage stickiness and/or other types of frictions, which I investigate in Section VI.

As a robustness test of the baseline results, I display the IRFs of labor market variables only in the US manufacturing sector in Figure 3. I choose to focus on manufacturing since this sector has a large share of unskilled workers, it experienced intense technological changes, which resulted in massive restructuring and reallocation of activity during the 1990s (Foster, Haltiwanger, and Krizan (2006)), and it also exhibits the elasticities of substitution between production inputs in line with capital-skill complementarity hypothesis (Blankenau and Cassou (2011)) imitating the main ingredient of the theoretical model. The IRFs in Figure 3 seem to qualitatively and quantitatively trace the IRFs reported earlier for the aggregate data in Figure 2.

D. FEVD

I assess the contribution of macroeconomic uncertainty shocks to the dynamics of variables of interest by performing a forecast error variance decomposition (FEVD). Table 1 reports the FEVD of the uncertainty shock computed from the IRFs at several horizons. The variance decomposition shows that macroeconomic uncertainty shocks account for around 20% of fluctuations of real GDP and 12% of fluctuations of real consumption over medium-run horizons (about 4 years). Meanwhile, macroeconomic uncertainty shocks

[14] Caggiano and Groshenny (2014), Fernandez-Villaverde and others (2015), Bonciani and van Roye (2016), Leduc and Liu (2016), and Basu and Bundick (2017a)

Table 1. Role of macroeconomic uncertainty. Forecast error variance decomposition of macroeconomic uncertainty shock.

	σ_t^g	$\log(y_t)$	$\log(i_t)$	$\log(c_t)$	n_t^s	$\frac{n_t^s}{n_t^u}$	w_t^s	$\frac{w_t^s}{w_t^u}$	π_t
1 quarter	1.000	0.0908	0.0347	0.0631	0.0010	0.0414	0.0013	0.0019	0.0049
4 quarters	0.8709	0.2256	0.2066	0.1543	0.1431	0.2379	0.0218	0.0053	0.0377
8 quarters	0.6860	0.2520	0.2471	0.1646	0.3315	0.3482	0.0249	0.0037	0.0454
16 quarters	0.5556	0.1903	0.2145	0.1213	0.3859	0.3444	0.0148	0.0109	0.0487
40 quarters	0.4865	0.1201	0.2227	0.0869	0.3433	0.3133	0.0407	0.0237	0.0739

have a more negligible impact on the forecast variance of inflation at all horizons. Notably, macroeconomic uncertainty is estimated to be responsible for an important share of variance of employment, accounting for around 15% of fluctuations in skilled employment over the horizon of 12 month, in line with Jurado, Ludvigson, and Ng (2015), and accounting for 35% of fluctuations in skilled employment and employment rate ratio. These results are in line with the literature arguing that macroeconomic uncertainty is an important driver of the business cycle (Bloom (2009), Jurado, Ludvigson, and Ng (2015), Caggiano and Groshenny (2014), among others). On the other hand, macroeconomic uncertainty is negligible for any fluctuations in wages, in line with studies by Charles, Darné, and Tripier (2017) and Henzel and Rengel (2017) that report a similar result.

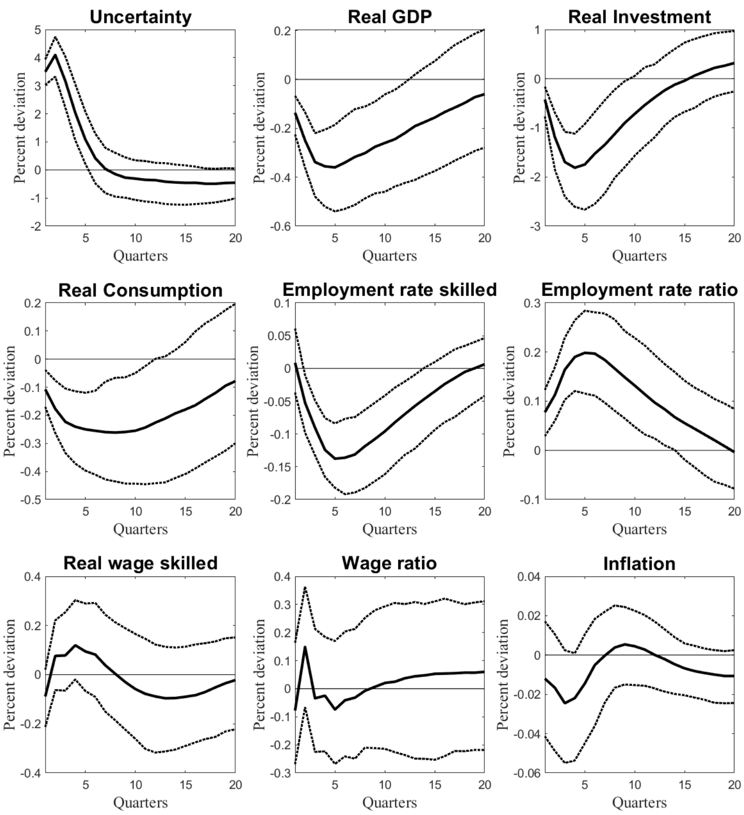
E. Further Discussion

The stylized facts relevant to a theoretical model presented in the next section to provide new insights about the interaction between macroeconomic uncertainty shocks and labor market can be briefly summarized as follows:

- Macroeconomic uncertainty shock is recessionary – it lowers aggregate output, consumption, investment, and both skilled and unskilled employment.
- An unexpected rise in macroeconomic uncertainty leads to a significant increase in the relative employment rate of skilled labor.
- The skill premium and wages do not respond significantly to the uncertainty shock.

These findings have an important implication for understanding the mechanisms through which the uncertainty shock affects the labor market. The SVAR corroborates previous

Figure 2. Impulse responses to 1-sd uncertainty shock.



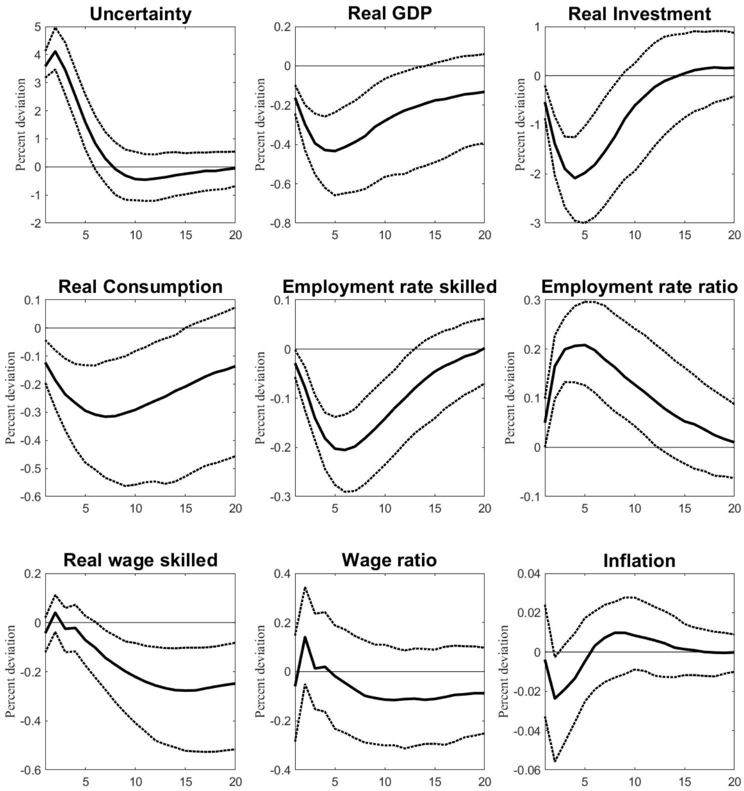
Note: Solid lines correspond to the median IRFs while the dashed lines are the 10^{th} and 90^{th} percentiles. Horizontal axes indicate quarters. I take logs of the uncertainty measure, to interpret the IRFs in percentage terms. Output, consumption, capital investment, and skilled wage are expressed in logs. Following the Akaike Information Criterion (AIC), the number of lags is set to 2. The JLN macroeconomic uncertainty index is measured in arbitrary units and has a mean of 0.65.

findings that uncertainty shocks lead to overall economic contraction and reduces employment. Regarding the relative responses of skilled and unskilled employment rates, there are important reasons why we should expect them to differ. In the present paper I focus on the explanation of the behavior of the relative employment relying on complementarity between skills and capital.[15]

The core idea of capital-skill complementarity is that skilled workers are more complementary to capital than unskilled workers are. In the presence of capital-skill complementarity, any changes in capital lead to corresponding adjustments in demand for more qualified labor, which in turn affects skilled employment and wages. For example, a re-

[15] Caggiano and Groshenny (2014) and Choi and Loungani (2015) are examples of previous studies that found the importance of this channel.

Figure 3. Impulse responses to 1-sd uncertainty shock in manufacturing sector.



Note: Solid lines correspond to the median IRFs while the dashed lines are the 10^{th} and 90^{th} percentiles. Horizontal axes indicate quarters. I take logs of the uncertainty measure, to interpret the IRFs in percentage terms. Output, consumption, capital investment, and skilled wage are expressed in logs. Following the AIC, the number of lags is set to 2.

duction in investment, which directly translates into a fall in capital stock, would lower skilled marginal product of labor. This complementarity is an important factor to affect the demand for labor and may be responsible for the different effects of uncertainty shocks on skilled and unskilled employment and wages. The stylized fact above indicates that elevated uncertainty has a more negative effect on unskilled employment than skilled employment. Qualified individuals may tend to exhibit a more precautionary behavior when uncertainty increases. They may increase their labor supply more relative to less skilled individuals as they would want to insure themselves against the possibility of adverse shocks arising in the future. This stronger precautionary behavior of skilled groups may be due to higher awareness of more qualified and/or educated individuals about the risks of future shocks brought about by higher uncertainty. Additionally, the higher relative employment might be due to the fact that skilled employment is usually more stable than unskilled employment. Labor hoarding could be another reason for an increase in the employment rate ratio. In downturns firms are likely to resort to hoarding of especially skilled, qualified and educated labor due to higher hiring and lay-off adjustment costs of skilled workers (see for example, Bentolila and Bertola (1990)). Additionally, firms that face uncertainty are more reluctant to adjust skilled employment due to skilled human capital being firm-specific (see for example, Becker (1964)).

The non-responsiveness of wages suggests the presence of wage rigidities consistent with concurrent findings in the literature that firms use variations in hours worked and pay forms different to wages in order to flexibilize labor cost, so that declines in base wages are exceedingly infrequent (see for example, Kurmann and McEntarfer (2019)). Since 2000s roughly 14% of workers among those who have not changed their jobs over the past year reported a zero wage change according to the US data from Wage Rigidity Meter.[16]

In the following section, I describe the theoretical model to rationalize the empirical findings.

III. The Model

To reproduce the empirical findings, I build a New Keynesian DSGE model featuring a technology process with stochastic volatility. The economy consists of a continuum of infinitely-lived households, a continuum of firms producing differentiated intermediate goods, a perfectly competitive firm producing a final good, a fiscal authority, and a central bank. The production technology is not of the standard neoclassical form, but of the form of an empirically plausible capital-skill complementarity through a CES production function.[17] Firms are of two types: wholesalers (or intermediate good firms), producing intermediate goods with skilled and unskilled labor and capital as inputs and facing capital adjustment costs, and one representative retailer, who combines intermediate goods to produce a homogeneous final good under staggered price setting à la Calvo (1983). Heterogeneity in the population shows through three types of households – entrepreneurs,

[16]The Wage Rigidity Meter is published by the Federal Reserve Bank of San Francisco. It is constructed from CPS data on individuals that have not changed jobs over the course of a year and it shows the percentage of workers with no wage change. It is available from https://www.frbsf.org/economic-research/indicators-data/nominal-wage-rigidity/

[17]This assumption on technology is in line with the empirical evidence provided by numerous studies (see Maliar, Maliar, and Tsener (2017), Skaksen and A. (2005), Krusell and others (2000), Lindquist (2004), Pourpourides (2011), Duffy, Papageorgiou, and Perez-Sebastian (2004), Cantore and others (2015)).

skilled and unskilled workers.[18] As for notation, for any real variable x_t I will denote its value in nominal terms with X_t and its steady state value with x.

A. Households

Population is composed of three different household types – skilled and unskilled workers, and entrepreneurs – who share some common features. These households are indexed by $i \in \{s,u,e\}$ corresponding to skilled, unskilled and entrepreneur households, and are of size π^i, $i \in \{s,u,e\}$, respectively. Total population of the economy is normalized to one so that $\sum_i \pi^i = 1$. The number of these three types of households in the population, π^i, is constant so that it is not possible to transition from one household type to another.[19] These households are ex-ante identical apart from that the entrepreneurs do not supply labor, but invest in capital, own firms and derive income from firms' dividends,[20] whereas workers receive only wage income. The reason entrepreneurs are in the model is to isolate labor income as well as to avoid any income effects and labor supply effects stemming from receiving dividends and owning capital in the economy. This assumption also captures the notion that equity ownership is extremely concentrated (see for example, Kuhn and Rios-Rull (2016)).

1. Skilled and Unskilled Worker Households

Two skilled and unskilled worker households indexed by $i \in (s,u)$ respectively are differentiated by their level of skills and supply labor. These households are also heterogenous and are indexed by $j \in (0;1)$, in the sense that they supply differentiated labor input to the labor packer. These worker households have similar characteristics apart from their roles in the production process. Time constraints of working households are normalized to 1 so that for a i-type household $h_t^i + l_t^i = 1$, where h_t^i is hours worked and l_t^i is leisure. Each household i consumes c_t^i and saves by purchasing zero-coupon nominal non-state contingent risk-free government bond holdings B_t, which pay a gross nominal return R_t, pays a tax t_t^i levied to finance government expenditure, receives a real labor income w_t^i for hours worked h_t^i, where w_t^i is the real wage. Inflation rate is defined as $\pi_t = \frac{p_t}{p_{t-1}}$. The utility of skilled and unskilled households is separable depending positively on consumption

[18] In modeling household types I follow the set-up similar to Dolado, Motyovszki, and Pappa (2021) and Broer and others (2020).

[19] Angelopoulos, Jiang and Malley (2017) show on time series data on relative skill supply that in business cycle frequencies there is not much labor movement between the skilled and unskilled sectors.

[20] The income from capital ownership could also be interpreted as income from human capital and therefore as a form of wage income. The key distinction is that capitalists supply their human capital inelastically and the return to human capital is flexible.

and negatively on labor. In the environment with complete markets and separable utility in consumption and labor, households will be identical in their choice of consumption and bond holdings, and will only differ in the wage they charge and labor supply (Erceg, Henderson, and Levin (2000)). Hence, I drop dependence on j for consumption and bonds, but leave it for wages and labor input.

The skilled and unskilled households maximize the following lifetime utility function

$$\mathscr{U}_t^i = \mathbb{E}_t \sum_{t=0}^{\infty} \beta \Big[\frac{(c_t^i - b_c c_{t-1}^i)^{1-\sigma_u^i}}{1-\sigma_u^i} - \kappa_h^{i,j} \frac{(h_t^{i,j})^{1+\phi^i}}{1+\phi^i} \Big] \tag{1}$$

where E_0 is the expectation operator conditional on the information available in period 0, $\beta \in (0,1)$ is the subjective discount factor, ϕ^i is the inverse of Frisch elasticity of labor supply, κ_h is a scale parameter, σ_u^i is the intertemporal elasticity of substitution, and b_c expresses the degree of habit in consumption.

Budget constraint of worker households is

$$c_t^i + t_t^i + \frac{B_{t+1}\pi_{t+1}}{R_t} = w_t^{i,j} h_t^{i,j} + B_t \tag{2}$$

where on the r.h.s. is the i-household's income in period t, which equals the sum of the wages, and the household's receipts from government bonds B_t and on the l.h.s. is the household's expenditure on consumption c_t^i, taxes t_t^i and new acquisition of bonds.

The problem of the worker household is to choose consumption, and asset holdings to maximize the intertemporal utility subject to the budget constraint (2). The Lagrangean of the problem of the household in real terms reads as

$$\mathscr{L}^i = \frac{(c_t^i)^{1-\sigma_u^i}}{1-\sigma_u^i} - \kappa_h^i \frac{(n_t^{i,j})^{1+\phi^i}}{1+\phi^i} - \lambda_t^i \left[c_t^i + t_t^i + \frac{B_{t+1}\pi_{t+1}}{R_t} - w_t^{i,j} h_t^{i,j} - B_t \right]$$

where λ_t^i is the Lagrangean multiplier associated with the budget constraint, also interpreted as the marginal utility of wealth.

The first order conditions with respect to B_{t+1} and c_t^i are

$$B_{t+1} \ : \ \beta \mathrm{E}_t \left\{ \lambda_{t+1}^i \frac{R_t}{\pi_{t+1}} \right\} = \lambda_t^i \tag{3}$$

$$c_t^i \ : \ \lambda_t^i = (c_t^i)^{-\sigma_u^i} \tag{4}$$

where λ_t^i is the Lagrangian multiplier associated to the budget constraint 2. Equation 3 is the Euler equation, which determines the intertemporal dynamics of the marginal utility of consumption as a function of the real return on bonds. Equation 4 describes the evolution of consumption.

Turning to the choice of labor and wages, there is a labor packer, which hires the labor supplied by each skilled household s, j and unskilled household u, j, combines it into a composite labor good that it then supplies to wholesale firms at wage rate $w_t^i, i \in (s,u)$.

$$h_t^i = \left[\int_0^1 (h_t^{i,j})^{\frac{\eta_w - 1}{\eta_w^i}} dj \right]^{\frac{\eta_w^i}{\eta_w^i - 1}} \tag{5}$$

where $0 \leq \eta_w^i \geq \infty$ is the elasticity of substitution among different types of skilled and unskilled labor ($i \in (s,u)$) and h_t^i is the aggregate labor-i demand. Labor packers maximize profits in a perfectly competitive environment. From the FOCs of the labor packers one obtains the input demand function associated with the problem of the labor packer

$$h_t^{i,j} = \left(\frac{w_t^{i,j}}{w_t^i} \right)^{-\eta_w^i} h_t^i \tag{6}$$

Aggregate wage is

$$w_t^i = \left[\int_0^1 (w_t^{i,j})^{1-\eta_w^i} dj \right]^{\frac{1}{1-\eta_w^i}} \tag{7}$$

Skilled and unskilled households set their wages following a Calvo's setting. I introduce nominal wage stickiness in the model by assuming that each period, a fraction $(1-\theta_w^s)$ of skilled and a fraction $(1-\theta_w^u)$ of unskilled households can change their wages. All other households can only set their wage equal to the nominal wage observed in the previous period in case of no wage indexation, or partially index their wage by past inflation. Indexation is controlled by the parameter $\chi^w \in [0,1]$. Therefore, the relevant part of the Lagrangian for the household $i \in (s,u)$ is then:

$$\begin{aligned}\mathscr{L}^{i,w} &= E_t \sum_{s=0}^{\infty} (\theta_w^i \beta)^s \left[-\kappa_h^i 1 + \phi^i \left(\prod_{k=1}^{s} \left(\frac{\pi_{t+k}}{\pi_{t+k-1}^{\chi^w}} \right)^{-1} \frac{w_t^{i,j}}{w_{t+s}^i} \right)^{-\eta_w^i (1+\phi^i)} (h_{t+s}^i)^{1+\phi^i} \right. \\ & \left. + \lambda_{t+s}^{i,j} \left(\prod_{k=1}^{s} \left(\frac{\pi_{t+k}}{\pi_{t+k-1}^{\chi^w}} \right)^{-1} \frac{w_t^{i,j}}{w_{t+s}^i} \right)^{1-\eta_w^i} w_t^i h_{t+s}^i \right] \end{aligned} \tag{8}$$

All skilled and unskilled households $i \in (s,u)$ set the same skilled and unskilled wage respectively because complete markets allow them to hedge the risk of the timing of wage change. Hence, I drop the j from the choice of wages and $\lambda_t^{i,j}$. The first order condition with respect to w_t^i therefore is:

$$\begin{aligned} E_t \textstyle\sum_{s=0}^{\infty} (\theta_w^i \beta)^s & \left[\frac{\eta_w^i}{w_t^{i,*}} \kappa_h^i \left(\prod_{k=1}^{s} \left(\frac{\pi_{t+k}}{\pi_{t+k-1}^{\chi^w}} \right)^{-1} \frac{w_t^{i,*}}{w_t^{i+s}} \right)^{-\eta_w^i (1+\phi^i)} (h_{t+s}^i)^{1+\phi^i} \right. \\ & \left. + (1-\eta_w^i) \lambda_{t+s}^i \left(\prod_{k=1}^{s} \left(\frac{\pi_{t+k}}{\pi_{t+k-1}^{\chi^w}} \right)^{-1} \frac{w_t^{i,*}}{w_{t+s}^i} \right)^{-\eta_w^i} h_{t+s}^i \right] \end{aligned} \tag{9}$$

The wage-setting equation can be rewritten in recursive form by first defining

$$f_t^{i,1} = \left(\frac{\eta_w^i - 1}{\eta_w^i} \right) w_t^{i,*} E_t \sum_{s=0}^{\infty} (\beta \theta_w^i)^s \lambda_{t+s}^i \left(\frac{w_{t+s}^i}{w_t^{i,*}} \right)^{\eta_w^i} h_{t+s}^i \prod_{k=1}^{s} \left(\frac{\pi_{t+k}}{\pi_{t+k-1}^{\chi^w}} \right)^{\eta_w^i - 1}$$

$$f_t^{i,2} = E_t \sum_{s=0}^{\infty} (\beta \theta_w^i)^s \kappa_h^i \prod_{k=1}^{s} \left(\frac{\pi_{t+k}}{\pi_{t+k-1}^{\chi^w}} \right)^{\eta_w^i (1+\phi^i)} \left(\frac{w_{t+s}^{i,*}}{w_t^{i,*}} \right)^{\eta_w^i (1+\phi^i)} (h_{t+s}^i)^{1+\phi^i}$$

so that the equality $f_t^{i,1} = f_t^{i,2}$ is the previous first order condition.

I consider a symmetric equilibrium where $w_t^{i,j,*} = w_t^{i,*}$. Expressing $f_t^{i,1}$ and $f_t^{i,2}$ recursively and defining $f_t^i = f_t^{i,1} = f_t^{i,2}$ I obtain the laws of motion for f_t^i

$$f_t^i = \left(\frac{\eta_w^i - 1}{\eta_w^i} \right) (w_t^{i,*})^{1-\eta_w^i} \lambda_t^i (w_t^i)^{\eta_w^i} h_t^i + (\beta \theta_w^i) E_t \left(\frac{\pi_t}{\pi_{t-1}^{\chi^w}} \right)^{\eta_w^i - 1} \left(\frac{w_{t+1}^{i,*}}{w_t^{i,*}} \right)^{\eta_w^i - 1} f_{t+1}^i \tag{10}$$

$$f_t^i = \kappa_h^i (h_t^i)^{1+\phi^i} (\frac{w_t^i}{w_t^{i,*}})^{\eta_w^i(1+\phi^i)} + (\beta\theta_w^i) E_t \left(\frac{\pi_t}{\pi_{t-1}^{\chi^w}}\right)^{\eta_w^i(1+\phi^i)} (\frac{w_{t+1}^{i,*}}{w_t^{i,*}})^{\eta_w^i(1+phi^i)} f_{t+1}^i \tag{11}$$

In a symmetric equilibrium, in every period, a fraction $(1-\theta_w^i)$ of skilled and unskilled households $i \in (s,u)$ set $w_t^{i,*}$ as their wage, while the remaining fraction θ_w^i set their wage equal to the nominal wage observed in the previous period in case of no wage indexation, or partially index their wages by past inflation. Thus, the real wage index of skilled and unskilled households evolves as

$$(w_t^i)^{1-\eta_w^i} = \theta_w^i \left(\frac{\pi_t}{\pi_{t-1}^{\chi^w}}\right)^{\eta_w^i - 1} (w_{t-1}^i)^{1-\eta_w^i} + (1-\theta_w^i)(w_t^{i,*})^{1-\eta_w^i} \tag{12}$$

2. Entrepreneurs

I assume that the entrepreneur households own firms, invest in physical capital, do not participate in the labor market and enjoy leisure equal to 1. Entrepreneurs' preferences are described by the following utility function

$$\mathscr{U}_t^e = \mathbb{E}_t \sum_{t=0}^{\infty} \beta \left[\frac{(c_t^e - b_c c_{t-1}^e)^{1-\sigma_u^e}}{1-\sigma_u^e}\right] \tag{13}$$

The entrepreneur household consumes c_t^e and saves by purchasing zero-coupon nominal non-state contingent government bonds B_t, which pay a gross nominal return R_t, or by investing in physical capital k_t^e, which it rents to intermediate goods firms at a rental rate R_t^k, receives dividends from firms, div_t. Budget constraint of the entrepreneur household is

$$c_t^e + t_t^e + \frac{B_{t+1}\pi_{t+1}}{R_t} + i_t^e = div_t + B_t + R_t^k k_{t-1}^e \tag{14}$$

where div_t is the household's share of firms' dividends, net of a government lump-sum tax.[21]

[21]Wholesalers' profits are redistributed to the entrepreneur households in the form of dividends, see Section (III.B).

$$\pi^e div_t = x_t y_t - \left(w_t^s n_t^s + w_t^u n_t^u + R_t^k k_t\right) \tag{15}$$

Capital accumulation evolves according to the law of motion

$$i_t^e = k_{t+1}^e - (1-\delta_i)k_t^e + D\left(k_{t+1}^e, k_t^e\right) \tag{16}$$

The function $D\left(k_{t+1}^e, k_t^e\right)$ denotes capital adjustment costs (see Lucas and Prescott (1971) or Christiano, Eichenbaum, and Rebelo (2011)). This function implies that it is costly to change the level of capital. This adjustment cost is increasing in the change in capital, and there are no adjustment costs in the steady state. The log-linearized dynamics around the steady state are influenced only by the curvature of the adjustment cost function, $D^{''}(1)$. I use the following specification of the functional form of capital adjustment cost $D\left(k_{t+1}^e, k_t^e\right)$

$$D\left(k_{t+1}^e, k_t^e\right) = \frac{\phi_i}{2}\left(\frac{k_{t+1}^e}{k_t^e} - 1\right)^2 k_t^e, \phi_i < 0$$

Parameter ϕ_i governs the magnitude of adjustment costs to capital accumulation and depreciation rate is $0 < \delta < 1$, $D(1) = D^{'}(1) = 0$. When $\phi_i \to \infty$ investment and the stock of capital become constant.

The problem of the entrepreneur household is to choose consumption c_t^e, asset holdings B_{t+1}, investment i_t^e and next period capital k_{t+1}^e to maximize the intertemporal utility subject to the budget constraint and the law of motion of capital. The Lagrangean of the entrepreneur households' problem in real terms reads as

$$\mathscr{L}^e = \frac{(c_t^e - b_c c_{t-1}^e)^{1-\sigma_u}}{1-\sigma_u} - \lambda_t^e \left[c_t^e + t_t^e + \frac{B_{t+1}\pi_{t+1}}{R_t} + i_t^e - div_t - B_t - R_t^k k_{t-1}^e\right]$$
$$- Q_t \left[k_{t+1}^e - (1-\delta)k_t^e + D\left(k_{t+1}^e, k_t^e\right) - i_t^e\right]$$

where λ_t^e is the entrepreneur Lagrangean multiplier associated with the budget constraint, also interpreted as the marginal utility of wealth; and $q_t^i = \frac{Q_t}{\lambda_t^e}$ is the Tobin's Q marginal ratio with Q_t – the Lagrange's multiplier associated with the dynamics of capital stock.

The first order conditions with respect to c_t^e, B_{t+1}, and k_{t+1}^e are

$$c_t^e : \lambda_t^e = (c_t^e - b_c c_{t-1}^e)^{-\sigma_u^e} - \beta b_c (c_{t+1}^e - b_c c_t^e)^{-\sigma_u^e} \tag{17}$$

$$B_{t+1} : \beta^t \mathbb{E}_t \frac{\lambda_{t+1}^e R_t}{\pi_{t+1}} = \lambda_t^e \tag{18}$$

$$k_{t+1}^e : \lambda_t^e \left(1 + \phi_i \left[\frac{k_{t+1}^e}{k_t^e} - 1\right]\right) = \beta \lambda_{t+1}^e \left(1 + R_{t+1}^k - \delta + \frac{\phi_i}{2}\left(\frac{k_{t+2}^e}{k_{t+1}^e}\right)^2 - 1\right) \tag{19}$$

I assume complete markets, the perfect risk-sharing and full insurance between households by following Dolado, Motyovszki, and Pappa (2021). Combining equations of households' F.O.C. (18) and (3) leads to the following perfect risk sharing condition:

$$\frac{\lambda^i_{t+1}}{\lambda^e_{t+1}} = \frac{\lambda^i_t}{\lambda^e_t} = \frac{\bar{\lambda}^i}{\bar{\lambda}^e} \text{ for } i \in (s,u) \tag{20}$$

This equation 20 keeps the ratio of different agents' marginal utilities constant at its steady-state value.

B. Wholesale Firms

There is a continuum of perfectly competitive wholesalers that produce a homogeneous wholesale good y_t with identical production functions and sell it to retailers at a relative price x_t. Retailers then produce a differentiated final good.[22] The assumption of constant returns to scale in production implies that all firms have the same capital-labor ratio as well as the marginal product of labor and allows to aggregate across firms without loss of generality. The wholesale good is produced by the aggregate production technology $\mathscr{Z}_t f(k_t, n^s_t, n^u_t)$, where $\mathscr{Z}_t$ is aggregate TFP, $k_t = \pi^e k^e_t$ is aggregate capital with π^e population share of entrepreneurs, $n^s_t = \pi^s h^s_t$ and $n^u_t = \pi^u h^u_t$ are labor supplies of skilled and unskilled households with π^s and π^u population shares of skilled and unskilled households respectively.

Consistent with the recent empirical literature on the behavior of the skill premium (see, e.g., Krusell and others (2000), I postulate that the production function exhibits capital-skill complementarity. The aggregate production function is a three factor-nested CES composite of production factors. This form of the production function allows me to capture capital-skill complementarity since it allows to set separately the elasticity of substitution between capital and skilled labor and the elasticity of substitution between skilled and unskilled labor.[23]

$$y_t \equiv \mathscr{Z}_t f(k_t, n^s_t, n^u_t) = \mathscr{Z}_t([\mu(n^u_t)^\sigma + (1-\mu)(\lambda k^\rho_t + (1-\lambda)(n^s_t)^\rho)^{\frac{\sigma}{\rho}}]^{\frac{1}{\sigma}}) \tag{21}$$

where k_t is aggregate capital, n^s_t is aggregate skilled labor and n^u_t is aggregate unskilled labor, and $\sigma, \rho \in (-\infty, 1)$ in order to maintain strict quasi-concavity of the production function. Parameter λ governs the capital intensity of production process and parameter μ governs how skill-intensive production process is. The elasticity of substitution be-

[22]There are two types of firms – wholesalers and retailers in order to keep traction.

[23]In choosing the functional form of production function I follow the capital-skill complementarity literature, namely Hamermesh (1993), Krusell and others (2000), Maliar and Maliar (2011), Lindquist (2004).

tween capital and skilled labor is $\varepsilon_{k,n^s} = \frac{1}{1-\rho}$ and the elasticity of substitution between capital and unskilled labor (the same as the elasticity of substitution between skilled and unskilled labor)[24] is $\varepsilon_{k,n^u} \equiv \varepsilon_{n^s,n^u} = \frac{1}{1-\sigma}$.[25] In the CES framework, the values of ε_{k,n^s} and ε_{k,n^u} play a critical role because they determine how changes in either technology or supplies affect demand and wages. Following Krusell and others (2000), capital-skill complementarity maintains if and only if the elasticity of substitution between capital and skilled labor is lower than the one between capital and unskilled labor, i.e. $\frac{1}{1-\rho} < \frac{1}{1-\sigma}$, which implies $\sigma > \rho$.[26]

Following the definition of Krusell and others (2000) the condition $\sigma > \rho$ imposes capital-skill complementarity, i.e. skilled labor is more complementary to capital than unskilled labor. One can show that the relative marginal product of skilled labor mpl_t^s/mpl_t^u associated with the production function in Equation 21 is decreasing in the relative demand for skilled workers, $\frac{\partial(mpl_t^s/mpl_t^u)}{\partial(n_t^s/n_t^u)} < 0$, all else held constant, which is the *relative supply effect*. The second effect is *capital-skill complementarity effect* – the skill premium is increasing in the capital-skill ratio, $\frac{\partial(mpl_t^s/mpl_t^u)}{\partial(k_t/n_t^s)} > 0$, all else held constant. The relative marginal product of skilled labor is given by

$$\frac{mpl_t^s}{mpl_t^u} = \frac{(1-\mu)(1-\lambda)}{\mu}\left[\lambda\left(\frac{k_t}{n_t^s}\right)^{\rho} + (1-\lambda)\right]^{\frac{\sigma}{\rho}-1}\left(\frac{n_t^u}{n_t^s}\right)^{(1-\sigma)} \tag{22}$$

where mpl_t^i is the marginal product of i-type labor.

Maximization of profits by wholesalers yields the following F.O.C. given the form of the production function in equation (21) with respect to capital, k_t, employment of skilled, n_t^s, and unskilled labor, n_t^u.

$$\frac{R_t^k}{x_t} = (1-\mu)\lambda\left(\lambda k_t^{\rho} + (1-\lambda)(n_t^s)^{\rho}\right)^{\frac{\sigma}{\rho}-1} k_t^{\rho-1} y_t^{1-\sigma} \tag{23}$$

$$\frac{w_t^s}{x_t} = (1-\mu)(1-\lambda)(\lambda k_t^{\rho} + (1-\lambda)(n_t^s)^{\rho})^{\frac{\sigma}{\rho}-1}(n_t^s)^{\rho-1} y_t^{1-\sigma} \tag{24}$$

$$\frac{w_t^u}{x_t} = \mu(n_t^u)^{\sigma-1} y_t^{1-\sigma} \tag{25}$$

[24]This CES three-factor-nested production function has a symmetry property that the elasticity of substitution between capital equipment and unskilled labor is the same as the elasticity of substitution between skilled and unskilled labor.

[25]To derive this, I solved for $w^s \equiv \frac{\partial y}{\partial n^s}$, $w^u \equiv \frac{\partial y}{\partial n^u}$ and $R^k \equiv \frac{\partial y}{\partial k}$, divided, reorganized, took logs, and took a derivative to find $\varepsilon_{k,n^s} = \frac{\partial \log(\frac{n^s}{k})}{\partial \log(\frac{w^s}{R^k})} = \frac{1}{1-\rho}$ and $\varepsilon_{k,n^u} \equiv \varepsilon_{n^s,n^u} = \frac{\partial \log(\frac{n^u}{k})}{\partial \log(\frac{w^u}{R^k})} = \frac{1}{1-\sigma}$.

[26]The elasticity of substitution registers the effect of a change in the quantity of one factor on the price of another factor, holding marginal cost and quantities of other factors constant. The higher the elasticity of complementarity, the larger the positive effect of an increase in the quantity of one input on the price of the other input, see Sato and Koizumi (1973), Hamermesh (1985), and Stern (2011).

C. Retailers

Wholesale firms sell the homogeneous good to a unit measure of retailers indexed by $j \in [0,1]$ at the relative price x_t. The retailer j transforms the homogeneous wholesale good into differentiated final goods $y_{j,t}$ with $p_{j,t}$ – the nominal sale price of this good, and sell them on to consumers. Retailers operate under monopolistic competition and face Calvo price adjustment costs. In this context, final output is produced according to the following constant return to scale technology:

$$y_t = \left(\int_0^1 y_{j,t}^{\frac{\varepsilon-1}{\varepsilon}} \mathrm{d}i \right)^{\frac{\varepsilon}{\varepsilon-1}} \tag{26}$$

where ε is the elasticity of demand for a producer of wholesale goods (the elasticity of substitution across differentiated retail goods) and p_t is the aggregate price index. The maximization of profits yields the demand curve of each monopolistic retailer

$$y_{j,t} = \left(\frac{p_{j,t}}{p_t} \right)^{-\varepsilon} y_t \tag{27}$$

with

$$p_t = \left(\int_0^1 p_{j,t}^{1-\varepsilon} \mathrm{d}i \right)^{\frac{1}{1-\varepsilon}} \tag{28}$$

Price setting in retailer sector is subject to the pricing scheme à la Calvo, in the benchmark version. Retailers choose the price that maximizes discounted real profits. In each period, a fraction $(1-\kappa_p)$ of firms can change their prices. All other firms can only index their prices by past inflation. The probability of a price change is constant overtime and independent of the time elapsed since the last adjustment. This assumption implies that a retail firm keeps the same price on average during $1/(1-\kappa_p)$ periods. Indexation is controlled by the exogenous parameter $\chi \in [0,1]$, where $\chi = 0$ implies no indexation and gives back the standard Calvo model with the price remaining constant between re-optimization period assumed in the benchmark model, and $\chi = 1$ – total indexation. All price-updating firms adjust to the same price, p^*.

The problem of the retail firms is then:

$$\max_{p_{j,t}} \quad \mathrm{E}_t \sum_{\tau=0}^{\infty} (\beta \kappa_p)^{\tau} \frac{\lambda_{t+\tau}^e}{\lambda_t^e} \left\{ \prod_{s=1}^{\tau} \pi_{t+s-1}^{\chi} \frac{p_{j,t}}{p_{t+\tau}} y_{j,t+\tau} - \mathbb{S}\left(y_{j,t+\tau} \right) \right\}$$

subject to $y_{j,t+\tau} = \left(\prod_{s=1}^{\tau} \pi_{t+s-1}^{\chi} \frac{p_{j,t}}{p_{t+\tau}}\right)^{-\theta_p} y_{t+\tau}$. θ_p is the price elasticity of demand for intermediate good j. The firms, which can change prices, set them to satisfy:

$$g_{1,t} = \lambda_t^e y_t x_t + \beta \kappa_p \mathbb{E}_t \left(\frac{\pi_t{}^{\chi}}{\pi_{t+1}}\right)^{-\theta_p} g_{1,t+1} \tag{29}$$

$$g_{2,t} = \lambda_t^e \pi_t^* y_t + \beta \kappa_p \mathbb{E}_t \left(\frac{\pi_t^{\chi}}{\pi_{t+1}}\right)^{1-\theta_p} \left(\frac{\pi_t^*}{\pi_{t+1}^*}\right) g_{2,t+1}, \text{ where } \pi_t^* = \frac{p_t^*}{p_t} \tag{30}$$

$$\theta_p g_{1,t} = g_{2,t} \left(\theta_p - 1\right) \tag{31}$$

Given pricing à la Calvo, the price index evolves:

$$1 = \kappa_p \left(\frac{\pi_{t-1}{}^{\chi}}{\pi_t}\right)^{1-\theta_p} + (1-\kappa_p)\, \pi_t^{*\,1-\theta_p} \tag{32}$$

I define price dispersion term $v_t^p = \int_0^1 \left(\frac{p_{j,t}}{p_t}\right)^{-\theta_p} di$. If there were no pricing frictions, all firms would charge the same price, and $v_t^p = 1$. By the properties of the index under Calvo's pricing the law of motion of price dispersion is

$$v_t^p = \kappa_p \left(\frac{\pi_{t-1}{}^{\chi}}{\pi_t}\right)^{-\theta_p} v_{t-1}^p + (1-\kappa_p)\, \pi_t^{*\,-\theta_p} \tag{33}$$

In the aggregation I obtain:

$$y_t = \frac{\mathscr{Z} f(k_t, n_t^s, n_t^u)}{v_t^p} \tag{34}$$

This is the aggregate production function. Since $v_t^p \geq 1$, price dispersion results in an output loss – firms produce less output than you would given TFP, aggregate labor and capital inputs if prices are disperse.

D. Exogenous Processes

The model features two exogenous stochastic driving processes for the aggregate productivity $\mathscr{Z}_t$ and its volatility $\sigma_t^{\mathscr{Z}}$, which is time-varying.

$$\mathscr{Z}_t = \rho^{\mathscr{Z}} \mathscr{Z}_{t-1} + \sigma_t^{\mathscr{Z}} \varepsilon_t^{\mathscr{Z}} \text{ where } \varepsilon_t^{\mathscr{Z}} \sim \mathrm{N}(0,1) \tag{35}$$

$$\sigma_t^{\mathscr{Z}} = \left(1 - \rho^{\sigma^{\mathscr{Z}}}\right) \sigma^{\mathscr{Z}} + \rho^{\sigma^{\mathscr{Z}}} \sigma_{t-1}^{\mathscr{Z}} + \eta_{\sigma^{\mathscr{Z}}} \varepsilon_t^{\sigma^{\mathscr{Z}}} \text{ where } \varepsilon_t^{\sigma^{\mathscr{Z}}} \sim \mathrm{N}(0,1) \tag{36}$$

where $\varepsilon_t^{\mathscr{Z}}$ and $\varepsilon_t^{\sigma^{\mathscr{Z}}}$ follow i.i.d. standard normal process.[27] A level shock $\varepsilon_t^{\mathscr{Z}}$ is a first-moment shock that varies the level of $\mathscr{Z}_t$, keeping its distribution unchanged. An uncertainty shock $\varepsilon_t^{\sigma^{\mathscr{Z}}}$ is a second-moment shock that affects the shape of the distribution by widening the tails of the level shock and keeping its mean unchanged. Parameters $\rho^{\mathscr{Z}}$ and $\rho^{\sigma^{\mathscr{Z}}}$ drive the persistence associated to the level and volatility of productivity shocks respectively, and $\eta_{\sigma^{\mathscr{Z}}}$ drives the magnitude of the productivity uncertainty shock.

E. Monetary Policy

The monetary authority sets the nominal interest rate, R_t, to stabilize inflation and output growth. Monetary policy adjusts short term nominal interest rates in accordance with the following standard Taylor rule with interest rate smoothing and potential reaction to the deviations of output and inflation from their steady-state values

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{\bar{R}}\right)^{\rho_R}\left(\left(\frac{\pi_t}{\pi}\right)^{\rho_\pi}\left(\frac{y_t}{y_{t-1}}\right)^{\rho_y}\right)^{(1-\rho_R)} \tag{37}$$

where $\rho_R \in [0,1]$ is a smoothing parameter to capture the empirical evidence of gradual movements in interest rates, ρ_π is the elasticity of nominal interest rate R_t with respect to inflation deviations from its steady-state value and ρ_{y_t} is the elasticity of R_t with respect to output gap, R is the steady-state gross nominal interest rate and y is the steady-state output.

F. Fiscal Policy

The government collects lump-sum taxes and runs a balanced budget in every period. The government budget constraint (38) equates current income (bond issues and tax revenues) with general expenditures and maturing government bonds. The government's budget constraint is thus given by

$$t_t + B_t = g_t + \frac{R_{t-1}B_{t-1}}{\pi_t} \tag{38}$$

where g_t is real general government spending, and B_t is the total amount of aggregate nominal government bonds held by the households ($B_t = \sum_i \pi^i B_t^i$ for $i \in (s,u,e)$). The dis-

[27] I use the stochastic volatility approach proposed by Fernandez-Villaverde and others (2011).

tribution of lump-sum taxes is assumed to be equal across households such that $t_t = \sum_i \pi^i t_t^i$ for $i \in (s,u,e)$. The real amount of lump-sum taxes is adjusted according to the fiscal rule

$$\frac{t_t}{t} = \left(\frac{B_{t-1}}{B}\right)^{(\phi_D)} \left(\frac{y_t}{y}\right)^{(\phi_Y)} \tag{39}$$

Finally, government spending follows a standard AR-(1) process:

$$\log\left(\frac{g_t}{\bar{g}}\right) \quad = \quad \rho^g \log\left(\frac{g_{t-1}}{\bar{g}}\right) + \varepsilon_t^g \tag{40}$$

G. Closing the Model

Combining the budget constraints of the households and the government the final good market clearing condition is obtained. Final output is used for private consumption, investment, government expenditures. Total demand is thus given by

$$y_t = c_t + i_t + g_t \tag{41}$$

where aggregate consumption is $c_t = \sum_i \pi^i c_t^i$ for $i \in (s,u,e)$, and aggregate investment is $i_t = \pi^e i_t^e$.

IV. Impact of Uncertainty Shocks: Dissecting the Mechanism

In this Section, I provide an insight into the transmission of uncertainty shocks onto skilled and unskilled labor markets. While the existing transmission channels do not distinguish between relative effects of uncertainty on segmented labor markets with respect to skills, I demonstrate that capital-skill complementarity gives rise to an additional propagation channel of aggregate uncertainty on relative skilled-to-unskilled wages and employment.

The revealed stylized facts relevant to this paper in Section II are that as a response to a rise in the macroeconomic uncertainty (i) the relative employment of skilled labor increases, and (ii) the skill premium, defined as the skilled to unskilled wage ratio, does not react. I illustrate the mechanism behind by looking at the interaction of *relative* skilled-to-unskilled (precautionary) labor supply and firms' *relative* skilled-to-unskilled labor demand. In this exercise, I suppose that *wages are flexible* meaning $\theta_w^s = \theta_w^u = 0$ and $w^{s,*} = w^s$ and $w^{u,*} = w^u$. In this case real wages are a markup $\frac{\eta_w^u}{\eta_w^u - 1}$ over the marginal rate of substitution between consumption and labor.[28] Firms' labor demand is characterized by the marginal product of labor being equal to the wage times a marginal cost. Relative labor demand is affected by the degree of complementarity/ substitutability of capital and skilled labor in production.[29] Households' labor supply and firms' labor demand in the flexible wage case read as

For skilled agents:	For unskilled agents:
$w_t^s = \dfrac{\eta_w^s}{\eta_w^s - 1} mrs_t^s$	$w_t^u = \dfrac{\eta_w^u}{\eta_w^u - 1} mrs_t^u$
$w_t^s = x_t mpl_t^s$	$w_t^u = x_t mpl_t^u$

Figure 4 illustrates what happens after an unexpected rise in uncertainty in the flexible wage case. The panels at the top describe the skilled (left panel) and unskilled (right panel) labor market. Uncertainty induces precautionary behavior of households due to the presence of risk aversion in the households' preferences. Households reduce demand for consumption goods, increase savings and labor supply as in discussion of the sticky-price case in Basu and Bundick (2017a).[30] In particular, skilled and unskilled labor supply curves shift to the right from point A to B (see top panels of Figure 4). Higher labor supply reduces firms' marginal costs. Output is demand-determined due to price stickiness, so that lower consumption translates to lower aggregate demand. Both price and wage markups increase due to nominal rigidities (see Basu and Bundick (2017a)). The rise in markups leads to a fall in labor demand, and we shift from point B to C (see top panels of Figure 4).

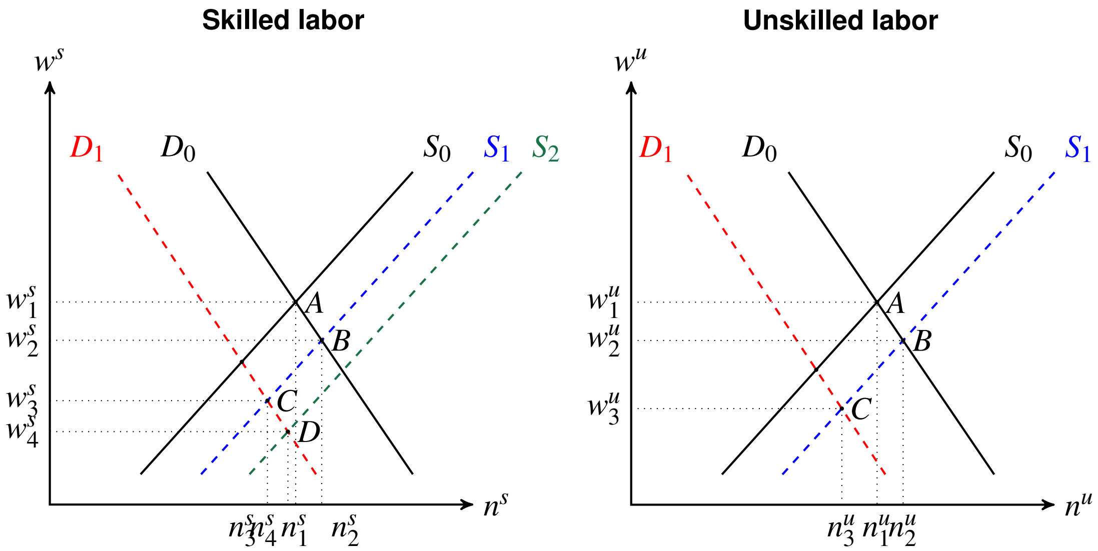
My contribution to the analysis is to show how labor demand for and labor supply of skilled and unskilled workers change in response to the uncertainty shock. Capital-to-skilled labor ratio increases since capital adjusts slower than labor in response to the shock. Complementarity between capital and skilled labor reduces the decline in the marginal product of skilled labor and dampens the decrease in skilled labor demand. As a consequence, a fall in the demand for skilled labor is smaller than for unskilled labor, which leads to an increase in the relative labor demand.

[28]Defining marginal rate of substitution between consumption and labor as $mrs^s = \frac{\kappa_h^s (h_t^s)^{\phi^s}}{\lambda_t^s}$ and $mrs^u = \frac{\kappa_h^u (h_t^u)^{\phi^u}}{\lambda_t^u}$ we have $w^s = \frac{\eta_w^s}{\eta_w^s - 1} mrs^s$ and $w^u = \frac{\eta_w^u}{\eta_w^u - 1} mrs^u$.

[29]In the model skilled and unskilled labor demands are given by equations 24 and 25 respectively, and labor supply conditions are given by equations 58 and 58.

[30]Basu and Bundick (2017a) provide a discussion on the effects of higher uncertainty in cases of flexible prices and sticky prices, Figure 2 in the paper.

Figure 4. Model intuition. Capital-skill complementarity & flexible wages case.



An additional ingredient – wealth effect on labor supply – drives the response of precautionary labor supply as households react to lower labor income by increasing hours worked. The more important the wealth effect is, the larger is an increase in precautionary labor supply. For example, if the relative wealth effect on labor supply of skilled households is larger, fall in equilibrium labor is dampened, and we move to the point D on the left panel of Figure 4. The first panel of Figure 4 displays that if skilled households increase labor supply in the same magnitude as unskilled households, their labor supply curve shifts from S_0 to S_1. However, a larger shift of skilled labor supply curve to S_2, rather than to S_1, causes a commensurately smaller decrease in corresponding equilibrium skilled labor. Larger precautionary labor supply by skilled households leads to an increase in relative skilled labor supply, and as a consequence, relative employment increases.

V. Solution and Calibration

A. Solution Method

I solve and simulate the model by a third-order perturbation method using the pruning algorithm as in Andreasen, Fernandez-Villaverde, and Rubio-Ramírez (2018).[31] As explained in Fernandez-Villaverde and others (2011), the third-order approximation of the

[31]The model is solved using Dynare 4.4.3 (MATLAB R2017b). In order to obtain a non-explosive behavior of the simulations, Dynare relies on the pruning algorithm described in Andreasen, Fernandez-Villaverde, and Rubio-Ramírez (2018). The version of Dynare used allows pruning also for third order perturbation algorithms.

policy function is necessary to analyze the effects of uncertainty shocks independently of the first moment shocks. The volatility shock enters as an independent argument in the approximated policy function without interacting with any other variable function only in a third-order approximation.

I am interested in the effects of an increase in volatility or a positive shock to $\sigma^{\mathscr{Z}}{}_t$ in Equation 36, while the level shock to TFP is zero. I consider impulse response functions (IRFs) that isolate the pure uncertainty effect resulting from higher volatility in the spirit of Fernandez-Villaverde and others (2011). I focus on the effect uncertainty has on expectations, and how expectations transmit to actual decisions, but ignore materialized shocks to the level of the exogenous processes. I compute impulse response functions of the respective variables in percentage deviation from the ergodic mean of the simulated data by the model in the absence of shocks. In linear models IRFs are usually computed using the deterministic steady state as an initial condition. In these models, IRFs do not depend on the state of the economy when the shock occurs, nor on the sign and size of the shock. In a higher order approximation to the solution of the model, impulse responses computed from the deterministic steady state do not converge as they are just one of the many IRFs of the non–linear model since in a third order approximation, the expected value of the variable will also depend on the variance of the shocks in the economy.[32] Therefore, it is more informative to compute impulse responses as percentage deviations from their mean, rather than their steady state.

B. Calibrated Parameters

The model is calibrated on quarterly US data. Parametrizion is based on values commonly found in the literature or on making the steady-state model match a set of empirical targets based on the quarterly US data in Section II. Variables without a time subscript denote steady-state values and an index $i \in \{s,u,e\}$ corresponds to skilled, unskilled and entrepreneur households respectively. The proportion of entrepreneurs in the population, π^e, is set to 10% as in Dolado, Motyovszki, and Pappa (2021). The proportion of skilled workers, π^s, is 21%, which is equal to the average share of workers in the CPS MORG dataset with college education, and the rest 69% are unskilled workers. The time discount factor is $\beta = 0.99$ and the relative risk aversion parameter of skilled and unskilled households is set to $\sigma_u^s = 1$ and $\sigma_u^u = 1$ respectively, the value commonly employed in the litera-

[32]Schmitt-Grohe and Uribe (2004) show that in a first-order approximation of the model, the expected value of any variable coincides with its value in the non-stochastic steady state, while in a second-order approximation of the model, the expected value of any variable differs from its deterministic steady-state value only by a constant.

ture,[33] with a moderate degree of consumption habit persistence $b_c = 0.5$ (as estimated in Born and Pfeifer (2014)) and the parameter governing taste for leisure, κ_h^i, is chosen so that households work h^i=1/3 of their time in steady state (as is commonly assumed in the macro literature). I set the skilled and unskilled inverse Frisch elasticities to $\phi^s = 2$ and $\phi^u = 2$ as the benchmark and will examine the quantitative implications of the model with higher Frisch elasticity. Regarding wage rigidity, I set the following parameters $\eta_w^u = 0.8$ and $\eta_w^s = 0.8$, $\theta_w^u = 0.75$ and $\theta_w^s = 0.75$ assuming high degree of real wage rigidity in line with the analysis of Krause and Lubik (2007) and Leduc and Liu (2016). I set the price adjustment cost parameter κ_p is to 0.75 implying average price duration of 4 quarters. The substitution elasticity parameters θ_p and η_w^s and η_w^u are set to 11, which implies a steady-state markup of 10%.

The depreciation rate of capital equipment is $\delta = 0.25$. I set the parameters governing the elasticities of substitution between skilled labor and capital and between unskilled labor and capital (or skilled labor) to $\rho = -0.495$ and $\sigma = 0.401$, which are the estimates by Krusell and others (2000) that are commonly used in the literature (see, for example Lindquist (2004), Pourpourides (2011), Angelopoulos, Asimakopoulos, and Malley (2014), Dolado, Motyovszki, and Pappa (2021)). This results in the elasticity of capital to skilled labor of $\frac{1}{1-\rho} = 0.67$ and the elasticity of capital to unskilled labor$\frac{1}{1-\sigma} = 1.67$. The remaining parameters of the production function are calibrated to ensure the steady-state predictions of the model are consistent with the data. I calibrate $\mu = 0.62$ to obtain the labor share in income of 69%, and the share of capital to composite input $\lambda = 0.8$ to target the skill premium of 1.67.[34] Both of these targets are consistent with the US data from Section II. Government spending-to-output ratio is set to 20% and public debt is calibrated to 67% of annual output. The Taylor rule parameters are conventional values with a moderate degree of interest rate smoothing, inflation and output feedback. An interest rate smoothing parameter ρ_R is set to 0.7, the elasticity of R_t with respect to inflation deviations ρ_π is 1.5, and the elasticity of R_t with respect to output gap ρ_{y_t} is 0.3. The parameters of the tax feedback rule are $\phi_D = 0.3$ and $\phi_Y = 0.34$.

Quantitative impact of uncertainty depends on the calibration of the size and persistence of the uncertainty shock process. For the exogenous process of technology I use persistence $\rho^{\mathscr{Z}}$ of 0.8 and the average standard deviation $\sigma_{\mathscr{Z}}$ is set to 0.01. The persistence of the volatility process is generally assumed to be quite high (Basu and Bundick (2017a) and Gilchrist, Sim, and Zakrajsek (2014)). SVAR evidence shows that my uncertainty indicator measure falls gradually to about 30% of its peak in 4 quarters. If I approximate the SVAR uncertainty shock by an AR(1) process in the DSGE model, the persistence param-

[33] See Schmitt-Grohe and Uribe (2007) and the references reported in their paper.
[34] Krusell and others (2000) do not report their estimates of unskilled labor weight in composite input share μ and capital weight in the composite input share λ.

eter $\rho^{\sigma^{\mathscr{Z}}}$ should be approximately equal to 0.65 at quarterly frequency. There is no general consensus regarding the value of the standard deviation of the volatility shock. I thus calibrate it to 0.03 to match the empirical standard deviation of my uncertainty measure in the SVAR. Table 2 summarizes model parameterization.

Table 2: Benchmark parameter calibration

Preferences		
β	0.99	Discount factor equivalent to 4% average risk-free real interest rate p.a.
ϕ^s	2	Parameter for skilled Frisch elasticity of labor supply
ϕ^u	2	Parameter for unskilled Frisch elasticity of labor supply
σ_u^s	1	Relative risk aversion parameter of skilled
σ_u^u	1	Relative risk aversion parameter of unskilled
b_c	0.5	Habit in consumption parameter
Production		
δ	0.025	Capital depreciation rate; 10% depreciation rate p.a.
ϕ_i	5	Investment adjustment cost
σ	0.401	Substitutability btw skilled (or capital) and unskilled labor
ρ	-0.495	Capital-skill complementarity
π^s	0.21	Share of skilled labor in population
π^u	0.69	Share of unskilled labor in population
π^e	0.10	Share of entrepreneurs in population
Calvo price rigidity		
θ_p	11	Elasticity of substitution between goods equivalent to 10% price markup
κ_p	0.75	Implied average price duration of 4 quarters
χ	0	Price indexation
θ_w^s	11	10% skilled wage markup
θ_w^u	11	10% unskilled wage markup
χ^w	0	Wage indexation
Monetary and fiscal policy		
ρ_r	0.7	Interest rate smoothing
ρ_π	1.5	Taylor-coefficient on inflation
ρ_y	0.3	Taylor-coefficient on output
ϕ_D	0.3	Tax feedback to debt
ϕ_Y	0.34	Tax feedback to output
$\frac{g}{y}$	0.2	Steady-state government spending to GDP
Shocks		
ρ^z	0.8	Technology autoregressive parameter
σ^z	0.01	Steady state TFP volatility
ρ^{σ^z}	0.65	Persistence of volatility of TFP shocks
η_{σ^z}	0.04	Magnitude of the productivity uncertainty shock

VI. Theoretical Results: Impulse Response Analysis and Inspecting the Transmission Channels of Uncertainty

In the following section I analyze the effects of an uncertainty shock on main macroeconomic aggregates and on relative skilled variables. The aim is to assess the importance of capital-skill complementarity and other ingredients of the model for response to increases in uncertainty. Therefore, I illustrate alternative specifications of the model.

A. IRF Analysis with Flexible Wages

First, I focus on the model with flexible wages in order to assess the role of capital-skill complementarity in driving the response to uncertainty shocks. First, I discuss the impact of an uncertainty shock on the economy. Then, I analyze in more detail the transmission of the uncertainty shock as well as the underlying amplification mechanisms.

1. Aggregate Economy

Figure 5 displays impulse responses of aggregate variables to a one standard deviation technology uncertainty shock. The solid black line shows the responses of the model with capital-skill complementarity as described in Section III. The dash-dot red line shows the responses of the corresponding model without capital-skill complementarity. First, I investigate the effects of an increase in aggregate uncertainty in the model with capital-skill complementarity. Consistent with the SVAR evidence presented in Section II, a one standard deviation shock to the volatility of productivity causes a persistent downturn in aggregate economic activity (see black solid lines in Figure 5). An uncertainty shock generates a reduction in aggregate demand, which leads to a contraction in output, consumption and investment. It leads to a rapid decrease in output of 0.1%, before output returns to its initial level after 10 quarters. Reacting to weaker consumer demand, firms decrease their demand for production inputs. Investment and employment fall, together with wages and capital rents.

When analyzing how uncertainty shocks affect economic activity in a general equilibrium framework, many channels play a role in determining the responses to these shocks. The responses of the endogenous variables depend on the interplay of precautionary household behavior, nominal rigidities and the capital-skill complementarity channels. The drop in aggregate output is caused by the interaction of precautionary households' behavior and nominal price rigidity. Risk-averse households are driven by precautionary motives and respond to higher uncertainty by adjusting consumption downward and increasing savings. As uncertainty about future income increases and the marginal utility of wealth goes up, households adjust their labor supply upward. From the production side, firms respond to the fall in demand by lowering demand for production inputs. Higher labor supply of both skilled and unskilled workers lowers firms' marginal costs. Due to the presence of nominal price rigidities, prices cannot adjust instantly to changing conditions, leading to an increase in firms' mark-ups. The wedge between markup and marginal cost increases resulting in a decrease in labor demand. When the degree of price stickiness is sufficiently high, uncertainty generates a downward shift in labor demand, which is large enough to translate in a fall in investment, labor hours, and output. The marginal products of capital, skilled and unskilled labor fall because of this demand-driven fall in output. This is the aggregate demand channel, which relies on the presence of price stickiness (see Basu and Bundick (2017a)).[35] At the same time, through the increase in markups, inflation rises. The response of inflation depends on the interaction of aggregate demand channel and upward nominal pricing bias channel,[36] which both rely on nominal price rigidities. The nominal pricing bias channel leads firms to increase their prices due to the asymmetry of the profit function – with price rigidities firms find it less costly to set a price that is too high relative to the competitors, rather than setting it too low. In the model the cumulative effect of these two channels produces an increase in inflation, which means that the effect of upward pricing by firms dominates the increase in households' precautionary savings. I find therefore that an increase in uncertainty leads to a rise in inflation due to the stronger upward nominal pricing bias channel, consistent with Born and Pfeifer (2014) and Fernandez-Villaverde and others (2015).

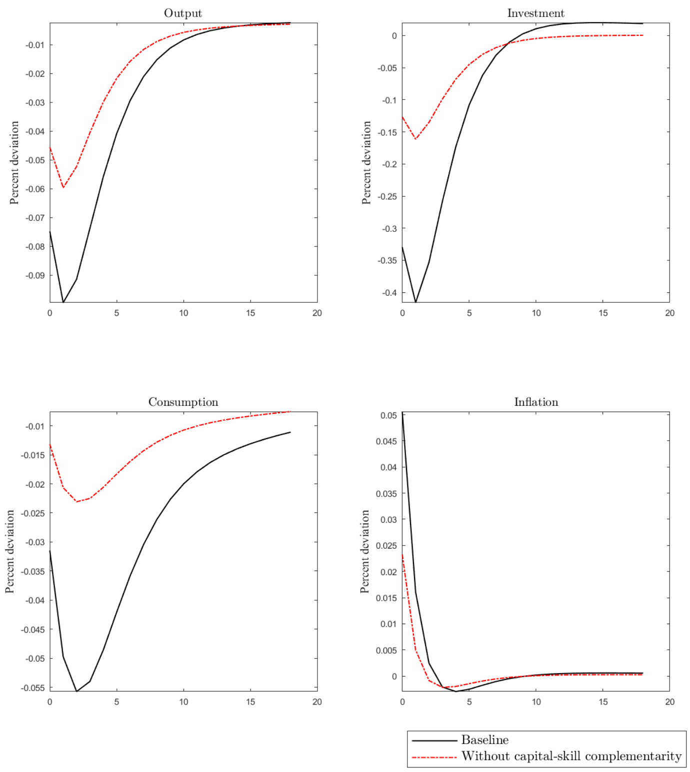
While the price stickiness channel plays an important role in driving aggregate consumption and output down, ***capital-skill complementarity*** plays an equally important role in understanding the effects of uncertainty on macroeconomic variables and is key to generate responses of relative wages and employment in line with the data. Figure 5 and Figure 6 display impulse responses in the the model with (solid black lines) and without capital-skill complementarity (dash-dot red lines) for aggregate and relative variables respectively. The difference between the two models comes from the production function. The presence of capital-skill complementarity in production considerably amplifies the responses of aggregate economy. The capital-skill complementarity channel acts on top of the aggregate demand and precautionary labor supply channels. Importantly, consistent with Dolado, Motyovszki, and Pappa (2021), capital-skill complementarity gives rise to

[35]The price stickiness channel is used by Basu and Bundick (2017a) to produce positive co-movement between consumption, investment, and output.

[36]The nominal pricing bias arises in the Phillips curve due to the presence of nominal rigidities that make firms more prudent when setting nominal prices of goods (see Fernandez-Villaverde and others (2015)).

a feedback loop between employment and capital investment: following aggregate uncertainty shocks that lower demand, capital investment is discouraged making complementary skilled workers less productive, which further reduces capital investment. This further fall in investment creates additional demand pressures leading to a sharper fall in aggregate output compared to the standard production function.

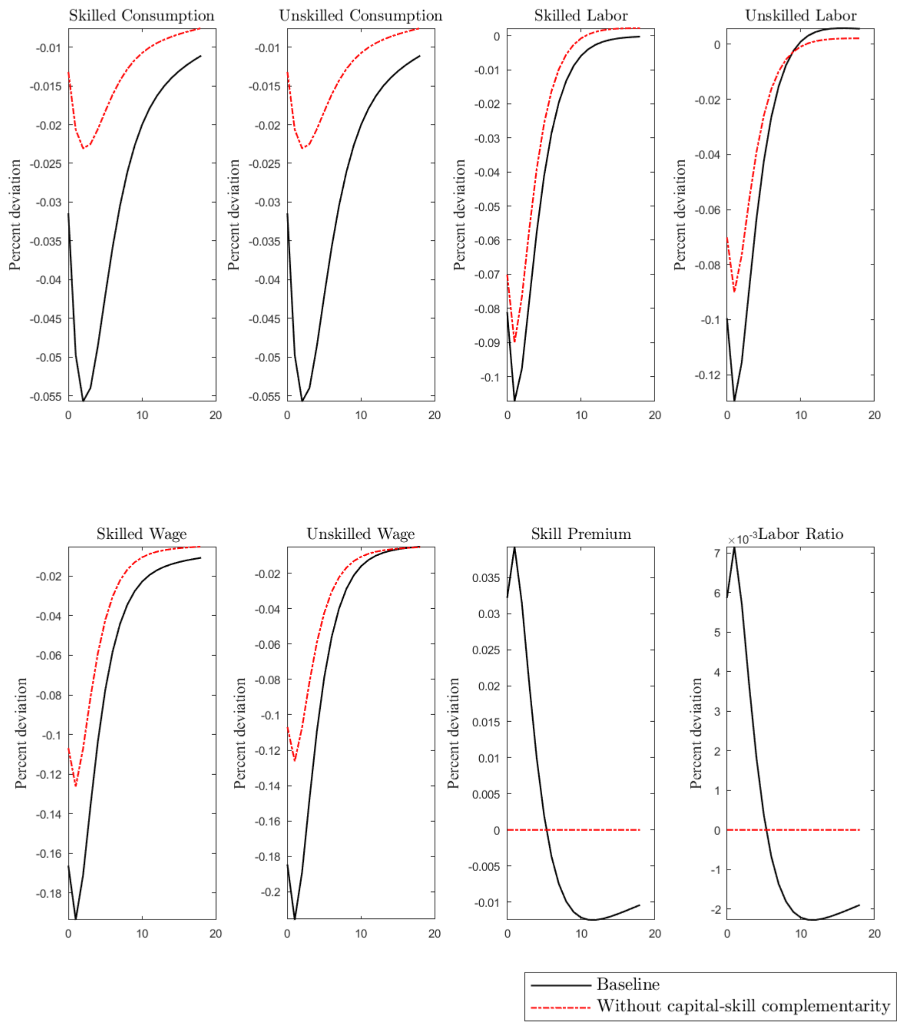
Figure 5. Impulse response functions to TFP uncertainty shock in the model with flexible wages.



2. Relative Variables

Now I turn to the responses of the relative variables of interest to a productivity uncertainty shock plotted in Figure 6. Without capital-skill complementarity, i.e. when skilled and unskilled labor are perfect substitutes, relative ratio of skilled labor and the skill premium do not react due to the equality of marginal products of the two types of labor. In the presence of capital-skill complementarity skilled and unskilled workers have different roles in production. This implies that skilled and unskilled workers do not endure the same decreases in marginal products of labor.

Figure 6. Impulse response functions to TFP uncertainty shock in the model with flexible wages.



The model generates an increase in the skilled-to-unskilled labor ratio and the skill premium following the uncertainty shock. As shown in Section IV, the response of the skill premium and relative ratio of skilled labor depend on the changes in capital-to-skilled labor ratio. In the model, capital-to-skilled labor ratio increases following the uncertainty shock since capital adjusts slower than labor in response to an increase in uncertainty. Higher capital-to-skilled labor ratio dampens the decline in skilled labor demand and marginal product of skilled labor. Thus, the relative ratio of skilled labor and the skill premium tend upward. Theoretical model in Section III with flexible wages is able to replicate the rise in the skill-to-unskilled labor ratio, but it generates the reduction in the skill premium in contradiction to the non-responsiveness obtained in Section II.

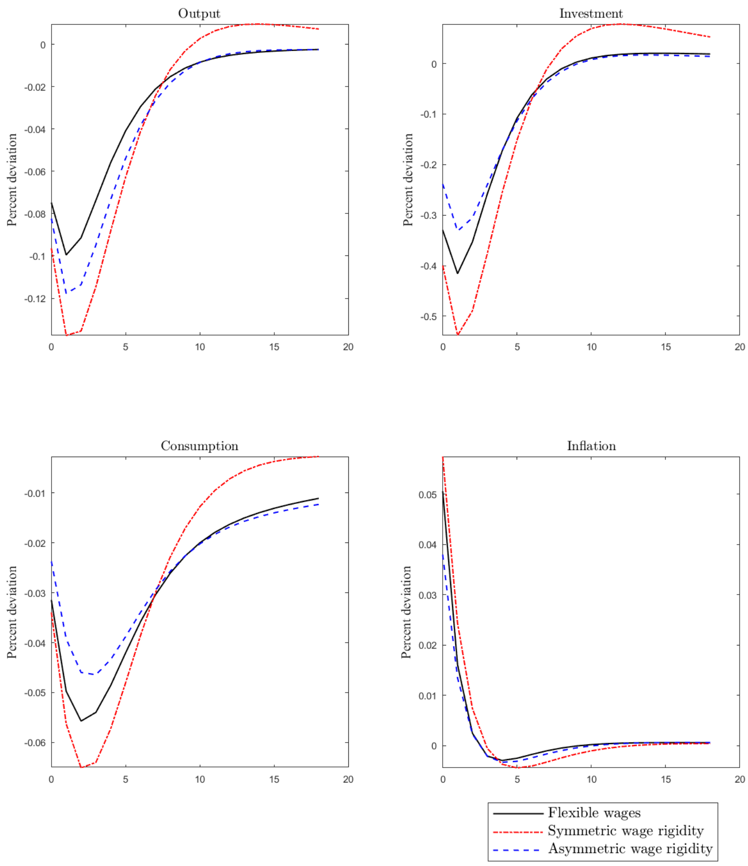
B. Extension: Sticky Wage Model

Due to the evidence on the US labor market that aggregate wages similar to prices are subject to rigidities, I extend the analysis to the variant of the model with wage stickiness by setting the parameters θ_w^s and θ_w^u. First, I look at the effects of uncertainty shocks in a model with symmetric wage rigidity, and then I focus on the role of asymmetric wage rigidity. Wage stickiness affects movements of the relative labor supply curves in response to uncertainty as detailed in Section IV, and thus, playing a role for responses of the variables related to skilled and unskilled workers. Wage rigidity induces a precautionary wage setting motive on behalf of households, similar to firms' precautionary price setting. Thus, this feature represents an additional transmission channel and it is worth inspecting how it affects the responses of aggregate as well as relative variables to the uncertainty shock.

Figure 7 plots IRFs in the model with wage rigidity for the aggregate variables and Figure 8 – for the variables related to skilled and unskilled households. The case with both price and wage rigidities is plotted with the black solid line, the asymmetric wage rigidity case (more rigid for the skilled) – with the blue dotted line, and the flexible wage case is – with the dash-dot red line. Parametrization for symmetric wage rigidity is $\theta_w^s = 0.75$ and $\theta_w^u = 0.75$, and for asymmetric wage rigidity – $\theta_w^s = 0.75$ and $\theta_w^u = 0.65$. Wage stickiness does not significantly affect aggregate variables – output, consumption and investment contract. In the model with both price and wage rigidities, an increase in uncertainty leads to an increase in both price markup (price over marginal cost) and wage markup (wage over marginal rate of substitution), which somewhat amplifies a drop in output.

Since rigidity attenuates wage movements, higher wage rigidity is associated with a weaker decline of the wage as illustrated in Figure 8. In the data, employment ratio of skilled-to-unskilled workers increases while the skill premium does not react significantly to uncertainty. In comparison with the case of no wage stickiness, adding symmetric wage rigidity (see Figure 8, black solid line) amplifies the rise in the relative labor ratio of skilled workers, and it generates a fall in the skill premium. Households set the wage as a markup over the marginal rate of substitution, similarly to how firms set price as a markup over marginal cost. The effect of the shock on the relative employment and wage ratios is driven by the interaction of capital-skill complementarity with wage rigidity. In particular, the response of the skill premium is driven by the capital-skill complementarity effect carried by the increase in the capital-to-skilled labor ratio and the relative supply effect, *i.e.* a rise in relative quantities of skilled to unskilled labor, which is in turn affected by the wage rigidity. Here, time-variation in the markups is a central element of transmission. Capital-skill complementarity dampens the fall in skilled labor demand making relative labor demand increase, so that unskilled labor falls more relative to skilled. Both skilled and unskilled wage markups increase, but the unskilled one increases more. Relatively larger increase in the wage markup of unskilled workers dampens the decline in unskilled wage relative to the skilled one resulting in a reduction in the skill premium.

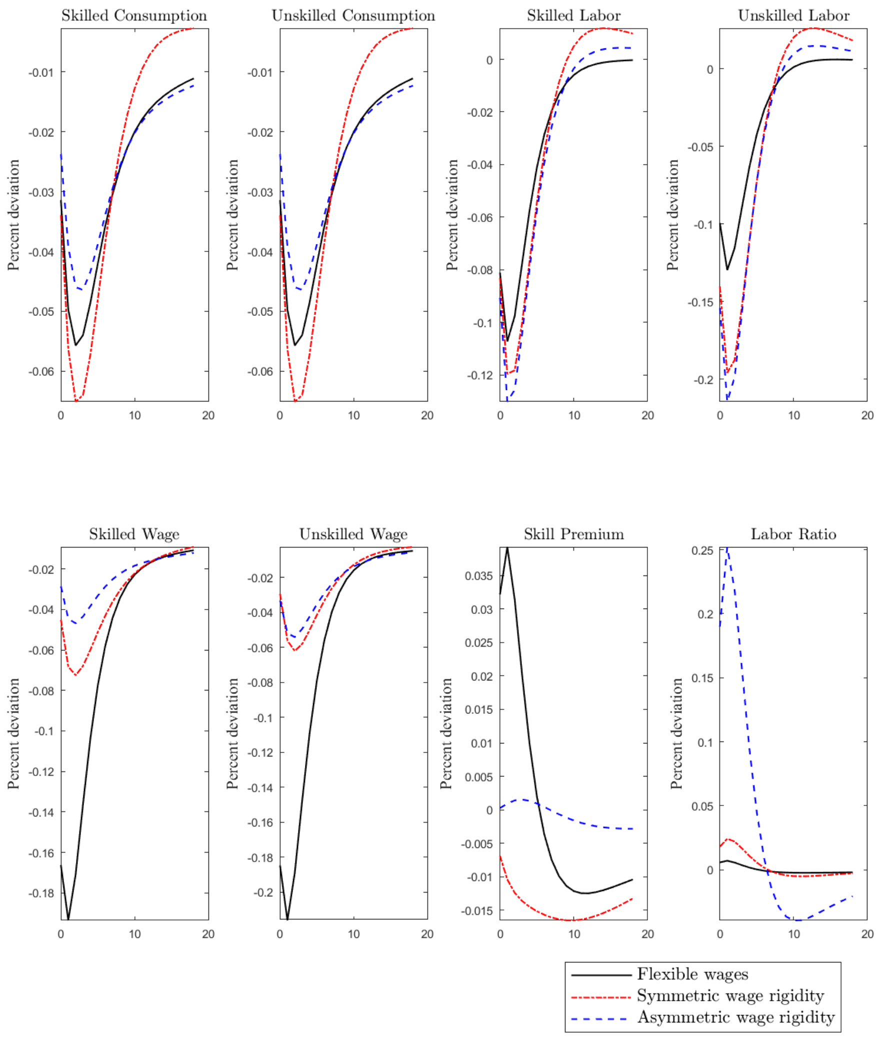
Figure 7. Impulse response functions to TFP uncertainty shock in the model with Calvo wages.



1. Asymmetric Sticky Wage

I assume higher aggregate wage rigidities for more skilled or white-collar workers than those for less skilled or blue-collar workers. There are several reasons – the effort of high-skilled workers is more valuable and more difficult to monitor, higher wage bargaining power of the skilled, hiring and training costs are higher for high-skilled and/or white-collar workers making firms more reluctant to cut their wages (see, for instance for the US – Shapiro and Stiglitz (1984), Akerlof (1982) and Akerlof and Yellen (1990), Campbell and Kamlani (1997), for Europe – Cahuc, Postel-Vinay, and Robin (2006), Du Caju, Fuss,

Figure 8. Impulse response functions to TFP uncertainty shock in the model with Calvo wages.

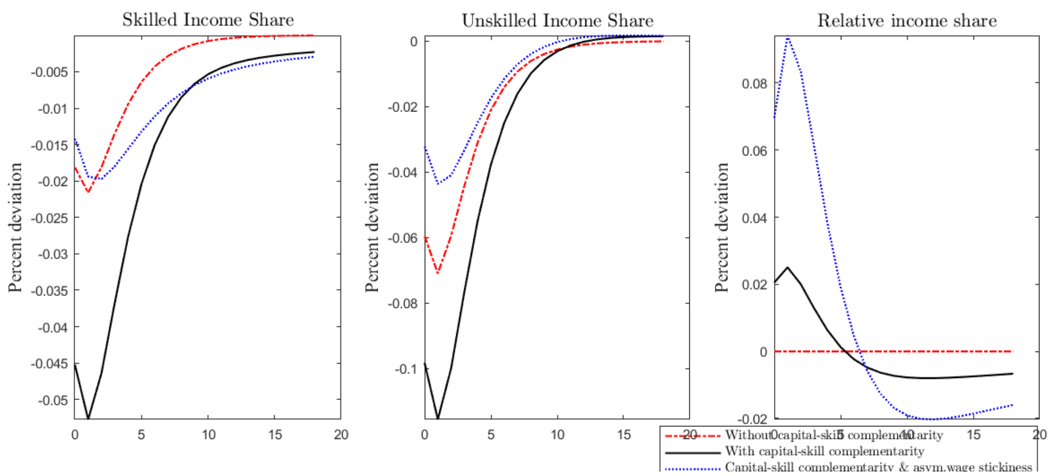


and Wintr (2009) and Babecký and others (2010)). I look at the effect of uncertainty in case of asymmetric wage rigidity and set the parameters θ_w^s and θ_w^u accordingly with $\theta_w^s = 0.75$ and $\theta_w^u = 0.65$.

In case of asymmetric wage rigidity, the increase in the relative labor ratio is magnified, and the fall in the relative wage ratio is dampened (see blue dotted lines in Figure 8). As skilled wage is more rigid, it reacts to the shock to a lesser extent decreasing less than in the symmetric rigitity case, and as a result, the response of the relative wage ratio is negligible. Thus, asymmetric wage rigidity allows to obtain an almost flat response of the skill premium to the uncertainty shock in line with the empirical results in Section II. Additionally, relatively smaller decline in the skilled wage implies a smaller increase in the skilled wage markup relative to the unskilled wage markup than in the symmetric rigidity case. This leads to a larger increase in the relative labor ratio.

Effects on labor income shares. Figure 9 shows that both income shares of skilled and unskilled labor fall in response to an increase in uncertainty. The relative skilled-to-unskilled labor income share ($\frac{w_t^s n_t^s}{w_t^u n_t^u}$) increases indicating that the aggregate effect of the uncertainty shock is more harmful for workers with lower skills – even though both types are worse off in absolute terms. Macroeconomic uncertainty shocks increase labor income inequality by raising the relative income share of skilled workers. The rise in the relative skilled-to-unskilled income share is driven by the increase in the relative employment of skilled workers. As explained above, capital-skill complementarity increases the relative demand for skilled labor, which contributes to an increase in the relative employment and in the relative skilled-to-unskilled income share. Additionally, the relative skilled-to-unskilled income share increases even more in the presence of asymmetric wage rigidity, as it amplifies a rise in the relative employment of skilled workers.

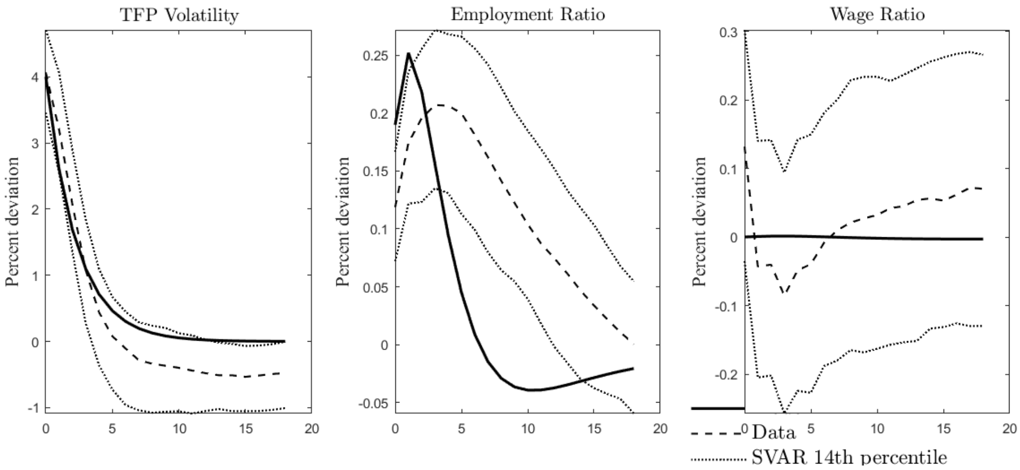
Figure 9. Impulse response functions to TFP uncertainty shock – income shares.



2. Comparison with Data

Figure 10 displays IRFs in the model and in the data for the key variables of interest. An increase in the relative employment of skilled labor is well matched, however it is less persistent in the model than in the data.

Figure 10. Impulse response functions in the model and in the data.



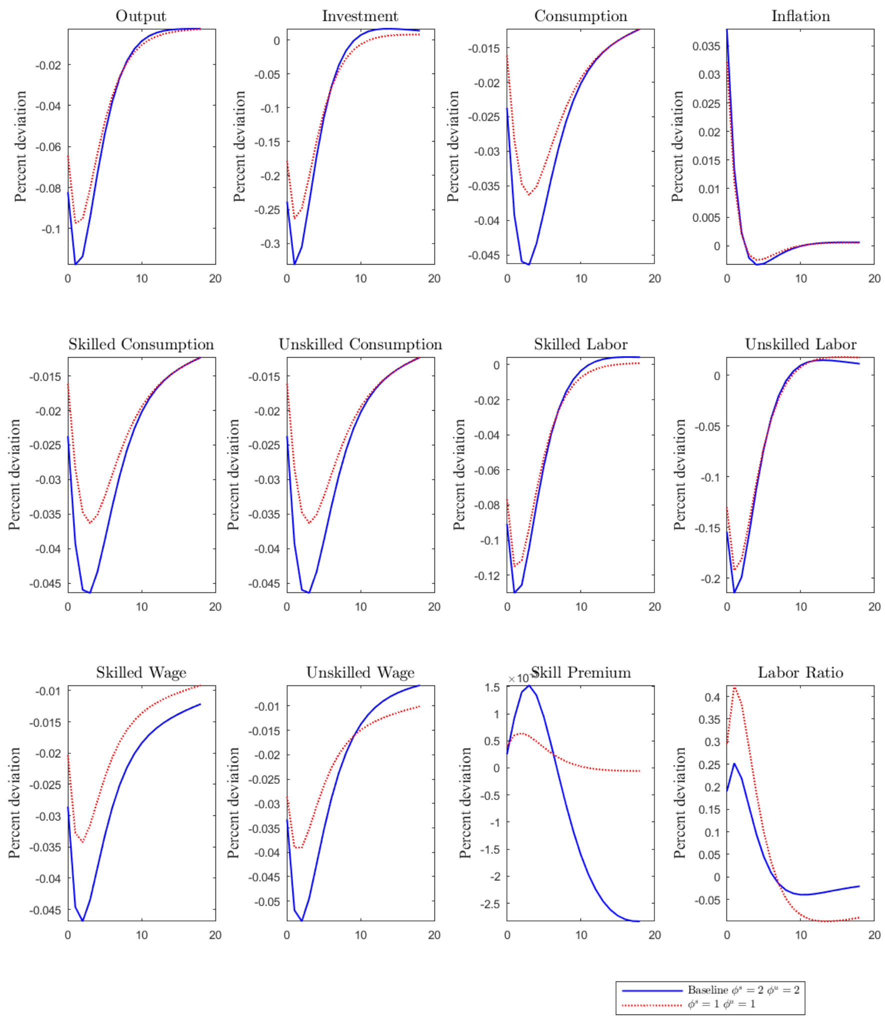
Note: Solid lines correspond to the model IRFs; dashed lines – to the median empirical IRFs while the dotted lines are the empirical 10^{th} and 90^{th} percentiles. Horizontal axes indicate quarters.

C. Sensitivity Analysis

The previous analysis has shown that the response of the economy and, in particular relative labor market variables, to the volatility shock relies on the interaction of capital-skill complementarity with precautionary motives and aggregate demand. In this subsection I explore the sensitivity of the model to various of its features, which allows to gain a deeper insight into the transmission mechanisms. In order to identify the roles played by these features of the model, I either vary or shut them off. In particular, I look at the degree of complementarity between production factors, labor supply elasticity, and nominal price rigidity. Sensitivity tests are done in a model with capital-skill complementarity and asymmetric wage rigidity.

Frisch elasticity of labor supply. Frisch elasticity governs the degree of precautionary labor supply since it indicates the extent to which workers change their labor supply in response to changes in the wage. Decreasing ϕ^s and ϕ^u to 1, *i.e.* increasing the Frisch elasticity, lowers the fall in output in response to an uncertainty shock through a smaller decline in hours worked. Higher Frisch elasticity increases the sensitivity of labor supply to changes in the wage, and thus increases the willingness of agents to supply labor if the wage decreases, which dampens the fall in aggregate employment, leading to a smaller contraction in output than that with a lower Frisch elasticity. On the other hand, lower Frisch elasticity attenuates precautionary labor supply motives and produces a stronger response of hours worked to changes in the wage. For lower responsiveness of hours to changes in the wage (lower labor supply elasticity), an uncertainty shock produces a stronger recession. Figure 11 displays impulse responses for cases of low (red dotted lines) and baseline (black solid lines) Frisch elasticity.

Figure 11. Impulse response functions to TFP uncertainty shock – Frisch elasticity.



Capital-skill complementarity: elasticity of substitution. The model captures capital-skill complementarity through the elasticity of substitution between capital and skilled labor, $\frac{1}{1-\rho}$. Figure 12 depicts responses of the variables of interest for different values of this elasticity in the model with asymmetric wage rigidity. Benchmark calibration of the elasticity between capital and skilled labor is 0.67, and that between capital and low-skilled labor is $\frac{1}{1-\sigma} = 1.67$. I consider an alternative case of strong complementarity (i.e. lower elasticity of substitution) $\frac{1}{1-\rho} = 0.37$, $\rho = -1.7$ (red dotted lines). Figure 12 plots the corresponding IRFs of strong complementarity in comparison with the baseline.

Higher degree of complementarity increases the responsiveness of skilled wage to the fall in capital in comparison with the baseline (see blue solid lines). In response to the drop in aggregate demand, lower capital investment makes skilled employment less productive, leading to a further decline in skilled wages. In turn, larger decrease in wages amplifies the drop in consumption via income effect resulting in a sharper decline in output.

In the next exercise, I change the elasticity of substitution between the skill-capital composite and unskilled labor, $\frac{1}{1-\sigma}$, while keeping the elasticity of substitution between capital and skilled labor, $\frac{1}{1-\rho}$, constant. In addition to the benchmark calibration with $\sigma = 0.401$, I consider an alternative values of σ used in the literature. One is estimated by Duffy, Papageorgiou, and Perez-Sebastian (2004), which gives $\sigma = 0.7899$ and implies higher elasticity of substitution ($\frac{1}{1-\sigma} = 4.76$) than in the baseline case. Figure 13 shows that, as σ becomes smaller, implying a weaker capital-skill complementarity, the effect of an increase in uncertainty becomes more muted. Higher elasticity of substitution between the capital-skill composite and unskilled labor makes firms more flexible. Degree of substitutability of production inputs presents a type of real rigidity. Larger σ decreases this real rigidity, thus dampening the recessionary effects of uncertainty.

Figure 12. Impulse response functions to TFP uncertainty shock – elasticity of substitution btw capital and skilled labor.

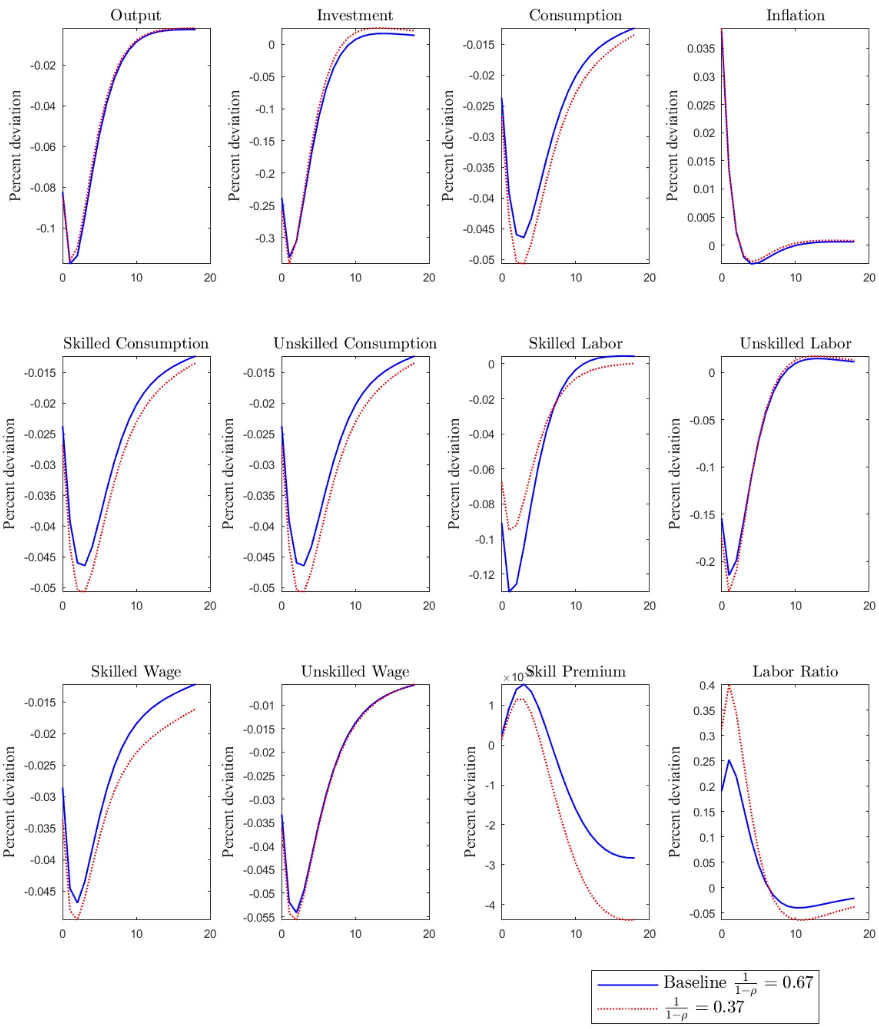
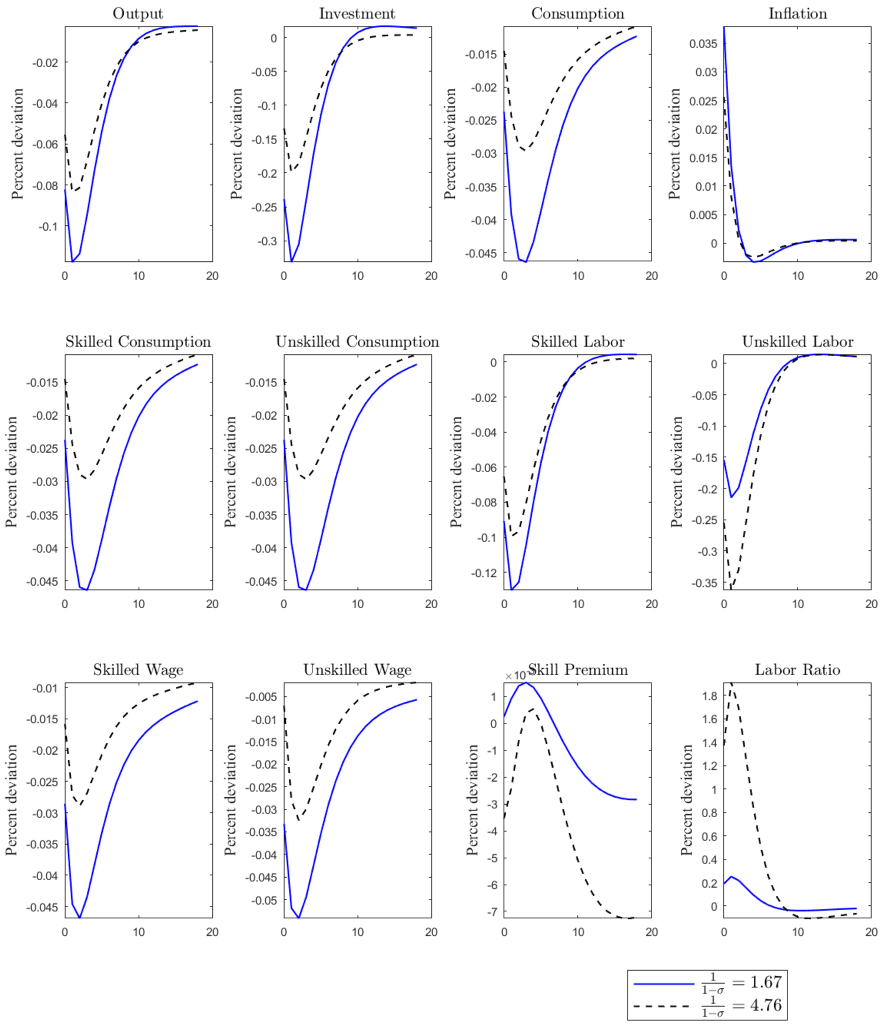
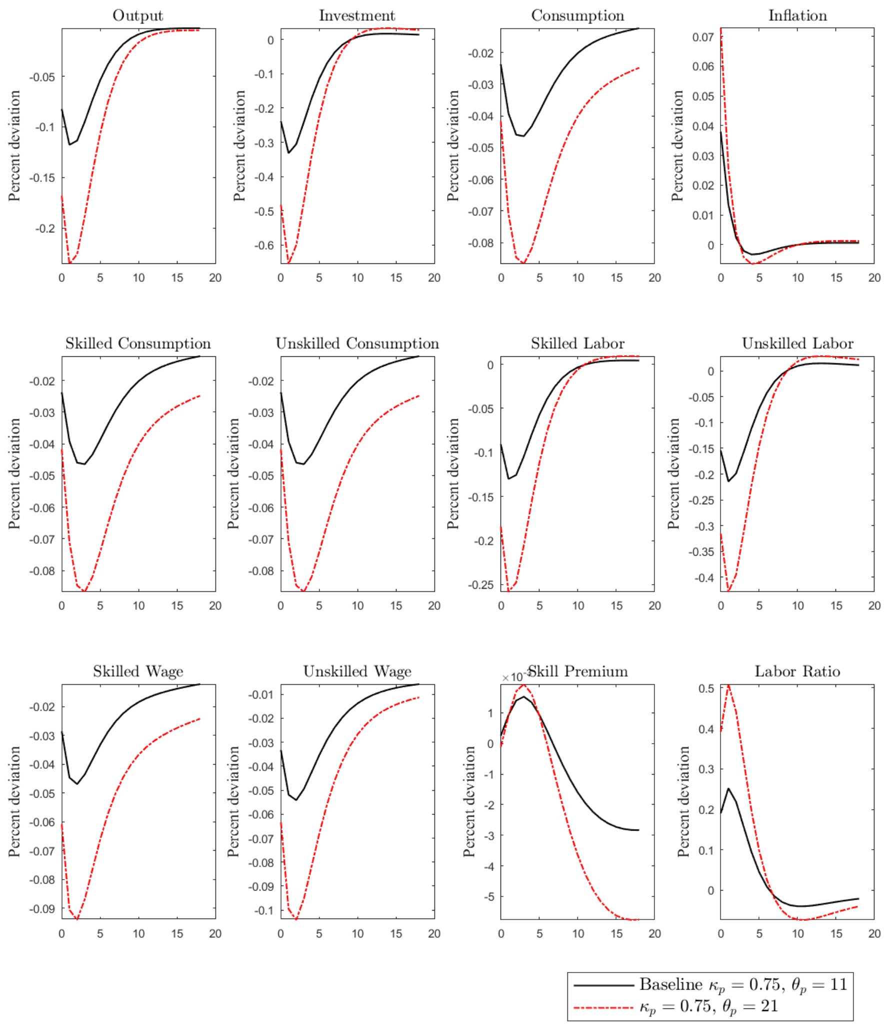


Figure 13. Impulse response functions to TFP uncertainty shock – elasticity of substitution btw capital and skilled labor composite and unskilled labor.



Nominal rigidities. I set the price elasticity to imply steady-state markups of 5% as used in Fernandez-Villaverde and others (2015). Baseline calibration of steady state price markups of 10% is more consistent with micro pricing studies, while the 5% steady state markup is consistent with macro studies (for example, as in Altig and others (2011)). Larger demand elasticity leads to larger output effects due to increasing the convexity of the marginal profit function and hence the precautionary pricing effect (see Born and Pfeifer (2014)).

Figure 14. Impulse response functions to TFP uncertainty shock – elasticity of substitution btw goods.



Simplified model. I test the need to resort to the large DSGE model to address the question and focus on a much simpler model. I perform this sensitivity check in Section 6.3. Figure 15 shows the IRFs to TFP uncertainty shock in the baseline model (black solid line) in comparison with the model without nominal price and wage rigidities (red dash-dot line). Figure 16 shows the IRFs to TFP uncertainty shock in the baseline model (black solid line) in comparison with the model without nominal price and wage rigidities, without habits in consumption and without investment adjustment costs (red dash-dot line). As can be seen from the IRFs, nominal rigidities are necessary to generate a recession in response to the uncertainty shock. In the model without nominal price and wage rigidities, the shock triggers a rise in output and investment. As explained in Basu and Bundick (2017a), The precautionary motive of households leads to a fall in consumption and an increase in labor supply, which reduces nominal marginal costs and wages. When prices are flexible, real marginal costs are unaffected by the increase in labor supply and firms' markups remain constant. Since capital is predetermined, the increase in labor supply leads to a rise in output. Nominal rigidity allows to obtain a co-movement between consumption and output.

Figure 15. Impulse response functions to TFP uncertainty shock in baseline model and in the model without nominal price and wage rigidity.

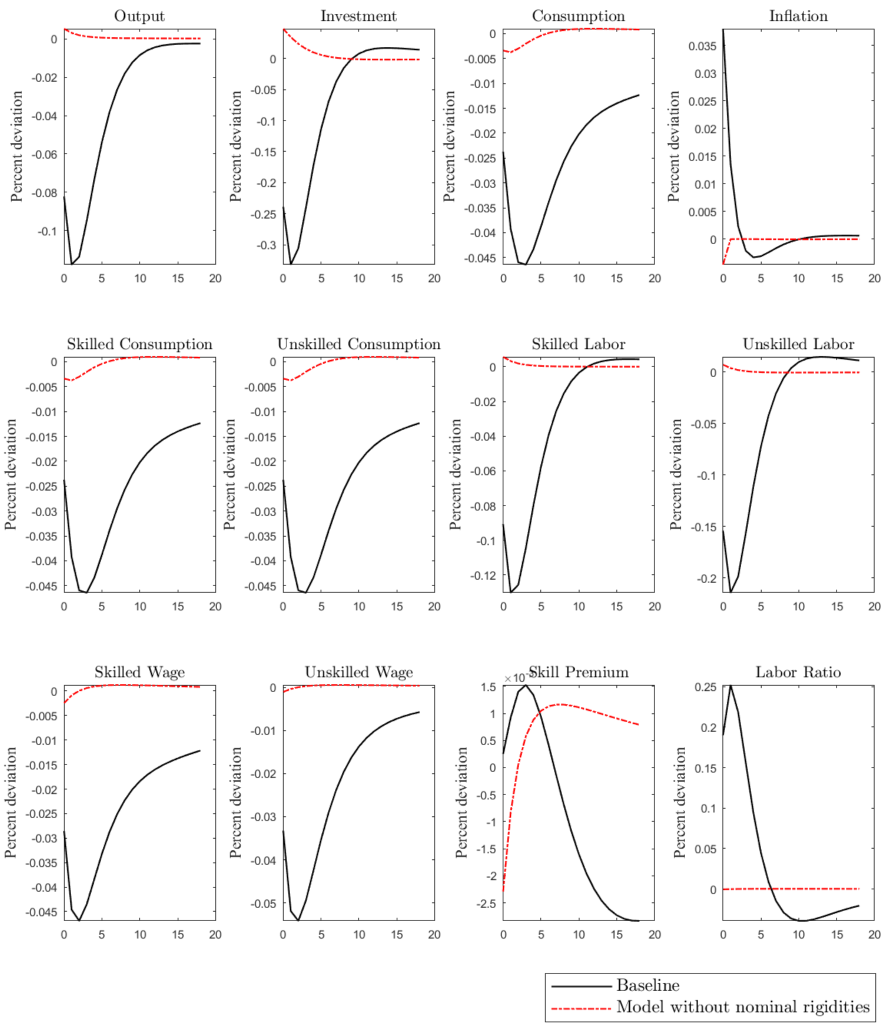
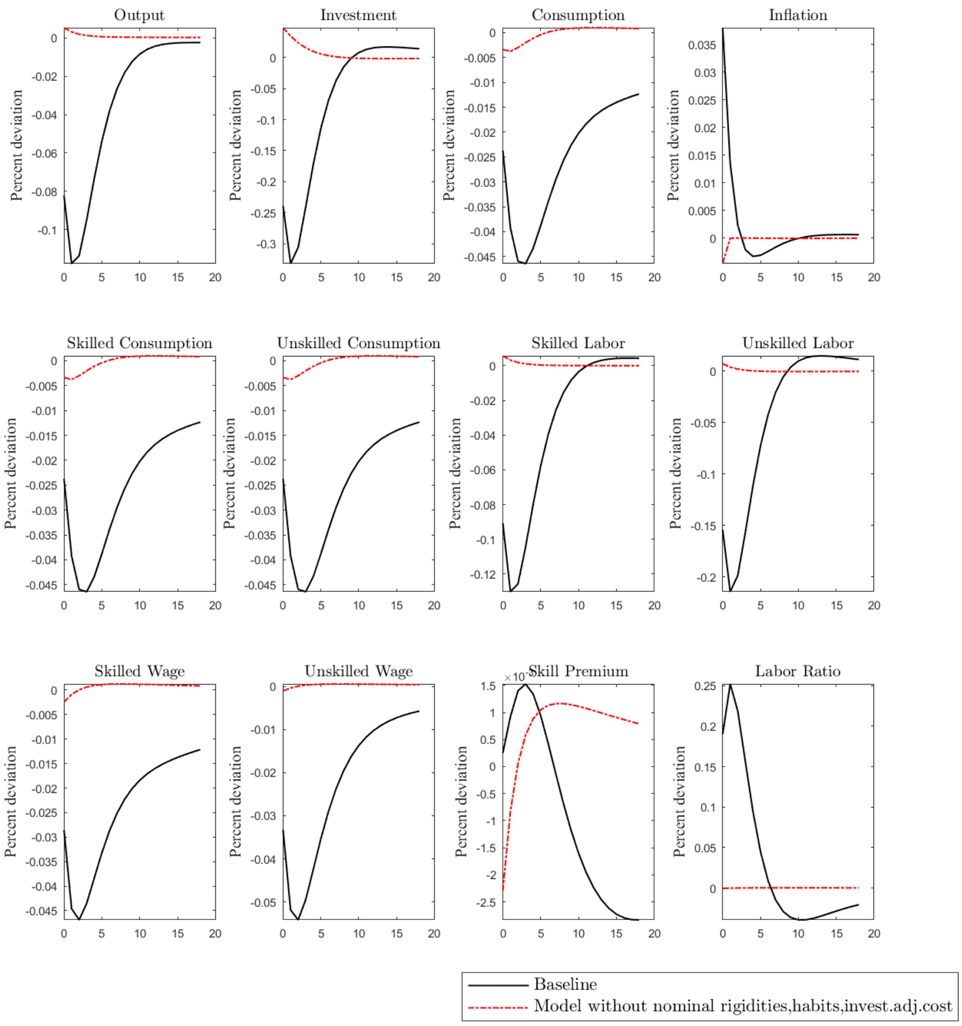


Figure 16. Impulse response functions to TFP uncertainty shock in baseline model and in the model without nominal price and wage rigidity, habit formation in consumption and investment adjustment costs.



VII. Conclusion

In this paper I showed that aggregate uncertainty has a heterogeneous impact on labor market outcomes for skilled and unskilled workers. On the empirical side, I documented that, while generating a contraction in aggregate economic activity, heightened uncertainty induces an increase in the relative skilled employment, while the skill premium does not react significantly to the shock. On the theoretical side, I built a New Keynesian DSGE model featuring skilled and unskilled labor, capital-skill complementarity in production, and wage rigidities. I find that macroeconomic uncertainty increases employment disparities between the skilled and unskilled by raising the relative employment of skilled workers. The interaction of capital-skill complemetarity, precautionary labor supply and wage stickiness is crucial for this result. Notably, capital-skill complementarity amplifies the responses of relative labor demand and relative labor supply. As such, these findings contribute to a deeper understanding of transmission mechanisms through which uncertainty affects the real economy. The results could help more accurately assess the transmission of uncertainty and frame economic policy in times of elevated uncertainty.

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Appendix A. Additional Details Concerning Model Derivations

A. Production Function without Capital-Skill Complementarity

In the benchmark model the form of the production function is a nested CES composite of production factors in Equation 21, and in the counterfactual model without capital-skill complementarity the form of production function is given by Equation 42. In the case without capital-skill complementarity I assume a production function, the structure of which allows to impose perfect substitutability between skilled and unskilled labor inputs. For this purpose, I generalize a constant returns to scale Cobb-Douglas form of production function with aggregate capital (k_t) and aggregate labor (n_t) services, i.e. $y = \mathscr{Z}_t k_t^{\iota} n_t^{1-\iota}$, where capital and aggregate labor are neither complements nor substitutes. In doing so I let labor input, n_t, be a constant elasticity of substitution (CES) function of composite skilled and unskilled labor, i.e. $n_t = (\omega(n_t^s)^{\nu} + (1-\omega)(n_t^u)^{\nu})^{\frac{1}{\nu}}$. I assume that skilled and unskilled hours are perfect substitutes by setting the elasticity of substitution between skilled and unskilled labor equal to one. The production function becomes

$$y = \mathscr{Z}_t k_t^{\iota} (\omega(n_t^s)^{\nu} + (1-\omega)(n_t^u)^{\nu})^{\frac{(1-\iota)}{\nu}} \tag{42}$$

with $\omega = 0.5$, $\nu = 1$ (governs substitution between 2 labor types with $\nu = 1$ perfect substitutes), and the income share of capital ι is calibrated to obtain a labor income share of 69%.

Optimality conditions associated with the production function in 42 are given by

$$r_t^k = x_t \frac{\partial y_t}{k_t} \tag{43}$$

$$\frac{\partial y_t}{k_t} = \mathscr{Z}_t k_t^{(\iota-1)} \iota \, (\omega(n_t^s)^{\nu} + (1-\omega)(n_t^u)^{\nu})^{\frac{(1-\iota)}{\nu}} \tag{44}$$

$$\frac{w_t^s}{x_t} = mpl_t^s = \mathscr{Z}_t (1-\iota) k_t^{\iota} \omega (n_t^s)^{(\nu-1)} (\omega(n_t^s)^{\nu} + (1-\omega)(n_t^u)^{\nu})^{(\frac{(1-\iota)}{\nu}-1)} \tag{45}$$

$$\frac{w_t^u}{x_t} = mpl_t^u = \mathscr{Z}_t (1-\iota) k_t^{\iota} (1-\omega) (n_t^u)^{(\nu-1)} (\omega(n_t^s)^{\nu} + (1-\omega)(n_t^u)^{\nu})^{(\frac{(1-\iota)}{\nu}-1)} \tag{46}$$

Labor share in income is

$$\frac{w_t^s n_t^s + w_t^u n_t^u}{y_t} = \tag{47}$$

$$\frac{\left((1-\iota) k_t^{\iota} (\omega(n_t^s)^{\nu} + (1-\omega)(n_t^u)^{\nu})^{(\frac{(1-\iota)}{\nu}-1)}\right) [\omega(n_t^s)^{\nu} + (1-\omega)(n_t^u)^{\nu}]}{\mathscr{Z}_t k_t^{\iota} (\omega(n_t^s)^{\nu} + (1-\omega)(n_t^u)^{\nu})^{\frac{(1-\iota)}{\nu}}}$$

A.1. Wage Stickiness

Motivated by the evidence that aggregate wages similar to prices are subject to rigidities, I introduce Calvo-type wage rigidity in the model. To introduce wage stickiness in an analogous way to price stickiness, I need households to supply differentiated labor input, which gives them some pricing power in setting their own wage. I introduce the concept of a labor packer, which combines different types of labor into a composite labor good that it then leases to wholesale firms at wage rate $w_t^i, i \in (s,u)$. The labor used by wholesale firms to be described below is supplied by a representative, competitive labor packer that hires the labor supplied by each skilled household s, j and unskilled household u, j. The labor packer aggregates the differentiated labor of households with the following production function

$$h_t^i = \left[\int_0^1 (h_t^{i,j})^{\frac{\eta_w - 1}{\eta_w^i}} dj \right]^{\frac{\eta_w^i}{\eta_w^i - 1}} \tag{48}$$

where $0 \leq \eta_w^i \geq \infty$ is the elasticity of substitution among different types of skilled and unskilled labor ($i \in (s,u)$) and h_t^i is the aggregate labor-i demand.

Labor packers maximize profits in a perfectly competitive environment. From the FOCs of the labor packers one obtains the input demand function associated with the problem of the labor packer

$$h_t^{i,j} = \left(\frac{w_t^{i,j}}{w_t^i} \right)^{-\eta_w^i} h_t^i \tag{49}$$

Aggregate wage is

$$w_t^i = \left[\int_0^1 (w_t^{i,j})^{1-\eta_w^i} dj \right]^{\frac{1}{1-\eta_w^i}} \tag{50}$$

In each period, a fraction $(1 - \theta_w^i)$ of skilled and unskilled households can change their wages. All other households can only partially index their wages by past inflation. Indexation is controlled by the parameter $\chi^w \in [0,1]$. Therefore, the relevant part of the Lagrangian for the household $i \in (s,u)$ is then:

$$\mathscr{L}^{i,w} = E_t \sum_{s=0}^{\infty} (\theta_w^i \beta)^s \left[-\kappa_h^i \frac{(h_{t+s}^{i,j})^{1+\phi^i}}{1+\phi^i} + \lambda_{t+s}^{i,j} \prod_{k=1}^{s} \left(\frac{\pi_{t+k}}{\pi_{t+k-1}^{\chi^w}} \right)^{-1} w_t^{i,j} h_{t+s}^{i,j} \right] \tag{51}$$

subject to the demand function

$$h_t^{i,j} = \left(\prod_{k=1}^{s} \left(\frac{\pi_{t+k}}{\pi_{t+k-1}^{\tilde{\chi}^w}} \right)^{-1} \frac{w_t^{i,j}}{w_{t+s}^i} \right)^{-\eta_w^i} h_{t+s}^i \tag{52}$$

substituting the demand function gives

$$\mathscr{L}^{i,w} = E_t \sum_{s=0}^{\infty} (\theta_w^i \beta)^s \left[-\kappa_h^i \frac{\left(\prod_{k=1}^{s} \left(\frac{\pi_{t+k}}{\pi_{t+k-1}^{\chi^w}} \right)^{-1} \frac{w_t^{i,j}}{w_{t+s}^i} \right)^{-\eta_w^i (1+\phi^i)}}{1+\phi^i} (h_{t+s}^i)^{1+\phi^i} \right. \tag{53}$$
$$\left. + \lambda_{t+s}^{i,j} \prod_{k=1}^{s} \left(\frac{\pi_{t+k}}{\pi_{t+k-1}^{\chi^w}} \right)^{-1} w_t^{i,j} \left(\prod_{k=1}^{s} \left(\frac{\pi_{t+k}}{\pi_{t+k-1}^{\chi^w}} \right)^{-1} \frac{w_t^{i,j}}{w_{t+s}^i} \right)^{-\eta_w^i} h_{t+s}^i \right]$$

which simplifies to

$$\mathscr{L}^{i,w} = E_t \sum_{s=0}^{\infty} (\theta_w^i \beta)^s \left[-\kappa_h^i \frac{\left(\prod_{k=1}^{s} \left(\frac{\pi_{t+k}}{\pi_{t+k-1}^{\chi^w}} \right)^{-1} \frac{w_t^{i,j}}{w_{t+s}^i} \right)^{-\eta_w^i (1+\phi^i)}}{1+\phi^i} (h_{t+s}^i)^{1+\phi^i} \right. \tag{54}$$
$$\left. + \lambda_{t+s}^{i,j} \left(\prod_{k=1}^{s} \left(\frac{\pi_{t+k}}{\pi_{t+k-1}^{\chi^w}} \right)^{-1} \frac{w_t^{i,j}}{w_{t+s}^i} \right)^{1-\eta_w^i} w_t^i h_{t+s}^i \right]$$

All skilled and unskilled households $i \in (s,u)$ set the same skilled and unskilled wage respectively because complete markets allow them to hedge the risk of the timing of wage change. Hence, I drop the j from the choice of wages and $\lambda_t^{i,j}$. The first order condition with respect to w_t^i therefore is:

$$E_t \sum_{s=0}^{\infty} (\theta_w^i \beta)^s \left[\frac{\eta_w^i}{w_t^{i,*}} \kappa_h^i \left(\prod_{k=1}^{s} \left(\frac{\pi_{t+k}}{\pi_{t+k-1}^{\chi^w}} \right)^{-1} \frac{w_t^{i,*}}{w_t^{i+s}} \right)^{-\eta_w^i (1+\phi^i)} (h_{t+s}^i)^{1+\phi^i} \right. \tag{55}$$
$$\left. +(1-\eta_w^i)\lambda_{t+s}^i \left(\prod_{k=1}^{s} \left(\frac{\pi_{t+k}}{\pi_{t+k-1}^{\chi^w}} \right)^{-1} \frac{w_t^{i,*}}{w_{t+s}^i} \right)^{-\eta_w^i} h_{t+s}^i \right]$$

To write the wage-setting equation in recursive form, I define

$$f_t^{i,1} = \left(\frac{\eta_w^i - 1}{\eta_w^i} \right) w_t^{i,*} E_t \sum_{s=0}^{\infty} (\beta \theta_w^i)^s \lambda_{t+s}^i \left(\frac{w_{t+s}^i}{w_t^{i,*}} \right)^{\eta_w^i} h_{t+s}^i \prod_{k=1}^{s} \left(\frac{\pi_{t+k}}{\pi_{t+k-1}^{\chi^w}} \right)^{\eta_w^i - 1} \tag{56}$$

and

$$f_t^{i,2} = E_t \sum_{s=0}^{\infty} (\beta \theta_w^i)^s \kappa_h^i \prod_{k=1}^{s} \left(\frac{\pi_{t+k}}{\pi_{t+k-1}^{\chi^w}} \right)^{\eta_w^i (1+\phi^i)} \left(\frac{w_{t+s}^i}{w_t^{i,*}} \right)^{\eta_w^i (1+\phi^i)} (h_{t+s}^i)^{1+\phi^i} \tag{57}$$

so that the equality $f_t^{i,1} = f_t^{i,2}$ is the previous first order condition.

I consider a symmetric equilibrium where $w_t^{i,j,*} = w_t^{i,*}$. Expressing $f_t^{i,1}$ and $f_t^{i,2}$ recursively and defining $f_t^i = f_t^{i,1} = f_t^{i,2}$ I obtain the laws of motion for f_t^i

$$f_t^i = \left(\frac{\eta_w^i - 1}{\eta_w^i} \right) (w_t^{i,*})^{1-\eta_w^i} \lambda_t^i (w_t^i)^{\eta_w^i} h_t^i + (\beta \theta_w^i) E_t \left(\frac{\pi_t}{\pi_{t-1}^{\chi^w}} \right)^{\eta_w^i - 1} \left(\frac{w_{t+1}^{i,*}}{w_t^{i,*}} \right)^{\eta_w^i - 1} f_{t+1}^i \tag{58}$$

and

$$f_t^i = \kappa_h^i (h_t^i)^{1+\phi^i} \left(\frac{w_t^i}{w_t^{i,*}} \right)^{\eta_w^i (1+\phi^i)} + (\beta \theta_w^i) E_t \left(\frac{\pi_t}{\pi_{t-1}^{\chi^w}} \right)^{\eta_w^i (1+\phi^i)} \left(\frac{w_{t+1}^{i,*}}{w_t^{i,*}} \right)^{\eta_w^i (1+\phi^i)} f_{t+1}^i \tag{59}$$

In a symmetric equilibrium, in every period, a fraction $(1-\theta_w^i)$ of skilled and unskilled households $i \in (s,u)$ set $w_t^{i,*}$ as their wage, while the remaining fraction θ_w^i set their wage equal to the nominal wage observed in the previous period in case of no wage indexation, or partially index their price by past inflation. The real wage index of skilled and unskilled households evolves as

$$(w_t^i)^{1-\eta_w^i} = \theta_w^i \left(\frac{\pi_t}{\pi_{t-1}^{\chi^w}} \right)^{\eta_w^i - 1} (w_{t-1}^i)^{1-\eta_w^i} + (1-\theta_w^i)(w_t^{i,*})^{1-\eta_w^i} \tag{60}$$

A.2. Wholesale Firms

Maximization of profits by wholesalers yields the following F.O.C. given the form of the production function in equation (21) with respect to capital, k_t, employment of skilled, n_t^s, and unskilled labor, n_t^u.

$$\begin{aligned} \frac{R_t^k}{x_t} &= \frac{\partial y_t}{\partial k_t} = (1-\mu)\lambda(\lambda k_t^\rho + (1-\lambda)(n_t^s)^\rho)^{\frac{\sigma}{\rho}-1} k_t^{\rho-1} \\ &\times \underbrace{\mathscr{Z}_t\left[\mu(n_t^u)^\sigma + (1-\mu)(\lambda k_t^\rho + (1-\lambda)(n_t^s)^\rho)^{\frac{\sigma}{\rho}}\right]^{\frac{1}{\sigma}-1}}_{\mathscr{Z}_t f(k_t, n_t^s, n_t^u)^{1-\sigma} \equiv y^{1-\sigma}} \\ &= (1-\mu)\lambda\left(\lambda k_t^\rho + (1-\lambda)(n_t^s)^\rho\right)^{\frac{\sigma}{\rho}-1} k_t^{\rho-1} y_t^{1-\sigma} \end{aligned} \tag{61}$$

$$\begin{aligned} \frac{w_t^s}{x_t} &= mpl_t^s = \frac{\partial y_t}{\partial n_t^s} = \mathscr{Z}_t(1-\mu)(1-\lambda)(\lambda k_t^\rho + (1-\lambda)(n_t^s)^\rho)^{\frac{\sigma}{\rho}-1}(n_t^s)^{\rho-1} \\ &\times \left[\mu(n_t^u)^\sigma + (1-\mu)(\lambda k_t^\rho + (1-\lambda)(n_t^s)^\rho)^{\frac{\sigma}{\rho}}\right]^{\frac{1}{\sigma}-1} \\ &= (1-\mu)(1-\lambda)(\lambda k_t^\rho + (1-\lambda)(n_t^s)^\rho)^{\frac{\sigma}{\rho}-1}(n_t^s)^{\rho-1} y_t^{1-\sigma} \end{aligned} \tag{62}$$

$$\begin{aligned} \frac{w_t^u}{x_t} &= mpl_t^u = \frac{\partial y_t}{\partial n_t^u} = \mathscr{Z}_t\mu\left[\mu(n_t^u)^\sigma + (1-\mu)(\lambda k_t^\rho + (1-\lambda)(n_t^s)^\rho)^{\frac{\sigma}{\rho}}\right]^{\frac{1}{\sigma}-1}(n_t^u)^{\sigma-1} \\ &= \mu(n_t^u)^{\sigma-1} y_t^{1-\sigma} \end{aligned} \tag{63}$$

The labor share in income is defined as

$$\begin{aligned} \frac{w_t^s n_t^s + w_t^u n_t^u}{y_t} &= \left[\mu(n_t^u)^\sigma + (1-\mu)\left(\lambda k_t^\rho + (1-\lambda)(n_t^s)^\rho\right)^{\frac{\sigma}{\rho}}\right]^{-1} \\ &\times \left[\mu(n_t^u)^\sigma + (1-\mu)\left(\lambda k_t^\rho + (1-\lambda)(n_t^s)^\rho\right)^{\frac{\sigma}{\rho}-1}(1-\lambda)(n_t^s)^\rho\right] \\ &= y^{-\sigma}\left[(1-\mu)(1-\lambda)(\lambda k^\rho + (1-\lambda)(n^s)^\rho)^{\frac{\sigma}{\rho}-1}(n^s)^\rho + \mu(n^u)^\sigma\right] \end{aligned} \tag{64}$$

APPENDIX B. EMPIRICAL ROBUSTNESS

The benchmark SVAR presented in Section II revealed two stylized facts – a 1-sd uncertainty shock raises the employment rate ratio and does not significantly impact the skill premium. In this section, I examine the robustness of these results along several dimensions. I show that the main results regarding the behavior of the aggregate variables, the skill premium and employment rate ratio hold, if stock prices are accounted for, uncertainty ordered last in the SVAR, with higher frequency estimation, analysis restricted to the pre-2007 financial crisis sample period.

A. Detrending Methods

I test the baseline results to alternative detrending methods, namely one-sided HP filter and linear detrending. First, Figure 17 plots the IRFs with data detrended using one-sided HP filter. A one-sided HP filter preserves the temporal ordering of the data (Stock and Watson (1999)), which ensures that the time ordering of the data remains undisturbed and the autoregressive structure is preserved. Second, Figure 18 shows IRFs with linearly detrended data. The results qualitatively and quantitatively resemble the benchmark specification.

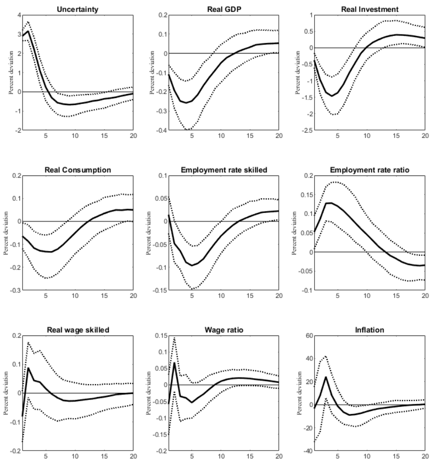
B. Uncertainty Ordered Last

I test an alternative identification scheme by changing the Cholesky ordering assumed in the benchmark specification. Thus, I order uncertainty last, allowing the uncertainty measure to respond on impact to all the other variables in the model. The other variables will respond with a one-period lag to an uncertainty shock. Figure 19 shows that the baseline results hold in aggregate economy and in Manufacturing sector.

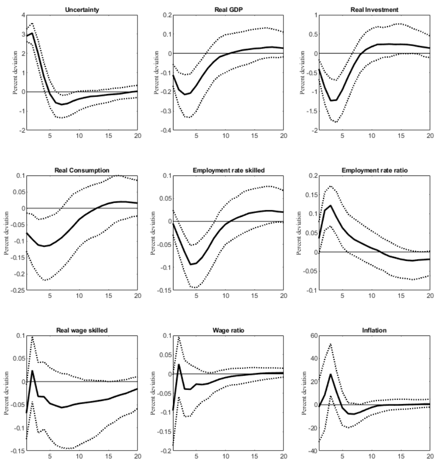
C. Increase the Number of Lags

I increase the number of lags included in the SVAR from 2 to 6 to show that the baseline results are not due to the number of lags, as shown in Figure 20.

Figure 17. SVAR impulse response functions to 1-sd uncertainty shock with detrended data using one-sided HP filter.



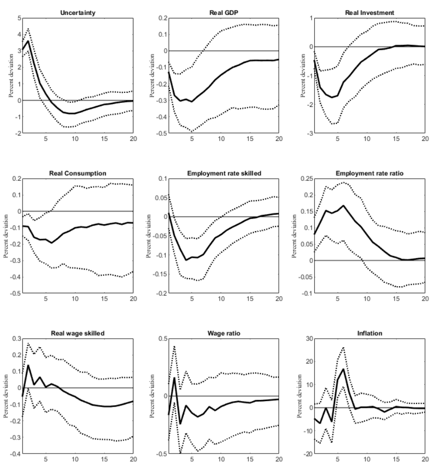
(a) Aggregate economy.



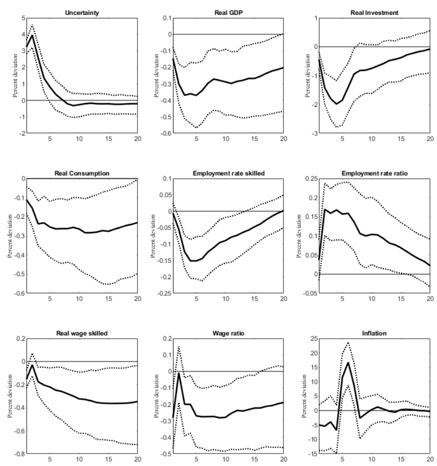
(b) Manufacturing sector.

Note: Solid lines correspond to the median IRFs while the dashed lines are the 10^{th} and 90^{th} percentiles. Horizontal axes indicate quarters. Following the AIC, the number of lags is set to 2.

Figure 18. SVAR impulse response functions to 1-sd uncertainty shock with linearly detrended data.



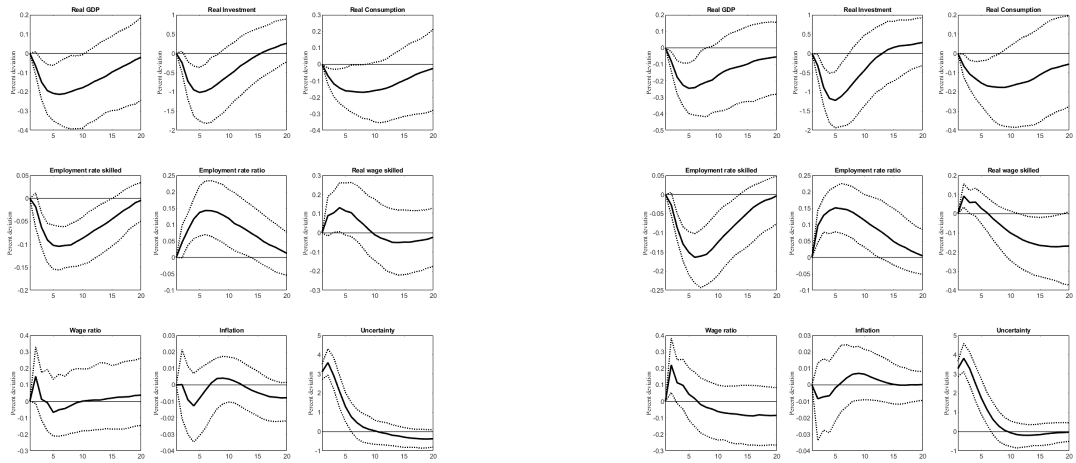
(a) Aggregate economy.



(b) Manufacturing sector.

Note: Solid lines correspond to the median IRFs while the dashed lines are the 10^{th} and 90^{th} percentiles. Horizontal axes indicate quarters. Following the AIC, the number of lags is set to 4.

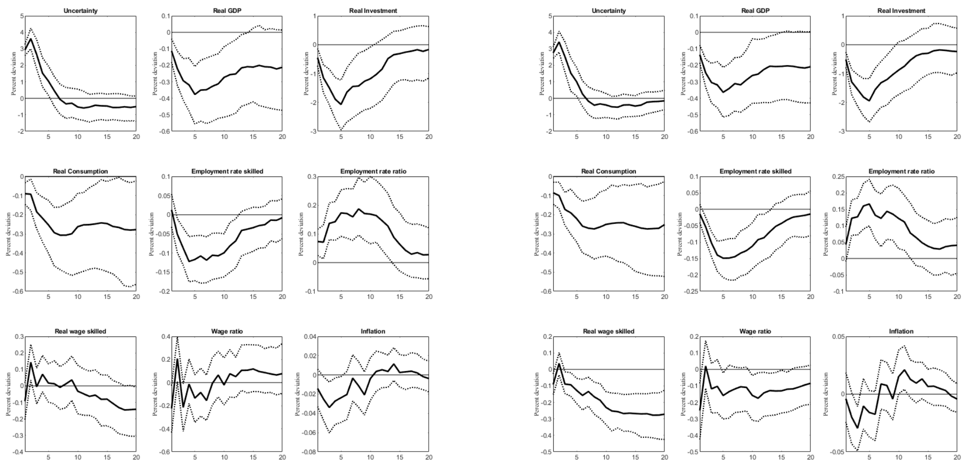
Figure 19. SVAR impulse response functions to 1-sd uncertainty shock with uncertainty ordered last.



(a) Aggregate economy. **(b) Manufacturing sector.**

Note: Solid lines correspond to the median IRFs while the dashed lines are the 10^{th} and 90^{th} percentiles. Horizontal axes indicate quarters. I take logs of the uncertainty measure, to interpret the IRFs in percentage terms. Output, consumption, capital investment, and skilled wage are expressed in logs. Following the AIC, the number of lags is set to 2.

Figure 20. SVAR impulse response functions to 1-sd uncertainty shock with 6 lags.



(a) Aggregate economy. **(b) Manufacturing sector.**

Note: Solid lines correspond to the median IRFs while the dashed lines are the 10^{th} and 90^{th} percentiles. Horizontal axes indicate quarters. I take logs of the uncertainty measure, to interpret the IRFs in percentage terms. Output, consumption, capital investment, and skilled wage are expressed in logs.

D. Alternative Measure of Uncertainty

I estimate the SVAR using a different measure of macroeconomic uncertainty, namely I use data from a forecasting dataset, the Survey of Professional Forecasters (SPF). This dataset provides information on the forecasts of macro variables made by professional forecasters. I use the measure of cross-sectional dispersion of quarterly forecasts for nominal GDP growth. Figure 21 plots the IRFs to a 1-sd shock to the SPF measure for aggregate economy and in manufacturing sector, which are qualitatively in line with the baseline results.

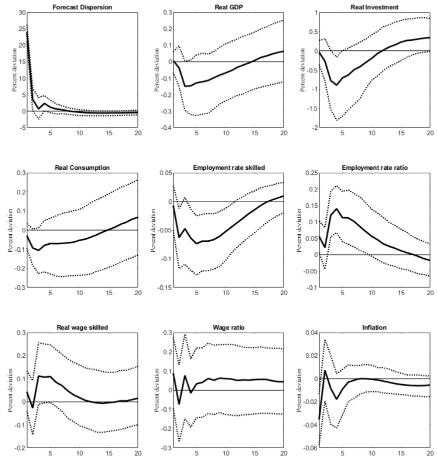
Baker et al. (2016) have constructed an index of economic policy uncertainty. It is more narrow than the JLN-uncertainty measure used in the baseline estimation since it only captures the economic-policy dimension of uncertainty. Despite the difference, the responses of the variables (Figure 22) are similar to the baseline. When using EPU, the sample only starts in 1985 due to non-availability of the EPU measure.

Caldara and others (2016) and Ludvigson and Ng (2021) have argued that financial uncertainty drives macroeconomic uncertainty, and it is important to account for both. In Figure 23 I display the IRFs in response to the financial uncertainty measure of Ludvigson and Ng (2021). The results show a familiar pattern to the baseline estimation using JLN-macro uncertainty measure.

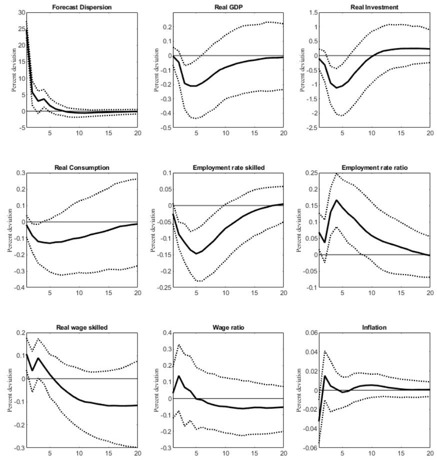
E. Alternative Measure of Skill Premium

As a robustness check, I use an alternative measure of the relative ratio of skilled wages – the skill premium from Balleer and van Rens (2013). Their measure is from 1979Q1 to 2005Q4. Figure 24 shows the IRFs, and that the baseline results are robust to this alternative measure.

Figure 21. SVAR impulse response functions to 1-sd shock to SPF forecast dispersion measure of uncertainty.



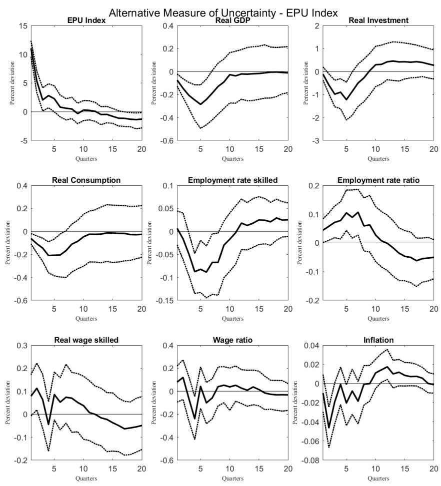
(a) Aggregate economy.



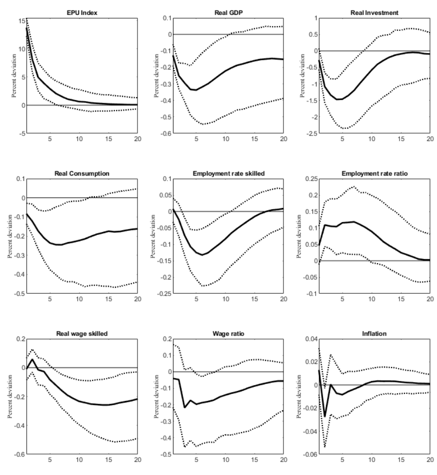
(b) Manufacturing sector.

Note: Solid lines correspond to the median IRFs while the dashed lines are the 10^{th} and 90^{th} percentiles. Horizontal axes indicate quarters. I take logs of the uncertainty measure, to interpret the IRFs in percentage terms. Output, consumption, capital investment, and skilled wage are expressed in logs. Following the AIC, the number of lags is set to 2.

Figure 22. SVAR impulse response functions to 1-sd shock to the EPU index.



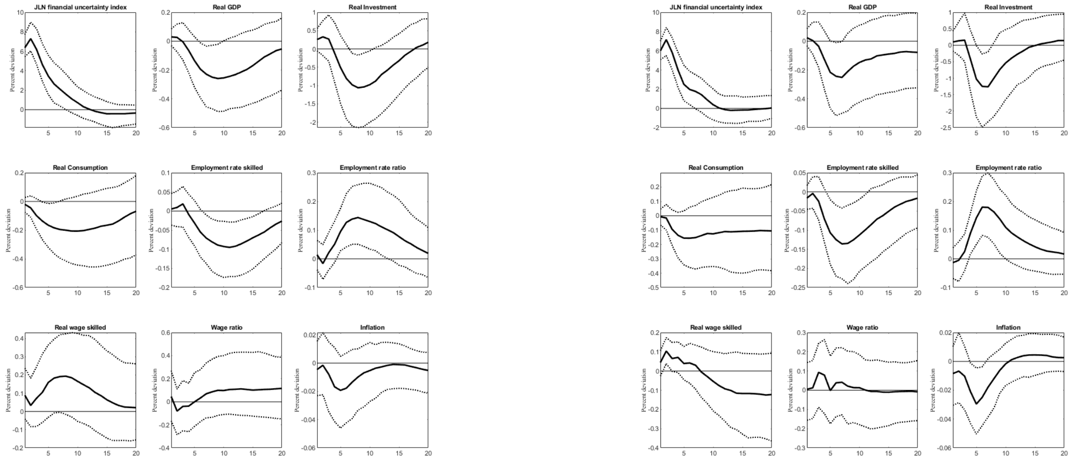
(a) Aggregate economy.



(b) Manufacturing sector.

Note: Solid lines correspond to the median IRFs while the dashed lines are the 10^{th} and 90^{th} percentiles. Horizontal axes indicate quarters. I take logs of the uncertainty measure, to interpret the IRFs in percentage terms. Output, consumption, capital investment, and skilled wage are expressed in logs. The EPU index is measured in arbitrary units and has a mean of 100. The number of lags is set to 2.

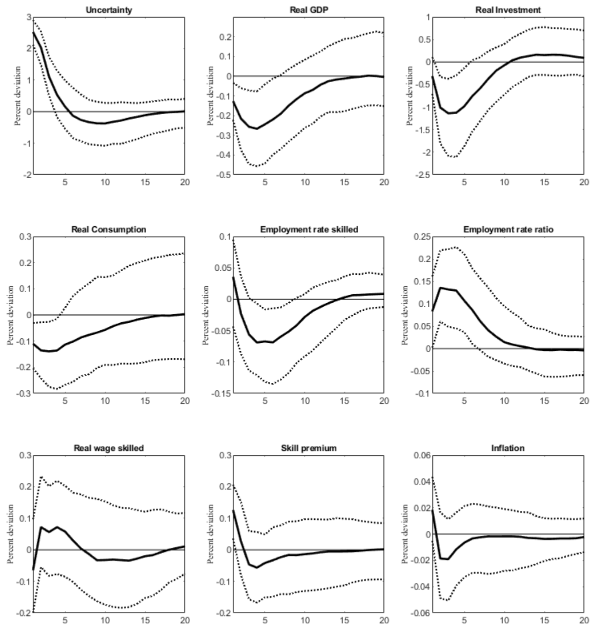
Figure 23. SVAR impulse response functions to 1-sd financial uncertainty shock (Ludvigson and Ng (2021)). The financial uncertainty index is measured in arbitrary units and has a mean of 0.91.



(a) Aggregate economy. **(b) Manufacturing sector.**

Note: Solid lines correspond to the median IRFs while the dashed lines are the 10^{th} and 90^{th} percentiles. Horizontal axes indicate quarters. I take logs of the uncertainty measure, to interpret the IRFs in percentage terms. The number of lags is set to 2.

Figure 24. SVAR impulse response functions to 1-sd uncertainty shock in aggregate economy.



Note: Solid lines correspond to the median IRFs while the dashed lines are the 10^{th} and 90^{th} percentiles. Horizontal axes indicate quarters. I take logs of the uncertainty measure, to interpret the IRFs in percentage terms. Output, consumption, capital investment, and skilled wage are expressed in logs. The number of lags is set to 2.

F. Control for the Stock Market

I include the Standard & Poor's 500 Stock Price Index ($S\&P500$) ordering it first in the benchmark specification of the SVAR, which allows to control for the movements in the stock market.[37] Ordering $S\&P500$ index first implies that the uncertainty measure is contemporaneously affected by shocks to the $S\&P500$ index, but not by the other variables. In the following periods, uncertainty responds to all shocks through its relation with the lags of the variables included in the model. This identification strategy is in line with that in Bloom (2009), Basu and Bundick (2017b), Bonciani and Oh (2020). Figure 25 shows that the results are very similar to the baseline specification.

G. Monthly Frequency

Baseline results are robust to using higher frequency estimation. In the benchmark SVAR, I aggregate monthly labor market data – wages and employment rates – to quarterly frequency, which comes at a disadvantage of not making full use of high-frequency information. In order to exploit higher-frequency series as well as to ensure the results are robust to the aggregation of labor market series, I estimate a version of the SVAR model with monthly frequency data. The estimated period ranges from to 1979M1 to 2018M12. The monthly SVAR-(p) model reads as follows:

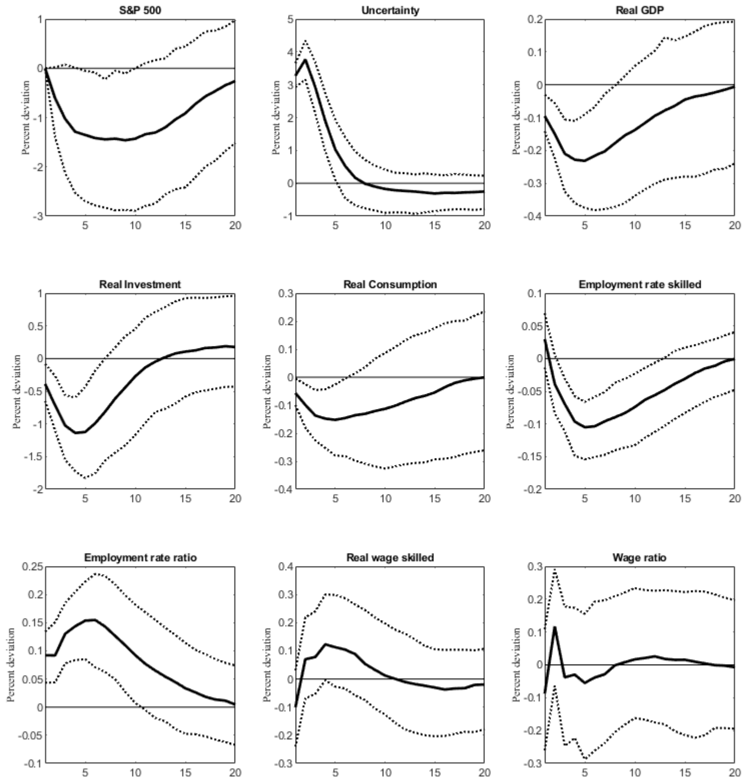
$$Y_t = c + \sum_{p=1}^{P} B_p Y_{t-p} + \varepsilon_t$$

where p is the number of lags, c is a vector of constants, B_p is the coefficient matrix for the p^{th} lag of Y_t, ε_t is the vector of reduced form zero-mean innovations, and $Y_t = [\sigma_t^z \quad y_t \quad i_t \quad c_t \quad n_t^s \quad \left(\frac{n^s}{n^u}\right)_t \quad w_t^s \quad \left(\frac{w^s}{w^u}\right)_t \quad \pi_t]'$ is a vector comprising the following variables: σ_t^z – the macroeconomic uncertainty index from Jurado, Ludvigson, and Ng (2015), y_t – Industrial Production (IP) Index, i_t – real gross private domestic investment,[38] c_t – personal consumption expenditures, n_t^s the skilled employment rate defined as the share of skilled employed workers in the skilled labor force, $\frac{n_t^s}{n_t^u}$ the employment rate ra-

[37] It is common practice to include stock prices in such empirical specifications, see other studies, for example, Bloom (2009), Basu and Bundick (2017b), Bonciani and Oh (2020)

[38] Since monthly series are not available, I temporally dissagregate quarterly time series of real gross private domestic investment into monthly series with Chow-Lin method using software JDemetra+ version 2.2.1. JDemetra+ is a tool for seasonal adjustment (SA) developed by the National Bank of Belgium (NBB) in cooperation with the Deutsche Bundesbank and Eurostat in accordance with the Guidelines of the European Statistical System (ESS).

Figure 25. SVAR impulse response functions to 1-sd uncertainty shock when including stock prices in the baseline specification.



Note: Solid lines correspond to the median IRFs while the dashed lines are the 10^{th} and 90^{th} percentiles. Horizontal axes indicate quarters. I take logs of the uncertainty measure, to interpret the IRFs in percentage terms. Output, consumption, capital investment, and skilled wage are expressed in logs. The number of lags is set to 2.

tio,[39] w_t^s weighted average of real hourly wage of employed in the skilled category,[40] $\frac{w_t^s}{w_t^u}$ is the wage ratio (the skill premium), π_t is chain-type price index for personal consumption expenditures. Monthly macroeconomics series are retrieved from FRED, Federal Reserve Bank of St. Louis. The monthly labor market time series are adjusted for seasonality using the X-13-ARIMA algorithm. I take logs of the uncertainty measure, to interpret the impulse response functions in percentage terms. IP index, real consumption, capital investment, and skilled wage enter the SVAR in log levels.

[39] I follow Dolado, Motyovszki, and Pappa (2021) and include in the SVAR the wage and employment gaps in addition to the individual variables for skilled workers since it allow to interpret the responses of the respective variables for unskilled workers.

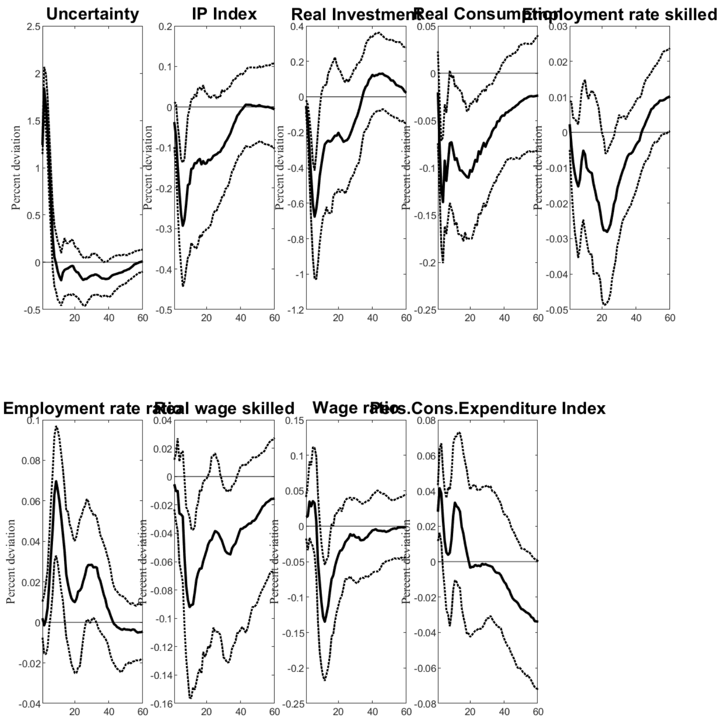
[40] Aggregated real hourly wage of employed in skilled category combines the usual hourly earnings for hourly workers (excluding otc), and non-hourly workers (including otc) in the usual hourly earnings.

Figure 26 shows the results of the monthly SVAR where the second panel displays a specification controlling for the stock market, with $S\&P500$ ordered first. The responses of aggregate variables as well as the wage ratio and employment rate ratio are in line with those obtained from the benchmark quarterly specification.

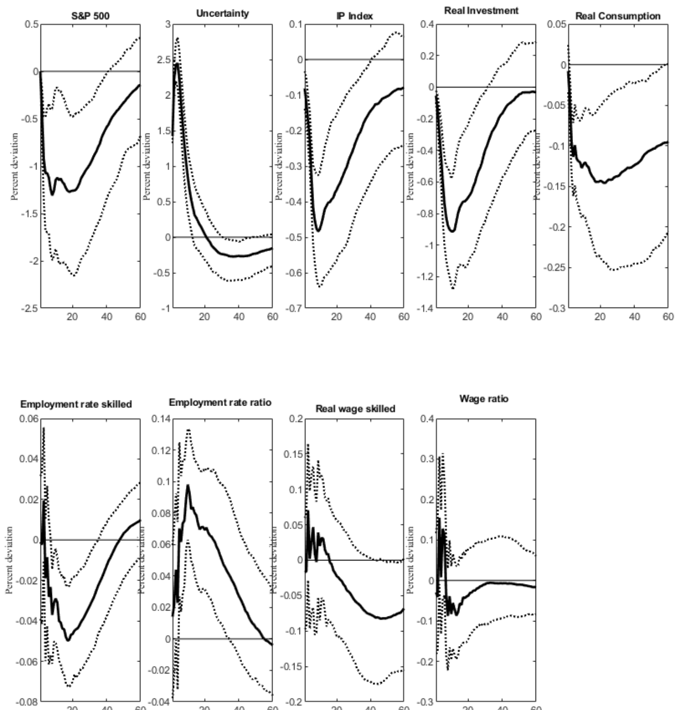
H. Period Prior to 2007

I reduce the sample until 2007M12 in order to exclude the global financial crisis, using monthly data to preserve sufficient length of the data series. Figure 27 shows that the results hold when excluding the post-2007 financial crisis years.

Figure 26. SVAR impulse response functions to 1-sd uncertainty shock with monthly data frequency.



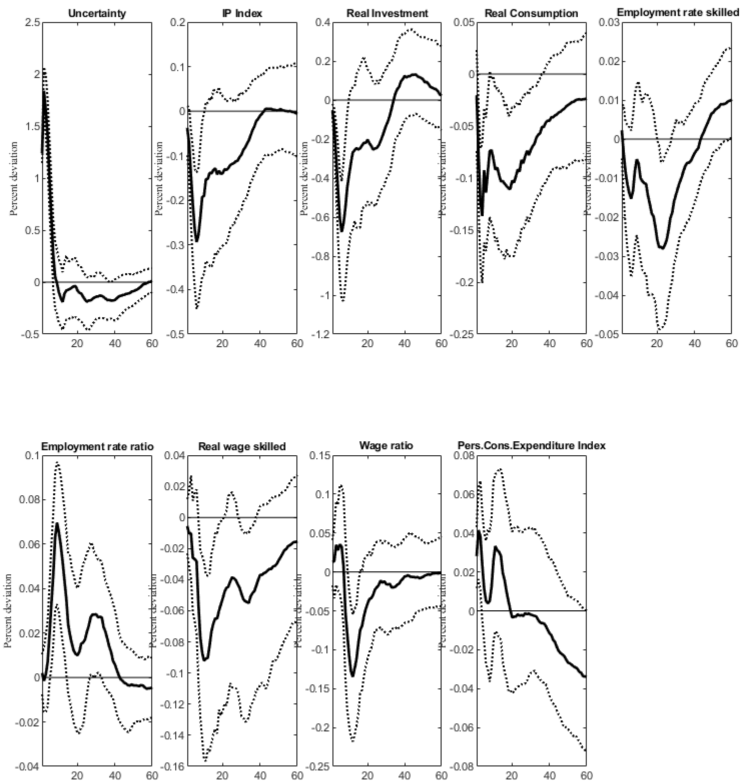
(a) Monthly frequency of the data with baseline specification.



(b) Monthly data frequency and controlling for the stock market.

Note: Solid lines correspond to the median IRFs while the dashed lines are the 10^{th} and 90^{th} percentiles. Horizontal axes indicate quarters.

Figure 27. Empirical impulse response functions to 1-sd uncertainty shock in the monthly specification of SVAR, period ranges from 1979M1 to 2007M12.



Note: Solid lines correspond to the median IRFs while the dashed lines are the 10^{th} and 90^{th} percentiles. Horizontal axes indicate quarters.

PUBLICATIONS

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