

Macroeconomic Uncertainty and Capital-Skill Complementarity

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Abstract

This paper investigates the implications of macroeconomic uncertainty on relative wages and relative employment of skilled vs. unskilled workers. First, I show empirically in a structural VAR model that uncertainty shocks are recessionary. As a result of the uncertainty shock, skilled workers experience a steeper fall in their wages than unskilled workers. On the other hand, relative employment increases. Second, I propose a dynamic New Keynesian model consistent with these findings. This model highlights the importance of distinguishing different roles of skilled and unskilled labor in production by the means of capital-skill complementarity. The uncertainty shock is contractionary and pushes the demand for labor and capital inputs down. The model uncovers novel propagation channel of uncertainty shocks, which explains effects of heightened uncertainty on the divergence of labor income and employment between skilled and unskilled labor.

JEL classification: Stochastic volatility; Capital-skill complementarity; Relative wages; Skill premium. *Keywords:* E32; J31.

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1 Introduction

After the financial crisis of 2007-2008, the subsequent Great Recession and the slow recovery, economic research have increasingly focused on the propagation of uncertainty to the aggregate economy. Starting with the seminal work by Bloom (2009) the recent uncertainty literature has shown that uncertainty shocks are important in accounting for fluctuations in output, investment and employment through complex transmission channels. In response to a rise in uncertainty households lower consumption, increase savings and hours worked, which lowers output due to nominal price rigidities¹. Investment irreversibilities, such as non-convex adjustment costs, induce firms to pause investment and hiring and "wait-and-see" until uncertainty is resolved². These channels yield a prediction of increased unemployment in response to an uncertainty shock. Frictions on the labor market have been shown to amplify the negative effects of heightened aggregate volatility³. However, existing transmission channels do not distinguish between relative effects of uncertainty shocks on the types of labor used in production process. Existing data and empirical work suggest that there are significant differences in labor market dynamics between skilled and unskilled workers at business cycle frequencies. It has been shown that the cyclical properties of employment differ between skilled and unskilled labor (see Hagedorn et al. (2016)). For example, the CPS data suggest that employment is more volatile for unskilled compared to skilled labor.

While the impact of uncertainty shocks on the real economy has been studied in the literature, the effects of uncertainty on skilled versus unskilled labor have not been investigated. Given these observations, this paper raises the question whether the effects of uncertainty differ between skilled and unskilled labor. Given evidence that uncertainty leads to contraction in real economic activity and in particular lower employment, the main focus of this paper is to explore whether aggregate uncertainty has an asymmetric impact on skilled compared to unskilled labor. More specifically, this paper proposes a mechanism through which a rise in uncertainty affects relative wages of skilled and unskilled workers (skill premium) and the gaps between their employment rates (relative employment). Given the key role of investment in periods of heightened uncertainty, I investigate the relation between capital and differently skilled labor by including capital-skill complementarity in

¹This is the aggregate demand channel studied by Basu and Budnick (2017)

²This option-value channel was documented by (Bernanke (1983) and Bloom (2009)

³Uncertainty shocks generate a fall in vacancies and an increase in unemployment since labor represents a particular type of real rigidity through the option-value channel that arises from labor search frictions (Leduc and Liu (2016))

production to the analysis. Capital-skill complementarity implies that the growth (fall) in the stock of capital will increase (decrease) the skill premium, since increases (decreases) in the capital stock increase (decrease) the marginal product of skilled labor, but decrease (increase) the marginal product of unskilled labor. To the best of my knowledge, this is a novel attempt in this area of research and there has not been any analysis on the business-cycle effects of capital-skill complementarity in production with the aim to study its implications for macroeconomic uncertainty shocks.

I investigate both empirically and theoretically the implications of higher macroeconomic uncertainty on macroeconomic aggregates. First, I motivate the analysis by estimating a structural vector autoregression (SVAR) model using data from the Current Population Survey (CPS). I recover that a macroeconomic uncertainty shock leads to a contraction in consumption, output and private investment. In particular, I find that total labor demand decreases, while the wage ratio falls and the relative employment rate increases. Then, I proceed to developing a general equilibrium model that replicates and rationalizes these empirical findings.

I build a New-Keynesian model, which allows for capital-skill complementarity in production. The relevance of capital-skill complementarity for the cyclical behavior of aggregate economy and, in particular the skill premium, has been documented by empirical research, (see Lindquist (2004), Balleer and van Rens (2013) and Maliar et al. (2017), Correa et al. (2019) among others)⁴. The model contains a simple mechanism that generates the observed patterns in the skill premium and relative employment in response to aggregate uncertainty shocks. This mechanism relies on the interaction of the capital-skill complementarity channel and households' precautionary labor supply. Capital-skill complementarity in production implies non-trivial interactions between availability of skills and spikes in uncertainty. The underlying intuition lies in the following. As uncertainty increases, the relative price of capital equipment falls, hence investment in new capital is discouraged. Given capital-skill complementarity, the expectation that the capital stock will be down in the future provides incentive for reduction in skilled wages, since decreases in equipment would reduce the marginal productivity of skilled workers, and thereby this drives down the skill premium. Capital-skill complementarity channel implies that uncertainty will lead to a sharper fall in marginal product of skilled than unskilled labor and, thus, lead to a decrease in the gap between skilled and unskilled

⁴Capital-skill complementarity is one explanation for variations in wage inequality (Krusell et al. (2000)). For the long-run, Goldin and Katz (2008) provide historical evidence for the 20th century demonstrating that wage inequality has developed within a production sector characterized by capital-skill complementarity.

wages. The change in relative employment of skilled versus unskilled labor depends on interaction of relative labor supply and demand. I show that the capital-skill complementarity channel amplifies precautionary labor supply by the skilled. Due to this and to the presence of wealth effects, an increase in skilled labor supply exceeds the decrease in skilled labor demand to generate a rise in the relative employment ratio.

This paper is part of the recently growing literature on uncertainty shocks as well as of the strand of literature on capital-skill complementarity. First, this paper is contributing to a growing and highly relevant literature on the propagation of uncertainty in the economy. Literature on macroeconomic uncertainty mostly finds that uncertainty shocks have contractionary effects on the economy⁵. Several recent studies explore the implications of uncertainty shocks on the dynamics of labor market through labor adjustment costs, search-and-matching frictions, and wage rigidities (Schaal (2017), Leduc and Liu (2016), Cacciatore and Ravenna (2020) and Guglielminetti (2016)). Namely, Caggiano and Groshenny (2014) and Choi and Loungani (2015) show that an increase in aggregate uncertainty leads to an increase in unemployment. Schaal (2017) finds that in periods of high uncertainty firing and quitting increase more than hiring does. However, few of these papers consider heterogeneity in the labor force with respect to skill levels. Guglielminetti (2016) and Leduc and Liu (2016) replicate in theoretical models the empirical evidence that unemployment significantly rises after a volatility shock. Nevertheless, these papers feature neither investment irreversibility nor different types of labor in contrast to this paper. This paper differs from the existing studies in that it investigates the effects of time-varying macroeconomic uncertainty on skilled and unskilled workers by distinguishing the roles of these two types of labor in production with regards to capital. 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 skilled vs. unskilled labor market outcomes.

This paper also relates to the literature that studies the role of capital-skill complementarity. Capital-skill complementarity implies that although capital is likely to be complementary to both skilled and unskilled labor, it tends to be more complementary to skilled labor. The literature on capital-skill complementarity in production focuses mostly on labor income inequalities (Griliches

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

(1969), Krusell et al. (2000), Angelopoulos et al. (2014), Lindquist (2004)). Krusell et al. (2000) show that capital-skill complementarity can be the source behind the increase in the skilled premium in the United States. The relevance of capital-skill complementarity for the cyclical behavior of aggregate economy and, in particular the skill premium, has been shown by empirical work by Lindquist (2004), Balleer and van Rens (2013) and Maliar et al. (2017), Correa et al. (2019) among others⁶. Capital-skill complementarity has been shown to match the dynamics of the skill premium in the data (see Maliar et al. (2017), Skaksen and A. (2005), Krusell et al. (2000), Lindquist (2004), Pourpourides (2011), Duffy et al. (2004)). The hypothesis of capital-skill complementarity is not new since it was first formalized by Griliches (1969)⁷ Today, capital-skill complementarity is believed to be in full blossom too as information communications technology (ICT) developments do exhibit a skill-biased component. Caselli and Coleman (2001) present robust findings that high levels of educational attainment are important determinants of computer-technology adoption. In a nutshell, empirical work suggests that new technologies tend to substitute for unskilled labor in the performance of routine tasks, while assisting skilled workers in executing more complex tasks. I offer an alternative way of incorporating capital-skill complementarity in the DSGE framework, which helps uncover the effects of uncertainty shocks.

On the one hand, the literature on uncertainty has demonstrated that uncertainty shocks depress employment. On the other hand, the literature on the skill premium has shown that there are significant differences in wage dynamics of skilled and unskilled labor. Given that uncertainty affects employment and its impact is associated with skill levels, the previous studies render the main question of this paper pertinent – whether uncertainty has an asymmetric impact on skilled compared to unskilled labor. Surprisingly, the business-cycle theoretical research on this subject has been scarce despite the empirical relevance of capital-skill complementarity hypothesis and labor market disparities between skilled and unskilled labor. The main contribution of this paper is to combine these two strands of literature, which proves to be crucial to replicate the data. On the empirical side, I document the effects of macroeconomic uncertainty shocks on relative employment of skilled versus

⁶Capital-skill complementarity is one explanation for variations in wage inequality (Krusell et al. (2000)). For the long-run, Goldin and Katz (2008) provide historical evidence for the 20th century demonstrating that wage inequality has developed within a production sector characterized by capital-skill complementarity.

⁷Griliches (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.

unskilled workers as well as on the wage gap between skilled and unskilled workers. The theoretical model developed in this paper replicates the empirical evidence and rationalizes the propagation mechanism of these uncertainty shocks.

The rest of the paper is organized as follows. In Section 2 I motivate the further analysis by estimating the dynamic effects of uncertainty shocks on the macroeconomy in a structural VAR (SVAR) model. Section 3 presents the setup of the theoretical model. Section 4 provides underlying intuitions of the transmission of macroeconomic uncertainty in the model. Section 5 describes the parametrization and solution method. Results and sensitivity analysis are presented and discussed in Section 6. A final section provides concluding remarks.

2 Empirical Evidence

In this Section I examine empirical effects of macroeconomic uncertainty shocks on aggregate economic dynamics and, in particular relative employment rates and relative wages (the skill premium) of skilled vs. unskilled workers by estimating a structural vector autoregression (SVAR) model and assessing impulse responses to orthogonalized shocks to macroeconomic uncertainty measure. SVAR estimates are based on United States data of quarterly frequency from 1979Q1 to 2018Q4.

As a measure of aggregate uncertainty, I use the macroeconomic uncertainty index estimated by Jurado et al. (2015) (JLN)⁸, which is a broad measure of macroeconomic uncertainty. Another advantage of using Jurado et al. (2015) index is that its sample period is the longest among other popular uncertainty measures. This index is also employed in empirical literature looking at the effects of TFP or aggregate uncertainty (for example, Born and Pfeifer (2017)⁹).

⁸The index of economic uncertainty developed by Jurado et al. (2015) is the common variation in uncertainty across hundreds of economic series. Jurado et al. (2015) measure uncertainty is based on squared forecast errors for a large panel of macroeconomic time series (using a two-sided filter to extract a latent volatility factor). Their measure reflects uncertainty around objective statistical forecasts, rather than perceived uncertainty by market participants. They focus on common, not idiosyncratic, uncertainty. Other proxies of macroeconomic uncertainty which are used, namely the changes in VIX, i.e. an implied volatility measure derived from US S&P 500 options prices, are more likely affected by shocks specific to the stock market rather than an increase in uncertainty about the aggregate economy (see e.g. Bekaert, Hoerova, and Duca 2013; Stock and Watson 2012; Caldara et al. 2016)). I use the Jurado et al. (2015) macroeconomic uncertainty index, available on the authors' personal websites. I use a quarterly average of monthly values for $h = 1$ (one month forecast horizon).

⁹Born and Pfeifer (2017) say that this is the broadest and at the same time cleanest uncertainty measure available. Also, Deutsche Bundesbank applies the methodology from Jurado et al. (2015) for the four largest euro area countries, see "Investment in the euro area", Deutsche Bundesbank, Monthly Report, January 2016, pp. 31-49.

The micro data on labor market variables come from the NBER extracts of the Current Population Survey (CPS) Merged Outgoing Rotation Groups (CPS MORG)¹⁰, which is a monthly household survey of employment and labor markets. These data are widely used by economists for constructing the data on wages and labor supply (see for example, Katz and Murphy (1992), Krusell et al. (2000) and Acemoglu and Autor (2011), Dolado et al. (2020) among others). 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 U.S. population. The data covers the period from 1979M1 to 2018M12. 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. 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 choose to classify workers as skilled and unskilled based on educational attainment. In this classification I follow an extensive literature, which has studied the division of the 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 et al. (2005)). The skilled group of workers encompasses individuals having an education qualification of college and above, and the unskilled group are all other individuals having lower than a college degree¹¹.

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 ORG 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

¹⁰Data were extracted from the NBER website: <https://data.nber.org/data/morg.html>.

¹¹Other studies, for example Acemoglu and Autor (2011), Angelopoulos et al. (2017), Dolado et al. (2020), use the same definition of skilled and unskilled workers.

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 since detrending might distort the dynamics in the underlying time series¹². The rest of the series are retrieved from the FRED database¹³.

The SVAR- (p) model reads as follows:

$$AY_t = B \sum_{p=1}^P B_p Y_{t-1} + \epsilon_t$$

where p is the number of lags, 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 $Y_t = [\sigma_t^z \quad y_t \quad i_t \quad c_t \quad n_t^s \quad (\frac{n^s}{n^u})_t \quad w_t^s \quad (\frac{w^s}{w^u})_t \quad \pi_t]'$ is a vector comprising the following variables: σ_t^z the macroeconomic uncertainty measure – JLN index from Jurado et al. (2015)¹⁴, 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 ratio¹⁵, w_t^s weighted average of real hourly wage of employed in the skilled category¹⁶, $\frac{w_t^s}{w_t^u}$ 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 an increase of one standard deviation in the JLN index of aggregate uncertainty. I identify the structural uncertainty shock via a widely-employed in the uncertainty

¹²As in Bachmann and Bayer (2013) and Jurado et al. (2015), I do not detrend any variables using the HP filter (Hodrick and Prescott (1997)) because since the HP filter uses information over the entire sample, it is difficult to interpret the timing of an observation. King and Rebelo (1993), Harvey and Jaeger (1993), Guay and Saint-Amant (2005) and Meyer and Winker (2005) discuss potential distortionary effects induced by using of HP filtered data. On the other hand, Bloom (2009) used the HP filter for every series except the volatility measure – VXO index.

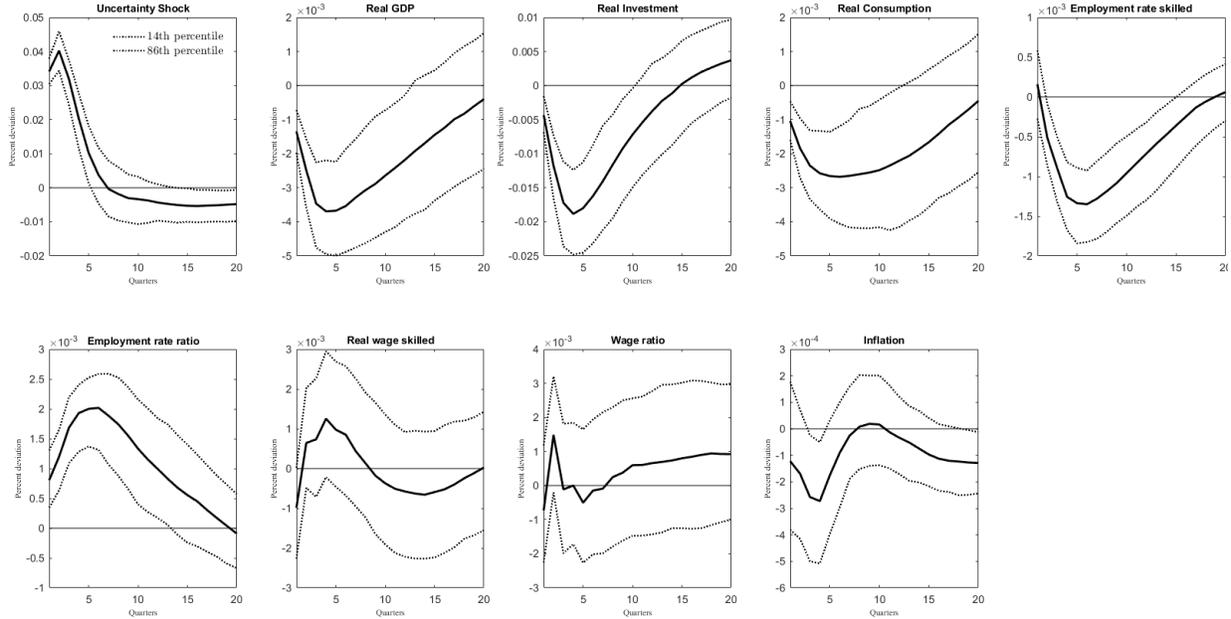
¹³Output is real GDP (GDPC1). Consumption is real personal consumption expenditures (PCEC9C6). Investment is real gross private domestic investment (GPDIC1). The economy-wide measure of the hourly real wage is compensation per hour in the business sector (HCOMPBS) divided by the GDP deflator (GDPDEF). I obtained inflation from the percentage change in implicit price deflator (GDPDEF).

¹⁴The Jurado et al. (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.

¹⁵Inclusion 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.

¹⁶Aggregated real hourly wage of employed in skilled category combines the usual hourly earnings for hourly workers (excluding otc), and nonhourly workers (including otc) in the usual hourly earnings.

Figure 2.1: Impulse responses to a 1-sd uncertainty shock



Note: Solid lines correspond to the median IRFs while the dashed lines are the 14th and 86th 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. Variables enter with two lags, selected according to the Akaike criterion.

literature recursive ordering (Cholesky decomposition), which ensures that the uncertainty shock is orthogonal to the other stochastic elements in the SVAR (see, for example, Bloom (2009), Fernandez-Villaverde et al. (2015), Leduc and Liu (2016) and Basu and Budnick (2017)). Thus, by ordering the uncertainty shock first, 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.

Figure 2.1 displays impulse responses to a one standard deviation uncertainty shock. Figure 2.1 shows that an exogenous increase in aggregate uncertainty leads to a persistent and significant decline in output. By the 4th quarter output falls by 0.36%, while consumption and capital investment drop by 0.24% and 1.76% respectively. A contemporaneous fall in inflation suggests that the uncertainty shock acts like a demand shock in line with Caggiano and Goshenny (2014), Fernandez-Villaverde et al. (2015), Bonciani and van Roye (2016), Leduc and Liu (2016), and Basu and Budnick (2017). Regarding the labor market variables, employment rate of skilled labor features a hump-shaped response and stays down for about 3 years with the lowest level occurring

after 6 quarters. The relative employment rate ratio increases suggesting that firms tend to adjust unskilled employment more than skilled jobs. On the other hand, the skill premium declines implying that earnings of skilled workers fall more than of unskilled workers after an uncertainty shock. The response of the skill premium suggests that inequality in terms of wage income between skilled and unskilled groups is negatively related to an unexpected rise in uncertainty. The responses of the employment rate ratio and the skill premium mean that the uncertainty shock has heterogeneous impact across different workers. Therefore, heterogeneity of workers in skills is an important feature of the data that should not be overlooked when studying the propagation of uncertainty shocks and disentangling mechanisms through which uncertainty affects the economy.

The stylized facts relevant to this paper can be briefly summarized as follows:

- Macroeconomic uncertainty shock is recessionary – it lowers aggregate output, consumption, investment and employment.
- The skill premium decreases after a rise in the macroeconomic uncertainty.
- The relative employment rate of skilled labor increases as a response to a rise in the macroeconomic uncertainty.

These findings have an important implication for understanding the mechanism through which the uncertainty shock affects the labor market. The SVAR recovers the result from uncertainty literature that uncertainty shocks lead to overall economic contraction. Regarding the responses of skilled and unskilled employment rates and wages, there are important reasons why we should expect them to differ. The decline in the skill premium suggests higher wage rigidity of unskilled wages in line with evidence that rigidity of wages increases as education declines reported by Doniger (2019). In the present paper I focus on the explanation of the behavior of the skill premium through complementarity between skills and capital¹⁷. The essential 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 wages. Reduction in investment directly translates into a fall in capital stock, which lowers skilled wages and the skill premium. This complementarity is an important factor to affect the demand for labor, which is responsible for the different effect of an uncertainty shock on skilled and unskilled wages. The 3rd stylized fact

¹⁷Caggiano and Groshenny (2014) and Choi and Loungani (2015) are examples of previous studies that found the importance of this channel.

is that the relative employment of skilled labor increases as a response to a rise in the aggregate uncertainty. This finding indicates that elevated uncertainty has a more negative effect on unskilled employment than skilled employment. Skilled individuals may tend to exhibit a more precautionary behavior when uncertainty increases. They might 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 workers tend to enjoy higher employment stability than less skilled workers. "Labor hoarding" could be another reason for an increase in the employment rate ratio. In downturns firms are likely to resort to labor hoarding of especially skilled, qualified and educated labor due to firm-specific human capital of skilled labor (see for example, Becker (1964)) and higher hiring and firing costs. Firms usually have higher hiring/lay-off adjustment costs for skilled workers and firms that face uncertainty are more reluctant to adjust skilled employment as it is more costly to fire (and hire later) this type of labor than the unskilled (see for example, Bentolila and Bertola (1990)). In the following Section I describe a theoretical model, which is able to replicate the empirical findings of this Section.

3 The Model

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 determining monetary policy. The model incorporates capital-skill complementarity framework through a CES production function¹⁸. 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 –

¹⁸This assumption on technology is in line with the empirical evidence provided by numerous studies (see Maliar et al. (2017), Skaksen and A. (2005), Krusell et al. (2000), Lindquist (2004), Pourpourides (2011), Duffy et al. (2004)). Cantore et al. (2015) find that a model with a CES production function explains the actual U.S. data better than a model with a Cobb-Douglas production function.

entrepreneurs, and skilled and unskilled workers¹⁹. As for notation, I will for any real variable x_t denote its value in nominal terms with X_t , its value in steady state x .

3.1 Households

Population is composed of three different types of household – skilled and unskilled workers and entrepreneurs – who share some common features. These households are indexed by $i \in s, u, e$ and are of size π^i , $i \in \{s, u, e\}$. 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 another²⁰. 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’ dividends²¹, whereas workers only receive 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)).

3.1.1 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 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 $\pi_t = \frac{p_t}{p_{t-1}}$. I use the functional form of the utility à la Jaimovich and Rebelo (2009) for households allowed to work, since it allows to control for the strength of the wealth effect. The magnitude of the wealth effect affects the response of labor supply to movements

¹⁹In modeling household types I follow the set-up as in Dolado et al. (2020). Broer et al. (2020) have a similar capitalist-worker framework, but they model workers as a single representative household without differentiation in skills.

²⁰Angelopoulos, 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.

²¹The 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.

in consumption. The utility of skilled and unskilled households depends positively on consumption and negatively on labor and reads as

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left\{ \frac{1}{1 - \sigma_u} \left[\left(c_t^i - b_c c_{t-1}^i - \kappa_h (h_t^i)^\phi X_t^i \right)^{1 - \sigma_u} - 1 \right] \right\} \quad (3.1)$$

where \mathbb{E}_0 is the expectation operator conditional on the information available in period 0, $\beta \in (0, 1)$ is the subjective discount factor, $(\phi - 1)^{-1}$ is the Frisch elasticity of labor supply, κ_h is a scale parameter, σ_u is the intertemporal elasticity of substitution, b_c expresses the degree of habit in consumption, and where

$$X_t^i = (c_t^i - b_c c_{t-1}^i)^{\sigma_X} (X_{t-1}^i)^{1 - \sigma_X} \quad (3.2)$$

Parameter σ_X controls the strength of the wealth effect on labor supply. I assume $\sigma_X, \phi, \kappa_h, b_c$ the same for skilled and unskilled households. Imposing $\sigma_X = 1$ gives the King et al. (1988) (KPR) preferences and $\sigma_X = 0$ gives Greenwood et al. (1988) preferences with zero wealth effect on labor supply, where supply of labor depends only on the current real wage, and is independent of the marginal utility of income. In this case X_t becomes a constant and can be normalized to one²². When σ_X and b_c are both small, anticipated changes in income will not affect current labor supply. As σ_X increases, the wealth elasticity of labor supply rises.

Budget constraint of worker households is

$$c_t^i + t_t^i + \frac{B_{t+1} \pi_{t+1}}{R_t} = w_t^i h_t^i + B_t \quad (3.3)$$

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 (3.3). The Lagrangean of the problem of the household in real terms reads as

$$\mathcal{L}^i = \frac{1}{1 - \sigma_u} \left[\left(c_t^i - b_c c_{t-1}^i - \kappa_h (h_t^i)^\phi X_t^i \right)^{1 - \sigma_u} - 1 \right] - \lambda_t^i \left[c_t^i + t_t^i + \frac{B_{t+1} \pi_{t+1}}{R_t} - w_t^i h_t^i - B_t \right]$$

where λ_t^i is the Lagrangean multiplier associated with the budget constraint, also interpreted as the

²²See Jaimovich and Rebelo (2009) for more details.

marginal utility of wealth.

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

$$B_{t+1} : \beta \mathbb{E}_t \left\{ \lambda_{t+1}^i \frac{R_t}{\pi_{t+1}} \right\} = \lambda_t^i \quad (3.4)$$

$$\begin{aligned} c_t^i : \lambda_t^i = & \left(c_t^i - b_c c_{t-1}^i - \kappa_h X_t^i (h_t^i)^\phi \right)^{-\sigma_u} - \beta b_c \left(c_{t+1}^i - b_c c_t^i - \kappa_h X_{t+1}^i (h_{t+1}^i)^\phi \right)^{-\sigma_u} + \\ & \sigma_X v_t^i (c_t^i - b_c c_{t-1}^i)^{\sigma_X - 1} (X_{t-1}^i)^{1 - \sigma_X} - \beta b_c \sigma_X v_{t+1}^i (c_{t+1}^i - b_c c_t^i)^{\sigma_X - 1} (X_t^i)^{1 - \sigma_X} \end{aligned} \quad (3.5)$$

$$X_t^i : v_t^i + \kappa_h (h_t^i)^\phi \left(c_t^i - b_c c_{t-1}^i - \kappa_h (h_t^i)^\phi X_t^i \right)^{-\sigma_u} = \beta (1 - \sigma_X) \mathbb{E}_t \left\{ v_{t+1}^i (c_{t+1}^i - b_c c_t^i)^{\sigma_X} (X_t^i)^{-\sigma_X} \right\} \quad (3.6)$$

$$h_t^i : \kappa_h \phi (h_t^i)^{\phi - 1} X_t^i \left(c_t^i - b_c c_{t-1}^i - \kappa_h X_t^i (h_t^i)^\phi \right)^{-\sigma_u} = \lambda_t^i w_t^i \quad (3.7)$$

where λ_t^i and v_t^i are the Lagrangian multipliers associated to the budget constraint 3.3 and 3.2 respectively. Equation 3.4 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 3.5 describes the evolution of consumption as a function of the marginal disutility of hours worked, and the dynamics of the wealth effect on labor supply. Equation 3.6 determines the dynamics of X_t , i.e. the wealth effect on labor supply. The last condition 3.7 is the labor supply equation, which states that households supply labor by equating the real wage to the intratemporal marginal rate of substitution.

3.1.2 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

$$\mathcal{U}_t^e = \mathbb{E}_t \sum_{t=0}^{\infty} \beta \left[\frac{(c_t^e - b_c c_{t-1}^e)^{1 - \sigma_u}}{1 - \sigma_u} \right] \quad (3.8)$$

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 , 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

$$c_t^e + t_t^e + \frac{B_{t+1}\pi_{t+1}}{R_t} + i_t^e = \text{div}_t + B_t + R_t^k k_{t-1}^e \quad (3.9)$$

where div_t is the household's share of firms' dividends, net of a government lump-sum tax²³.

Capital accumulation evolves according to the law of motion

$$i_t^e = k_{t+1}^e - (1 - \delta_i)k_t^e + D(k_{t+1}^e, k_t^e) \quad (3.11)$$

The function $D(k_{t+1}^e, k_t^e)$ denotes capital adjustment costs (see Lucas and Prescott (1971) or Christiano et al. (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 $D(k_{t+1}^e, k_t^e)$

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

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 $\phi_i \rightarrow \infty$ 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

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

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.

²³Wholesalers' profits are redistributed to the entrepreneur households in the form of dividends, see Section (3.2).

$$\text{div}_t = x_t y_t - (w_t^s h_t^s + w_t^u h_t^u + R_t^k k_t^e) \quad (3.10)$$

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

$$c_t^e : \lambda_t^e = (c_t^e - b_c c_{t-1}^e)^{-\sigma_u} - \beta b_c (c_{t+1}^e - b_c c_t^e)^{-\sigma_u} \quad (3.12)$$

$$B_{t+1} : \beta^t \mathbb{E}_t \frac{\lambda_{t+1}^e R_t}{\pi_{t+1}} = \lambda_t^e \quad (3.13)$$

$$k_{t+1}^e : \lambda_t^e \left(1 + \phi_i \left[\frac{k_{t+1}}{k_t} - 1 \right] \right) = \beta \lambda_{t+1}^e \left(1 + R_{t+1}^k - \delta + \frac{\phi_i}{2} \left(\frac{k_{t+2}}{k_{t+1}} \right)^2 - 1 \right) \quad (3.14)$$

I assume complete markets, the perfect risk-sharing and full insurance between households. Combining equations of households' F.O.C. (3.13) and (3.4) leads to the following perfect risk sharing condition:

$$\frac{\lambda_{t+1}^i}{\lambda_{t+1}^e} = \frac{\lambda_t^i}{\lambda_t^e} = \frac{\bar{\lambda}^i}{\bar{\lambda}^e} \text{ for } i \in (s, u) \quad (3.15)$$

3.2 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 good²⁴. 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 $\mathcal{Z}_t f(k_t, n_t^s, n_t^u)$, where \mathcal{Z}_t is aggregate TFP, $k_t = \pi^e k_t^e$ is aggregate capital with π^e population share of entrepreneurs, $n_t^s = \pi^s h_t^s$ and $n_t^u = \pi^u h_t^u$ are labor supplies of skilled and unskilled households with π^s and π^u population shares of skilled and unskilled households respectively.

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

²⁴There are two types of firms – wholesalers and retailers in order to keep traction.

elasticity of substitution between skilled and unskilled labor²⁵.

$$y_t \equiv \mathcal{Z}_t f(k_t, n_t^s, n_t^u) = \mathcal{Z}_t([\mu(n_t^u)^\sigma + (1 - \mu)(\lambda k_t^\rho + (1 - \lambda)(n_t^s)^\rho)^{\frac{\sigma}{\rho}}]^{\frac{1}{\sigma}}) \quad (3.1)$$

where $\rho \leq 1$ and $\sigma \leq 1$, k_t is aggregate capital, n_t^s is aggregate skilled labor and n_t^u is aggregate unskilled labor. Parameter λ governs the capital intensity of production process and parameter μ governs how skill-intensive production process is.

Essential role is played by the values of the elasticities of substitution between capital and skilled labor denoted by ε_{k,n^s} and between capital and unskilled labor (the same as the elasticity of substitution between skilled and unskilled labor)²⁶ denoted by ε_{k,n^u} (or equivalently ε_{n^s,n^u}). These elasticities are given by $\varepsilon_{k,n^s} = \frac{1}{1-\rho}$ and $\varepsilon_{k,n^u} \equiv \varepsilon_{n^s,n^u} = \frac{1}{1-\sigma}$ ²⁷. 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. I assume that the elasticity of substitution between capital and skilled labor is higher than the elasticity of substitution between capital and unskilled labor, which implies that $\frac{1}{1-\rho} < \frac{1}{1-\sigma}$ and $\sigma > \rho$ ²⁸. Since the values of the parameters ρ and σ dictate the values of these elasticities, ρ and σ should respect these conditions in order to comply with the capital-skill complementarity hypothesis:

- The elasticity of substitution between capital and skilled labor lies between 0 and 1 ($\varepsilon_{k,n^s} \in [0, 1]$). Larger ρ in absolute value is, higher is the degree of complementarity between capital and skilled labor.
- The elasticity of substitution between capital equipment and unskilled labor is more than 1 ($\varepsilon_{k,n^u} > 1$), which implies that capital (skilled labor) and unskilled labor are substitutes. Larger σ is, higher is the degree of substitutability between the two types of labor. When $\sigma = 1$ skilled and unskilled workers are perfect substitutes²⁹.

²⁵In choosing the functional form of production function I follow the capital-skill complementarity literature, namely Hamermesh (1993), Krusell et al. (2000), Maliar and Maliar (2011), Lindquist (2004).

²⁶This 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.

²⁷To 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 $\varepsilon_{k,n^u} \equiv \varepsilon_{n^s,n^u} = \frac{\partial \log(\frac{n^u}{k})}{\partial \log(\frac{w^u}{R^k})} = \frac{1}{1-\sigma}$.

²⁸The 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), ?, and Stern (2011).

²⁹To return to the usual Cobb-Douglas case without capital-skill complementarity either ρ or σ need to be zero so that the elasticities of substitution $\frac{1}{(1-\sigma)}$, $\frac{1}{(1-\rho)}$ are 1. In order to maintain strict quasi-concavity of the production

These conditions can be summarized in a single condition $1 > \sigma > \rho$, which, if holds, ensures that capital is more complementary (less substitutable) to skilled workers than unskilled workers. As a result, an increase in capital will increase the marginal product of skilled labor more than the marginal product of unskilled labor.

Maximization of profits by wholesalers yields the following F.O.C. with respect to capital, k_t , employment of skilled, n_t^s , and unskilled labor, n_t^u . Given the form of the production function in equation (3.1) I define the following F.O.C.

$$\begin{aligned} \frac{R_t^k}{x_t} &= \frac{\partial y_t}{\partial k_t} = (1 - \mu)\lambda(\lambda k_t^\rho + (1 - \lambda)(n_t^s)^\rho)^{\frac{\sigma}{\rho} - 1} k_t^{\rho - 1} \\ &\quad \times \underbrace{\mathcal{Z}_t [\mu(n_t^u)^\sigma + (1 - \mu)(\lambda k_t^\rho + (1 - \lambda)(n_t^s)^\rho)^{\frac{\sigma}{\rho}}]_{\frac{1}{\sigma} - 1}}_{\mathcal{Z}_t f(k_t, n_t^s, n_t^u)^{1 - \sigma} \equiv y_t^{1 - \sigma}} \\ &= (1 - \mu)\lambda(\lambda k_t^\rho + (1 - \lambda)(n_t^s)^\rho)^{\frac{\sigma}{\rho} - 1} k_t^{\rho - 1} y_t^{1 - \sigma} \end{aligned} \quad (3.2)$$

$$\begin{aligned} \frac{w_t^s}{x_t} &= mpl_t^s = \frac{\partial y_t}{\partial n_t^s} = \mathcal{Z}_t (1 - \mu)(1 - \lambda)(\lambda k_t^\rho + (1 - \lambda)(n_t^s)^\rho)^{\frac{\sigma}{\rho} - 1} (n_t^s)^{\rho - 1} \\ &\quad \times [\mu(n_t^u)^\sigma + (1 - \mu)(\lambda k_t^\rho + (1 - \lambda)(n_t^s)^\rho)^{\frac{\sigma}{\rho}}]_{\frac{1}{\sigma} - 1} \\ &= (1 - \mu)(1 - \lambda)(\lambda k_t^\rho + (1 - \lambda)(n_t^s)^\rho)^{\frac{\sigma}{\rho} - 1} (n_t^s)^{\rho - 1} y_t^{1 - \sigma} \end{aligned} \quad (3.3)$$

$$\begin{aligned} \frac{w_t^u}{x_t} &= mpl_t^u = \frac{\partial y_t}{\partial n_t^u} = \mathcal{Z}_t \mu [\mu(n_t^u)^\sigma + (1 - \mu)(\lambda k_t^\rho + (1 - \lambda)(n_t^s)^\rho)^{\frac{\sigma}{\rho}}]_{\frac{1}{\sigma} - 1} (n_t^u)^{\sigma - 1} \\ &= \mu(n_t^u)^{\sigma - 1} y_t^{1 - \sigma} \end{aligned} \quad (3.4)$$

where mpl_t^i is the marginal product of i -type labor. Since labor markets are competitive, the real wages w_t^s and w_t^u are simply given by the value of marginal product of labor times marginal cost.

Similarly to Krause and Lubik (2007) and Leduc and Liu (2016), I allow for real wage rigidity via the following form à la Hall (2005):

$$\tilde{w}_t^s = (\tilde{w}_{t-1}^s)^{\rho_w^s} (w_t^s)^{(1 - \rho_w^s)} \quad (3.5)$$

$$\tilde{w}_t^u = (\tilde{w}_{t-1}^u)^{\rho_w^u} (w_t^u)^{(1 - \rho_w^u)} \quad (3.6)$$

where \tilde{w}_t^s and \tilde{w}_t^u are the effective wages of skilled and unskilled workers respectively and ρ_w^s and

function, both ρ and σ are restricted to lie in the interval of $\rho \in (-\infty, 1)$ and $0 < \sigma \leq 1$.

ρ_w^u indicate the indexation to previous period wage (indexes the degree of wage rigidity) of skilled and unskilled workers respectively.

I also define the labor share in income as

$$\begin{aligned} \frac{w_t^s n_t^s + w_t^u n_t^u}{y_t} &= \left[\mu (n_t^u)^\sigma + (1 - \mu) (\lambda k_t^\rho + (1 - \lambda) (n_t^s)^\rho)^{\frac{\sigma}{\rho}} \right]^{-1} \\ &\times \left[\mu (n_t^u)^\sigma + (1 - \mu) (\lambda k_t^\rho + (1 - \lambda) (n_t^s)^\rho)^{\frac{\sigma}{\rho} - 1} (1 - \lambda) (n_t^s)^\rho \right] \\ &= y^{-\sigma} \left[(1 - \mu) (1 - \lambda) (\lambda k^\rho + (1 - \lambda) (n^s)^\rho)^{\frac{\sigma}{\rho} - 1} (n^s)^\rho + \mu (n^u)^\sigma \right] \end{aligned} \quad (3.7)$$

3.3 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:

$$y_t = \left(\int_0^1 y_{j,t}^{\frac{\varepsilon-1}{\varepsilon}} di \right)^{\frac{\varepsilon}{\varepsilon-1}} \quad (3.1)$$

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

$$y_{j,t} = \left(\frac{p_{j,t}}{p_t} \right)^{-\varepsilon} y_t \quad (3.2)$$

with

$$p_t = \left(\int_0^1 p_{j,t}^{1-\varepsilon} di \right)^{\frac{1}{1-\varepsilon}} \quad (3.3)$$

Calvo price setting 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 $\chi = 1 - \text{total indexation}$. All price-updating firms adjust to the same price, p^* .

The problem of the retail firms is then:

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

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:

$$g_{1,t} = \lambda_t^e y_t x_t + \beta \kappa_p \mathbb{E}_t \left(\frac{\pi_t^\chi}{\pi_{t+1}} \right)^{-\theta_p} g_{1,t+1} \quad (3.4)$$

$$g_{2,t} = \lambda_t^e \pi_t^* y_t + \beta \kappa_p \mathbb{E}_t \left(\frac{\pi_t^\chi}{\pi_{t+1}} \right)^{1-\theta_p} \left(\frac{\pi_t^*}{\pi_{t+1}^*} \right) g_{2,t+1}, \text{ where } \pi_t^* = \frac{p_t^*}{p_t} \quad (3.5)$$

$$\theta_p g_{1,t} = g_{2,t} (\theta_p - 1) \quad (3.6)$$

Given pricing à la Calvo, the price index evolves:

$$1 = \kappa_p \left(\frac{\pi_{t-1}^\chi}{\pi_t} \right)^{1-\theta_p} + (1 - \kappa_p) \pi_t^{*1-\theta_p} \quad (3.7)$$

We 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

$$v_t^p = \kappa_p \left(\frac{\pi_{t-1}^\chi}{\pi_t} \right)^{-\theta_p} v_{t-1}^p + (1 - \kappa_p) \pi_t^{*-\theta_p} \quad (3.8)$$

In the aggregation I obtain:

$$y_t = \frac{\mathcal{Z}f(k_t, n_t^s, n_t^u)}{v_t^p} \quad (3.9)$$

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.

3.4 Exogenous processes

The model features two exogenous stochastic driving processes for the aggregate productivity Z_t and its volatility σ_t^Z , which is time-varying.

$$Z_t = \rho^Z Z_{t-1} + \sigma_t^Z \varepsilon_t^Z \text{ where } \varepsilon_t^Z \sim N(0, 1) \quad (3.1)$$

$$\sigma_t^Z = \left(1 - \rho^{\sigma^Z}\right) \sigma^Z + \rho^{\sigma^Z} \sigma_{t-1}^Z + \eta_{\sigma^Z} \varepsilon_t^{\sigma^Z} \text{ where } \varepsilon_t^{\sigma^Z} \sim N(0, 1) \quad (3.2)$$

where ε_t^Z and $\varepsilon_t^{\sigma^Z}$ follow i.i.d. standard normal process³⁰. A level shock ε_t^Z is a first-moment shock that varies the level of Z_t , keeping its distribution unchanged. An uncertainty shock $\varepsilon_t^{\sigma^Z}$ 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 ρ^Z and ρ^{σ^Z} drive the persistence associated to the level and volatility of productivity shocks respectively, and η_{σ^Z} drives the magnitude of the productivity uncertainty shock.

3.5 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

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R} \left(\left(\frac{\pi_t}{\pi}\right)^{\rho_\pi} \left(\frac{y_t}{y}\right)^{\rho_y}\right)^{(1-\rho_R)} \quad (3.1)$$

where $\rho_R \in [0, 1]$ is a smoothing parameter, ρ_π is the elasticity of R_t with respect to inflation deviations 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.

3.6 Fiscal policy

The government collects lump-sum taxes and runs a balanced budget in every period. The government budget constraint (3.1) equates current income (bond issues and tax revenues) with general expenditures and maturing government bonds. The government's budget constraint is thus given by

³⁰I use the stochastic volatility approach proposed by Fernandez-Villaverde et al. (2011).

$$t_t + B_t = g_t + \frac{R_{t-1}B_{t-1}}{\pi_t} \quad (3.1)$$

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 distribution 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

$$\frac{t_t}{t} = \left(\frac{B_{t-1}}{B} \right)^{(\phi_D)} \left(\frac{y_t}{y} \right)^{(\phi_Y)} \quad (3.2)$$

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

$$\log \left(\frac{g_t}{\bar{g}} \right) = \rho^g \log \left(\frac{g_{t-1}}{\bar{g}} \right) + \varepsilon_t^g \quad (3.3)$$

3.7 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

$$y_t = c_t + i_t + g_t \quad (3.1)$$

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

4 Impact of Uncertainty Shocks: Dissecting the Mechanism

In this Section, I provide an insight on the transmission of uncertainty shocks on skilled vs. unskilled labor assuming a partial equilibrium framework. I demonstrate that capital-skill complementarity plays an essential role in accounting for the effects of uncertainty on these types of labor while the existing transmission channels do not distinguish between relative effects of uncertainty on different types of labor with regard to skill level.

The revealed stylized facts about relative wages and relative employment in Section 2 are that (i) the skill premium decreases after a rise in the macroeconomic uncertainty, and (ii) the relative employment of skilled labor increases as a response to a rise in the macroeconomic uncertainty. In

order to reconcile the empirical effect of uncertainty on wages and employment of skilled to unskilled workers from Section 2, I show how the introduction of capital-skill complementarity gives rise to an additional propagation channel of aggregate uncertainty shocks. The responses of relative wages and employment are triggered by the interaction of households' *relative* precautionary labor supply and firms' *relative* labor demand, which in turn is affected by the complementarity of capital and skilled labor in production. Skilled and unskilled labor demands are given by equation 3.3 and 3.4 respectively, and labor supply conditions are given by equation 3.7, which read as

For skilled agents:

$$\lambda_t^s w_t^i = \kappa_h \phi (h_t^s)^{\phi-1} X_t \left(c_t^s - b_c c_{t-1}^s - \kappa_h X_t (h_t^s)^\phi \right)^{-\sigma_u}$$

$$w_t^s = x_t \text{mpl}^s(\mathcal{Z}_t, k_t, n_t^s, n_t^u)$$

For unskilled agents:

$$\lambda_t^u w_t^u = \kappa_h \phi (h_t^u)^{\phi-1} X_t \left(c_t^u - b_c c_{t-1}^u - \kappa_h X_t (h_t^u)^\phi \right)^{-\sigma_u}$$

$$w_t^u = x_t \text{mpl}^u(\mathcal{Z}_t, k_t, n_t^s, n_t^u)$$

Capital-skill complementarity implies that skilled and unskilled labor have different roles in production with relation to capital and shows up in the marginal products of labor and thereby affects the responses of the demands for skilled and unskilled labor to shocks. While existing channels, such as the aggregate demand channel, have the same effect on the labor demand for skilled and the labor demand for unskilled labor³¹, capital-skill complementarity introduces potential differences in these effects. I make an assumption that labor markets are perfectly competitive, in which case wages are proportional to marginal products. The skill premium defined as the ratio of skilled wage to unskilled wage and associated with the production function under capital-skill complementarity 3.1 is given by the following equation

$$\frac{w_t^s}{w_t^u} \equiv \frac{\text{mpl}_t^s}{\text{mpl}_t^u} = \frac{(1-\mu)(1-\lambda)}{\mu} \left[\lambda \left(\frac{k_t}{n_t^s} \right)^\rho + (1-\lambda) \right]^{\frac{\sigma}{\rho}-1} \left(\frac{n_t^u}{n_t^s} \right)^{(1-\sigma)} \quad (4.1)$$

This equation essentially represents a "demand for skill". As explained in Section 3 the conditions on the parameters ρ and σ (i.e. $1 > \sigma > \rho$) impose capital-skill complementarity. One can show that w_t^s/w_t^u is decreasing in the relative demand for skilled workers, $\frac{\partial w_t^s/w_t^u}{\partial n_t^s/n_t^u} < 0$, all else held constant (the relative quantity effect), and the skill premium is increasing in the capital-skill ratio,

³¹See the literature on the aggregate effects of uncertainty shocks, for example Bloom (2014) and Basu and Budnick (2017).

$\frac{\partial w_t^s/w_t^u}{\partial k_t/n_t^s} > 0$, all else held constant (the capital-skill complementarity effect).

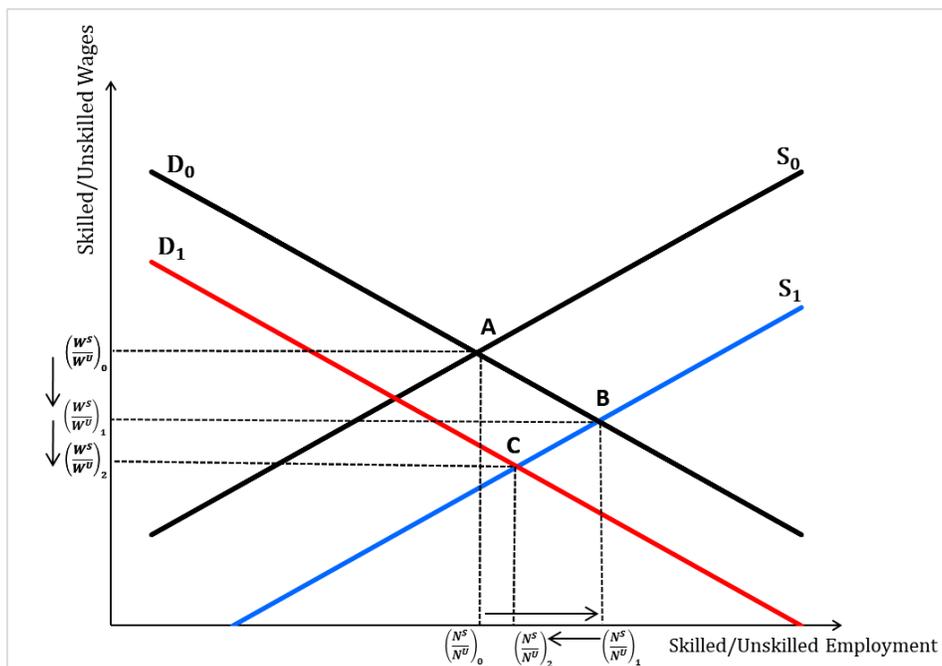
Under capital-skill complementarity, the change in the skill premium in response to a decrease in capital is negative provided the quantities of the two types of labor remain constant³². This essentially is a critical implication of capital-skill complementarity. As shown on Figure 2.1, investment falls after a rise in uncertainty. This decline in firms' investment directly lowers the capital stock, which in turn reduces the relative marginal product of labor if $1 > \sigma > \rho$. Skilled labor demand decreases more than unskilled labor demand. Skilled workers are willing to accept lower wages when the demand for their skills has fallen. The relative labor demand falls as illustrated by a shift of the relative labor demand curve to the left, D_0 to D_1 on Figure 4.1. The skill premium falls since it is decreasing in the relative demand for skilled workers, $\frac{\partial w_t^s/w_t^u}{\partial n_t^s/n_t^u} > 0$ all else held constant. Less capital means that the ratio of capital to skilled labor is reduced, driving a further fall in the skill premium since it is increasing in the capital-skill ratio ($\frac{\partial \frac{w_t^s}{w_t^u}}{\partial k_t/n_t^s} > 0$) all else held constant. The relative wages (the skill premium) decline from $(\frac{w^s}{w^u})_0$ to $(\frac{w^s}{w^u})_1$.

For households heightened uncertainty induces precautionary labor supply. Both skilled and unskilled households are risk-averse and manifest precautionary behavior in response to higher uncertainty. Faced with uncertainty, they want to self-insure against possible negative events occurring in the future, and thus, increase savings and cut consumption. Due to the presence of the wealth effect, households react to lower labor income by increasing hours worked. Skilled and unskilled labor supplies increase (see Equation 3.7) and the household labor supply curves shift to the right. Figure 4.1 shows that the relative labor supply curve increases, i.e. skilled households increase their labor supply more relative to unskilled households. This is because skilled workers experience a steeper decline in their wages in comparison with unskilled ones, and consequently the income effect is more important for skilled households. As a result, skilled households cut consumption and increase their labor supply more than unskilled households. Thus, relative labor supply goes up. On Figure 4.1 the shift of the relative labor supply curve to the right from S_0 to S_1 leads to a decline in the relative wages (the skill premium), which move from $(\frac{w^s}{w^u})_1$ to $(\frac{w^s}{w^u})_2$. The capital-skill complementarity channel amplifies the decline in the demand for skilled labor as well as it amplifies precautionary labor supply of skilled households. This altogether induces the falls in wages leading to a reduction in the skill premium.

³²The differentiation shows that as long as $1 > \sigma > \rho$, $\frac{\partial w_t^s/w_t^u}{\partial k_t} > 0$.

Figure 4.1 shows that if the outward shift in relative labor supply exceeds the inward shift of relative labor demand, i.e. the magnitude of the increase in skilled labor supply is larger than of the decrease in skilled labor demand, the ratio of skilled to unskilled labor, $\frac{N^s}{N^u}$, will increase. Since capital-skill complementarity channel acts on top of the precautionary labor supply channel and amplifies a rise in labor supply by skilled households, the relative labor supply increases so that $(\frac{N^s}{N^u})_1$ shifts to $(\frac{N^s}{N^u})_2$ in line with the empirical response, which the theoretical model presented in Section 3 is able to replicate. Overall, the interplay of changes in both relative labor supply and relative labor demand contributes to movements in the skill premium and the relative employment.

Figure 4.1: Model intuition: Relative labor demand & relative labor supply. Impact of an uncertainty shock on relative wages and employment.



Notes: D_0 is an initial relative labor demand curve and S_0 is an initial relative labor supply curve. The initial equilibrium wage differential between skilled workers (w^s) and unskilled workers (w^u) is denoted $((w^s/w^u)_0)$. It is determined by the intersection of the relative demand curve for skills (D_0) and the relative supply curve for skills (S_0). This equilibrium is associated with an initial relative employment ratio of skilled to unskilled workers $((N^s/N^u)_0)$.

5 Solution Method and Calibration

I solve and simulate the model by a third-order perturbation method using the pruning algorithm by Andreasen et al. (2018)³³. As explained in Fernandez-Villaverde et al. (2011), the third-order approximation of the policy function is necessary to analyze the effects of uncertainty shocks independently of the first moment shocks. The volatility shock plays an independent role and enters as an independent argument in the approximated policy 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 σ^z_t , while the level shock to TFP is zero. Thus, I follow Fernandez-Villaverde et al. (2011) and consider impulse response functions (IRFs) that isolate the pure uncertainty effect resulting from higher volatility. 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 (IRFs) of the respective variables in percentage deviation from the ergodic mean of the model simulated data 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 economy³⁴. Therefore, it is more informative to compute impulse responses as percentage deviations from their mean, rather than their steady state.

The model is calibrated so that its steady-state is consistent with the quarterly US data. Parametrization is based on values commonly found in the literature or on making the steady-state model replicate some empirical targets, that I base on the evidence reported in Section 2. Variables without a time subscript denote the 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 popu-

³³The model is solved using Dynare 4.4.3 (MATLAB R2018a). In order to obtain a non-explosive behavior of the simulations, Dynare relies on the pruning algorithm described in Andreasen et al. (2018). The latest version of Dynare allows pruning also for third order perturbation algorithms.

³⁴Schmitt-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.

lation, π^e , is set equal to 10%. The proportion of skilled workers, π^s , is 21%, which is equal to the average share of workers in the CPS MORG data set with college education, and the rest 69% are unskilled workers. The time discount factor is $\beta = 0.99$ and the relative risk aversion parameter is set to $\sigma^c = 1$, the value commonly employed in the literature³⁵, $\phi = 1.4$ which corresponds to the Frisch elasticity of 2.5 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). Degree of real wage rigidity is high – consistent with the analysis Krause and Lubik (2007) and Leduc and Liu (2016) (among others). I assume that wage rigidity is asymmetric with unskilled wages being more sticky $\rho_w^u = 0.8 > \rho_w^s = 0.65$. This assumption is supported by empirical evidence (The Wage Rigidity Meter at the San Francisco Fed, Doniger (2019), Parker and Vissing-Jorgensen (2010)).

The depreciation rate of capital equipment is $\delta = 0.25$. I set the elasticities of substitution between skilled labour and capital and between unskilled labour and capital (or skilled labour) $\rho = -0.495$ and $\sigma = 0.401$, which are the estimates by Krusell et al. (2000) and which are frequently used in the literature (see e.g. Lindquist (2004), Pourpourides (2011), Angelopoulos et al. (2014)). This results in the elasticity of capital to skilled labour $\frac{1}{1-\rho} = 0.67$ and the elasticity of capital to unskilled labor $\frac{1}{1-\sigma} = 1.67$. The remaining parameters in 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 I choose share of capital to composite input $\lambda = 0.8$ to target the skill premium of 1.67³⁶. Both of these targets are consistent with the U.S. data for the period 1979–2018 used in Section 2. Government spending to output ratio is set equal to 20% and public debt is calibrated at 67% of annual output. An interest rate smoothing parameter ρ_r is set to 0.9, 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 $\phi_Y = 0.34$.

The quantitative impact of uncertainty on the macroeconomy depends on the calibration of the size and persistence of the uncertainty shock process. For the exogenous process of technology I use the value of persistence of 0.8 and the average standard deviation σ_Z is set to 0.01. The persistence of

³⁵See, e.g. Schmitt-Grohe and Uribe (2007) and the references reported in their paper.

³⁶Krusell et al. (2000) do not report their estimates of unskilled labor weight in composite input share μ and capital weight in the composite input share λ .

the volatility process is generally assumed to be quite high (Basu and Budnick (2017) and Gilchrist et al. (2014)). SVAR evidence shows that my measure of macroeconomic uncertainty 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 parameter should be about 0.7 at quarterly frequencies. There is no general consensus regarding the value of the standard deviation of the volatility shock. I thus calibrate it at 0.03 to match the empirical standard deviation of my uncertainty indicator in the SVAR. The calibrated values of the model parameters are summarized in Table 5.

Steady state: The results indicate that the model's predictions for the great ratios match those implied by the data quite well. For example, in the data for 1979-2018: $\frac{c}{y} = 0.6523$ (0.6498 in the data), $\frac{i}{y} = 0.1477$ (0.1621 in the data), $\frac{k}{y} = 5.9073$.

Table 5: Benchmark parameter calibration

Preferences		
β	0.99	Discount factor; 4% average annualized real interest rate; 4% risk-free rate p.a.
ϕ	5	Inverse Frisch elasticity of labor supply
σ^u	1	Relative risk aversion parameter
b_c	0.5	Habit in consumption parameter
σ_X	0.2	Wealth effect on labor supply
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
$\rho^{w,s}$	0.65	degree of real wage rigidity of skilled workers
$\rho^{w,u}$	0.8	degree of real wage rigidity of low-skilled workers
Calvo Price rigidity		
θ_p	11	Elasticity of substitution of goods; 10% price markup
κ_p	0.85	Nominal rigidities
χ	1	Price indexation
Monetary and fiscal policy		
ρ_r	0.9	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}	0.7	Persistence of volatility of TFP shocks
η_{σ^z}	0.0338	Magnitude of the productivity uncertainty shock

6 Theoretical Results

6.1 The Aggregate Effects of Productivity Uncertainty Shocks

This Section investigates the effects of a rise in aggregate uncertainty in the benchmark model with capital-skill complementarity. When analyzing how uncertainty shocks affect economic activity in a general equilibrium framework, it is important to bear in mind that many channels play a role in determining the responses from a qualitative and a quantitative point of view. The responses of the endogenous variables are caused by the interplay of different channels, which rely on precautionary household behavior, and price stickiness. In this Section I will show that propagation of productivity uncertainty shocks on labor market for skilled and unskilled workers, more specifically on the skill premium and employment ratio, crucially depend on the capital-skill complementarity channel.

Consistent with the SVAR presented in Section 2, a 1-sd positive shock to the volatility of productivity causes a long-run recessionary decline of economic activity (see blue solid lines in Figure 6.1). An uncertainty shock generates a reduction in aggregate demand, which leads to a contraction in output, aggregate consumption and investment (see blue solid lines in Figure 6.1). A one-standard deviation uncertainty shock leads to a quick decrease in output of 0.47%, 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. Different roles in production due to capital-skill complementarity imply that skilled and low-skilled workers do not experience the same decrease in labor income. As a result of the uncertainty shock, skilled workers experience a steeper fall in their wages than lower skilled workers leading to a fall in the skill premium of about -0.1%. On the other hand, employment ratio of skilled to low-skilled workers increases by 0.15% (see solid lines in Figure 6.2).

The drop in aggregate output is driven by the interaction of precautionary households' behavior

and nominal price rigidity. Risk-averse households 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, leading to a decrease in labor demand. When the degree of price stickiness is sufficiently high, uncertainty generates a large enough downward shift in labor demand that translates to 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 Budnick (2017)). The response of inflation depends on the interplay of price stickiness (aggregate demand) channel and upward pricing bias channel³⁷, 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. Similar to Born and Pfeifer (2014) and Fernandez-Villaverde et al. (2015), I find therefore that an increase in uncertainty leads to a rise in inflation due to the upward pricing bias channel.

While the price stickiness channel plays an important role in driving aggregate consumption and output down following an uncertainty shock³⁸, complementarity channel 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 6.2 displays model impulse responses to the uncertainty shock for the relative variables, which are consistent with the empirical responses in Section 2. The capital-skill complementarity channel acts on top of the nominal rigidity (aggregate demand) channel since it amplifies the fall in relative labor demand in a dynamic manner, as detailed in Section 4. A rise in uncertainty triggers an initial reduction in

³⁷The nominal pricing bias arises in the Phillips curve due to the presence of nominal rigidities that makes firms more prudent when setting nominal prices of goods (see Fernandez-Villaverde et al. (2015)).

³⁸The price stickiness channel is used by Basu and Budnick (2017) to produce positive co-movement between consumption, investment, and output.

capital investment making complementary skilled labor less productive, which further discourages investment and decreases marginal productivity of skilled workers. Thus, capital-skill complementarity channel induces a sharper reduction in the skilled wage, which results in an inward shift of the skill premium. It also contributes to a higher relative labor supply of skilled to unskilled workers. Since skilled households experience a relatively sharper reduction in their labor income, they react by increasing precautionary labor more than unskilled households. This results in the outward shift of the relative labor supply curve. This is in the partial equilibrium framework.

In the general equilibrium framework the capital-to-skilled labor ratio K_t/N_t^s , and the skilled-to-unskilled labor ratio N^s/N^u increase following the uncertainty shock as shown on Figure 6.2. When general equilibrium effects are taken into account the capital-to-skilled labor ratio increases since capital cannot immediately adjust in response to the shock. Complementarity between capital and skilled labor reduces the decline in the marginal product of skilled labor from the shock and dampens the decrease in skilled labor demand. The final change in the relative employment depends on the interaction between the precautionary labor supply and capital-skill complementarity channel. Capital-skill complementarity channel dampens the decrease in skilled labor demand. This effect together with higher precautionary labor supply by the skilled workers leads to the increase in the skilled-to-unskilled labor ratio N_t^s/N_t^u in line with the empirical response.

Now I turn to the response of the skill premium. As detailed in Section 4 the skill premium is increasing in the capital-to-skilled labor ratio K_t/N_t^s (the capital-skill complementarity effect) and it is decreasing in the skilled-to-unskilled labor ratio N_t^s/N_t^u (the relative quantity effect). Since in general equilibrium capital stock adjusts in a slow manner, K_t/N_t^s increases more significantly than N_t^s/N_t^u does. The sum impact of these two effects produces a rise in the skill premium, opposite to the fall in the skill premium documented in Section 2. Asymmetric wage rigidity allows to restore the fall in the skill premium in line with the data. Assumption of asymmetric wage rigidity is supported by recent empirical literature on the US labor market, which finds that low-skill wages are more sticky than skilled wages³⁹. The Wage Rigidity Meter at the San Francisco Fed uses the same data source as I do in this paper and reports that nominal wage rigidities decrease with educational attainment⁴⁰. Assumption of asymmetric wage rigidity implies that skilled wages are easier to ad-

³⁹Calibration of the benchmark model is $\rho_w^u = 0.8 > \rho_w^s = 0.65$

⁴⁰The Wage Rigidity Meter at the San Francisco Fed shows that the fraction of workers receiving an annual wage change of zero is much higher among the U.S. workers who completed only high school than among those who obtained

just than unskilled wages. Additionally, Doniger (2019) provides evidence for the United States in support of wages of workers with a bachelor’s degree or more being less rigid and pro-cyclical than wages of high school dropouts. Parker and Vissing-Jorgensen (2010) documents the same finding that high-skilled earnings are more cyclical than lower-skilled ones. Thus, the theoretical model presented in Section 3 is able to replicate the reduction in the skill premium as well as the rise in the labor ratio by relying on the interaction of complementarity of capital and skilled labor with motives for precautionary labor supply and wage rigidities.

As a consequence of the uncertainty shock, income shares of both skilled and unskilled labor decrease. The cumulative changes, i.e. the fall in relative wages and the increase in relative employment, produce a rise in relative labor share $\frac{w_t^s n_t^s}{w_t^u n_t^u}$. This implies 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. The result is that a macroeconomic uncertainty shock increases labor income inequality by raising the relative income share of skilled workers. Although firms cut wages of skilled workers more than of unskilled workers, the more skilled are more likely to preserve their employment. Thus, the overall effect of the uncertainty shock on relative labor share depends on the magnitude of households’ precautionary behavior. Skilled households supply relatively more labor and despite a steeper fall in the skilled wage, the skilled labor share is reduced by less than the low-skilled labor share.

6.2 Inspecting the Transmission Channels of Uncertainty

The Role of Capital-Skill Complementarity The previous subsection has shown that the response of the economy and relative labor market variables to the shock to the volatility of productivity relies on the interaction of capital-skill complementarity with precautionary motives of households and nominal price rigidity. In order to identify roles of the separate ingredients of the model in the transmission of uncertainty, I either vary or shut off some features of the model. The results of this exercise for aggregate variables are shown in Figure 6.5, where for comparison the blue solid line depicts the responses in the benchmark model. I start with identifying the role of capital-skill complementarity by comparing the effects of an uncertainty shock in the benchmark model and the model without capital-skill complementarity. In the benchmark model the form of the production function is a nested CES composite of production factors, and in the counterfactual form

a college degree. The data for these statistics were drawn from a matched Current Population Survey dataset.

of production function is given by Equation 6.1. 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. $y = \mathcal{Z}_t k_t^\iota n_t^{1-\iota}$, 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

$$y = \mathcal{Z}_t k_t^\iota (\omega(n_t^s)^\nu + (1 - \omega)(n_t^u)^\nu)^{\frac{(1-\iota)}{\nu}} \quad (6.1)$$

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%.

Figure 6.1 displays impulse responses in the two models for the aggregate variables. Solid lines represent the benchmark model. The results of the model without capital-skill complementarity are displayed in dashed lines. The introduction of capital-skill complementarity in the production function reinforces the responses of aggregate variables. Figure 6.2 shows responses of relative variables. In the absence of capital-skill complementarity, i.e. when skilled and unskilled labor are perfect substitutes, the wage of skilled workers declines in the same magnitude as the wage of unskilled workers due to the equality of marginal products of labor, and the skill premium does not move. Labor ratio stays constant as well since skilled and unskilled workers are perfect substitutes.

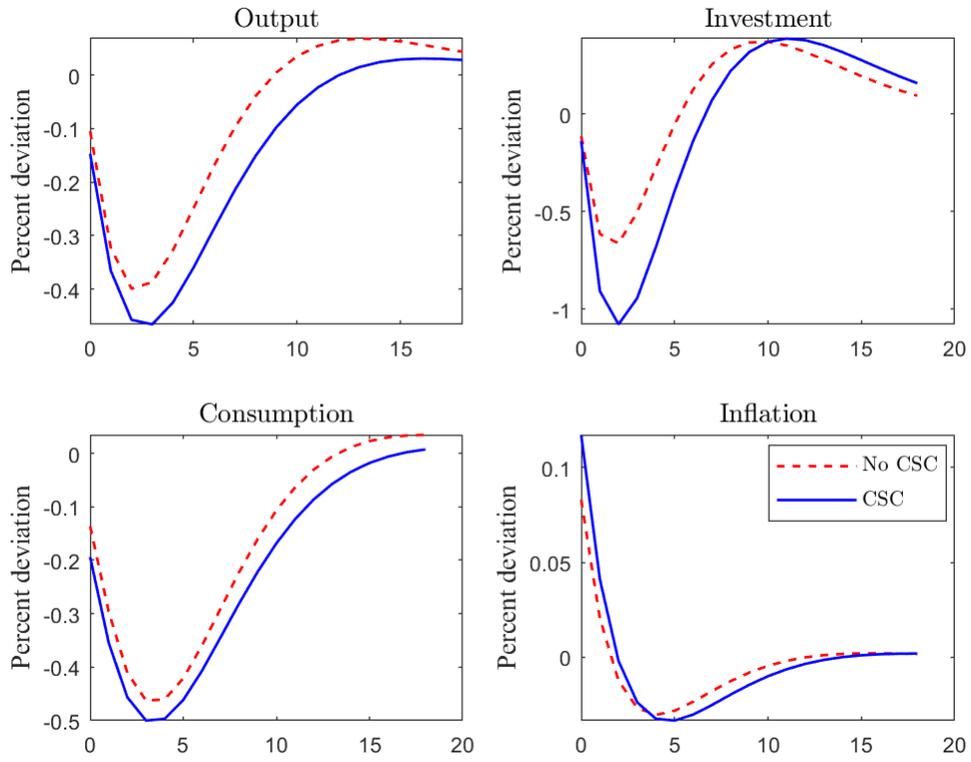


Figure 6.1: Impulse response functions to TFP uncertainty shock in the benchmark model with and without CSC – aggregate variables.

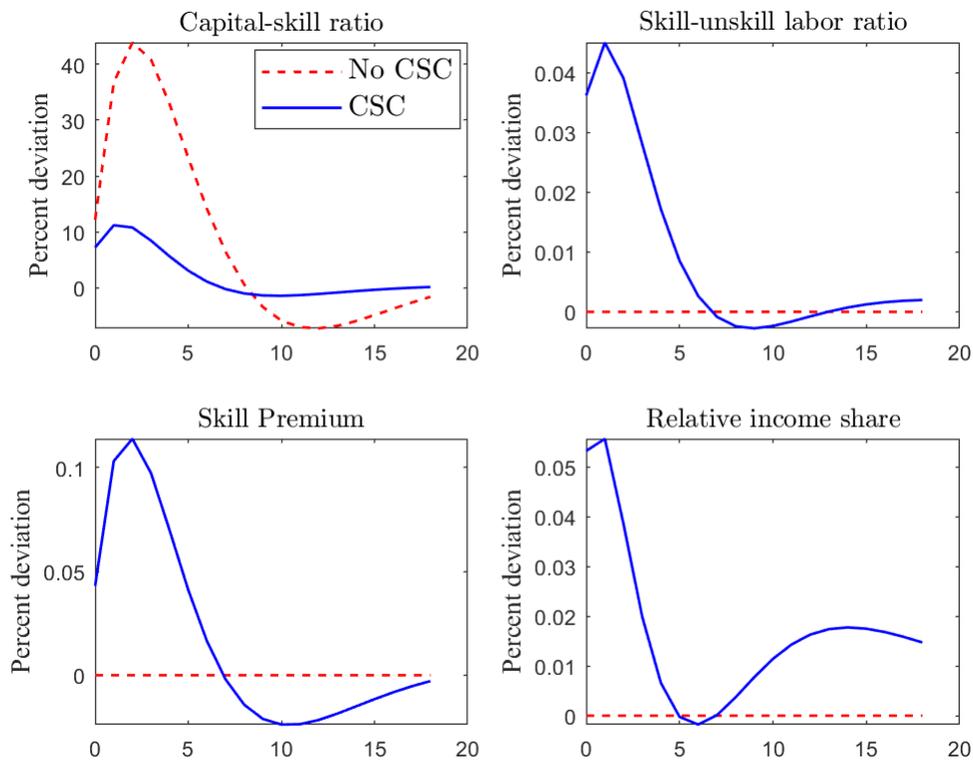


Figure 6.2: Impulse response functions to TFP uncertainty shock in the benchmark model with and without CSC – relative variables.

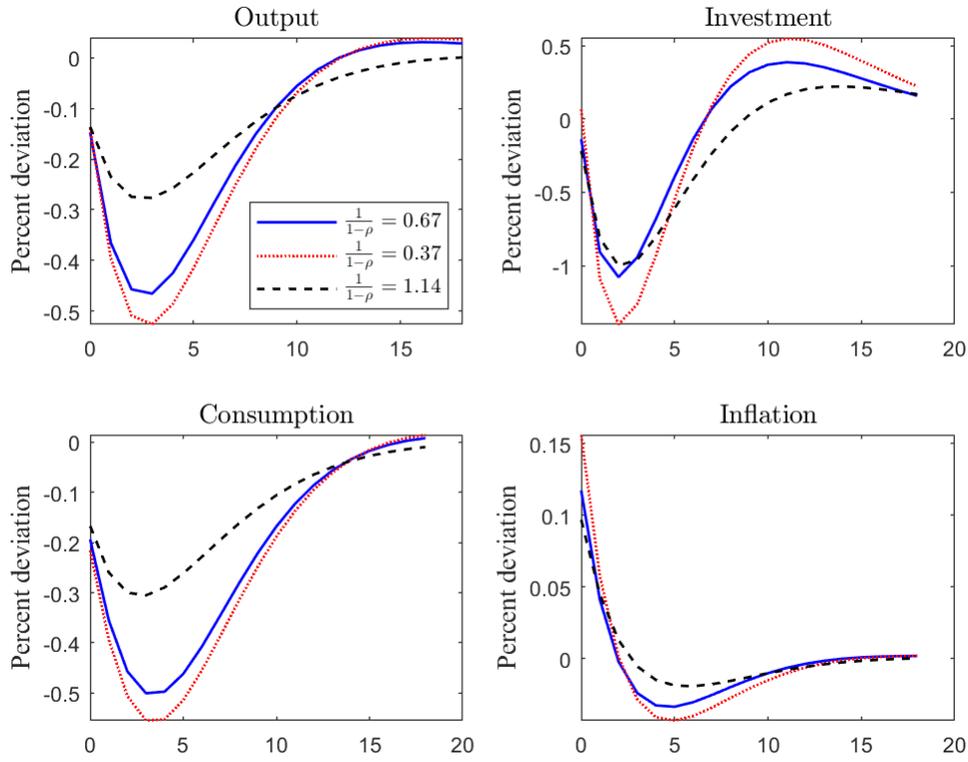
Sensitivity with Respect to Capital-Skill Complementarity (Elasticity of Substitution)

Capital-skill complementarity is captured in the model through the elasticity of substitution between capital and skilled labor, $\frac{1}{1-\rho}$. Figure 6.3 depicts responses of the key variables of interest when we vary this elasticity. Benchmark calibration of the elasticity of capital and skilled labor is 0.67 and the elasticity of capital and low-skilled labor is $\frac{1}{1-\sigma} = 1.67$. I consider cases of strong complementarity (i.e. lower elasticity of substitution) $\frac{1}{1-\rho} = 0.37, \rho = -1.7$ (red dotted line) and of weak complementarity $\frac{1}{1-\rho} = 1.14, \rho = 0.12$ (black dashed line). In this case I still keep the elasticity of substitution between capital and skilled labor lower than the elasticity of substitution between capital and unskilled labor, even though capital and skilled labor are now substitutes, i.e. and $\frac{1}{1-\sigma} > \frac{1}{1-\rho}$. Figure 6.3 plots the corresponding impulse response functions of the two cases in comparison with the benchmark model.

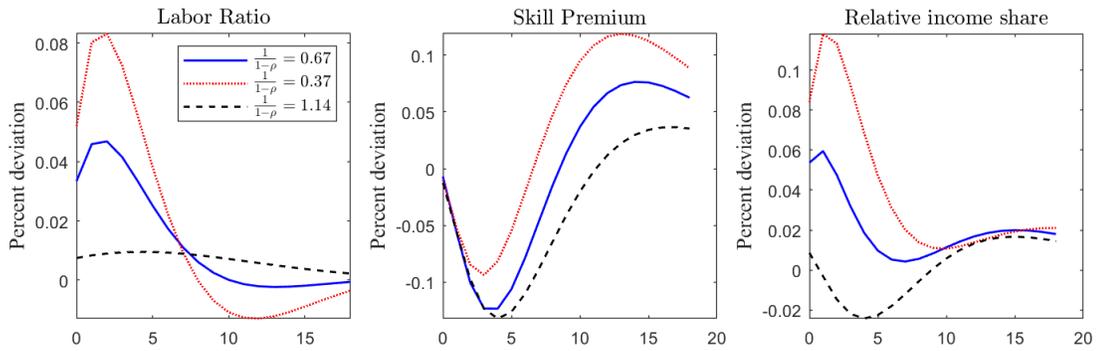
Higher degree of complementarity, which corresponds to lower elasticity of substitution (see red

dotted lines), increases the responsiveness of skilled wage to the fall in capital. In response to a contraction in aggregate demand, the fall in capital investment makes skilled employment less productive, inducing a further fall in skilled wages. Larger decreases in wages in turn amplify the drop in consumption via income effect leading to a sharper decline in output. Higher degree of complementarity disfavors labor income of skilled households even more than in the benchmark case, further decreasing the skill premium (see Figure 6.3b). Imposing substitutability between capital and skilled labor (see black dashed line in Figure 6.3) dampens responses to an uncertainty shock. When capital and skilled labor are substitutes, firms will not decrease their demand for skilled labor as much as when they are complements.

As 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 et al. (2004), which gives $\sigma = 0.7899$ that implies higher elasticity of substitution ($\frac{1}{1-\sigma} = 4.76$) than in the benchmark case. Figure 6.4 shows that, as σ becomes smaller, the effects of an increase in uncertainty become 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. Smaller σ decreases this real rigidity, which tends to dampen the recessionary effects of uncertainty. A smaller value of σ implies weaker capital-skill complementarity, so that the fall in investment induced by uncertainty is associated with a smaller decline in the skill premium and a weaker incentive for reducing skilled employment.

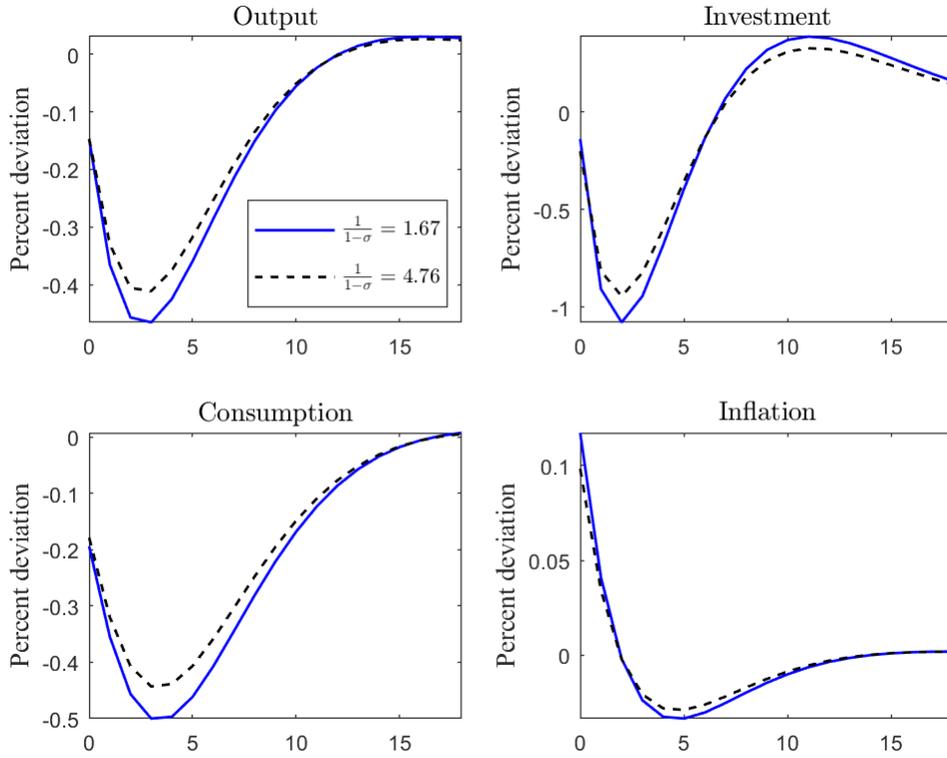


(a) Impulse response functions to TFP uncertainty shock in the benchmark model – aggregate variables.

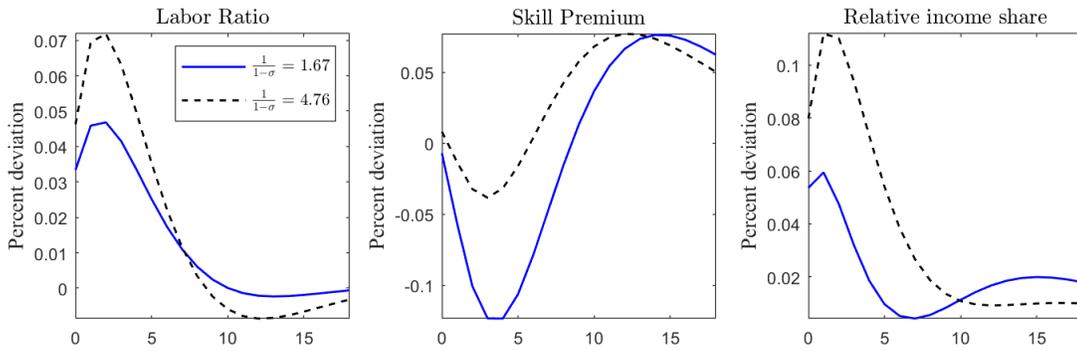


(b) Impulse response functions to TFP uncertainty shock in the benchmark model – relative variables.

Figure 6.3: Impulse response functions to TFP uncertainty shock – elasticity of substitution btw capital and skilled labor.



(a) Impulse response functions to TFP uncertainty shock in the benchmark model – aggregate variables.



(b) Impulse response functions to TFP uncertainty shock in the benchmark model – relative variables.

Figure 6.4: Impulse response functions to TFP uncertainty shock – elasticity of substitution btw capital and skilled labor composite and unskilled labor.

The Role of Precautionary Labor Supply The degree of households' precautionary behavior depends on the value of relative risk aversion. The effect of varying increasing the risk aversion parameter σ_u is shown in rose dash-dotted line. When I increase this parameter from the benchmark value 1 to 2, the agents' precautionary motive becomes more pronounced and consumption drops

by 0.33 percentage points more than in the benchmark calibration.

Lower Frisch elasticity, magnifies negative impact of the uncertainty shocks on the economy (see green dotted lines). Lower the Frisch elasticity decreases the willingness of agents to work if the wage decreases. Thus, it attenuates precautionary labor supply motives and produces a stronger response of hours worked. For lower responsiveness of hours to changes in the wage (lower labor supply elasticity), an uncertainty shock produces a stronger recession. For illustrational purposes, I consider no habit formation with $b_c = 0$. Marginal utility of consumption in Equation 3.5 with $b_c = 0$ writes as

$$\lambda_t^i = \left(c_t^i - \kappa_h X_t^i (h_t^i)^\phi \right)^{-\sigma_u} + \sigma_X v_t^i (c_t^i)^{\sigma_X - 1} (X_{t-1}^i)^{1 - \sigma_X} \quad (6.2)$$

A positive shock to the volatility of productivity leads to an increase in the marginal utility of consumption, as detailed in the preceding analysis of impulse responses. $(h_t^i)^\phi$ is increasing in the value of the Frisch elasticity of labor supply $\frac{1}{\phi - 1}$ provided $h_t^i \in (0, 1)$. Equation 6.2 shows that a fixed amount of drop in current consumption translates into a larger increase in the marginal utility of wealth λ_t^i when the Frisch elasticity is high, holding everything else constant. Consequently, higher λ_t^i encourages households to supply more labor, which dampens the fall in aggregate employment, leading to a smaller contraction in output than that with a lower Frisch elasticity.

The effect of changes in the wage on employment and hours is captured by the Frisch elasticity as well as the wealth effects on labor supply. I set $\sigma_X = 0$ so that the benchmark preferences of the form à la Jaimovich and Rebelo (2009) collapse to the Greenwood et al. (1988) (GHH) preference specification. The results are displayed by orange solid line. The effect of uncertainty is amplified by the preferences of the GHH form relative to the benchmark moderate wealth effect ($\sigma_X = 0.2$). With GHH preferences there is zero wealth effect and the labor supply becomes more elastic. No-wealth effect implies that (i) labour supply depends only on the real wage and not consumption and (ii) expected consumption growth depends on the real interest rate and on the growth rate of expected labor. Therefore, movements in consumption do not affect labor supply. The difference with the benchmark case is that, in the benchmark labor supply equation 3.7, variations in consumption do affect labor supply. GHH preference amplify the impact of the uncertainty shock as shown on Figure 6.5 (orange solid line).

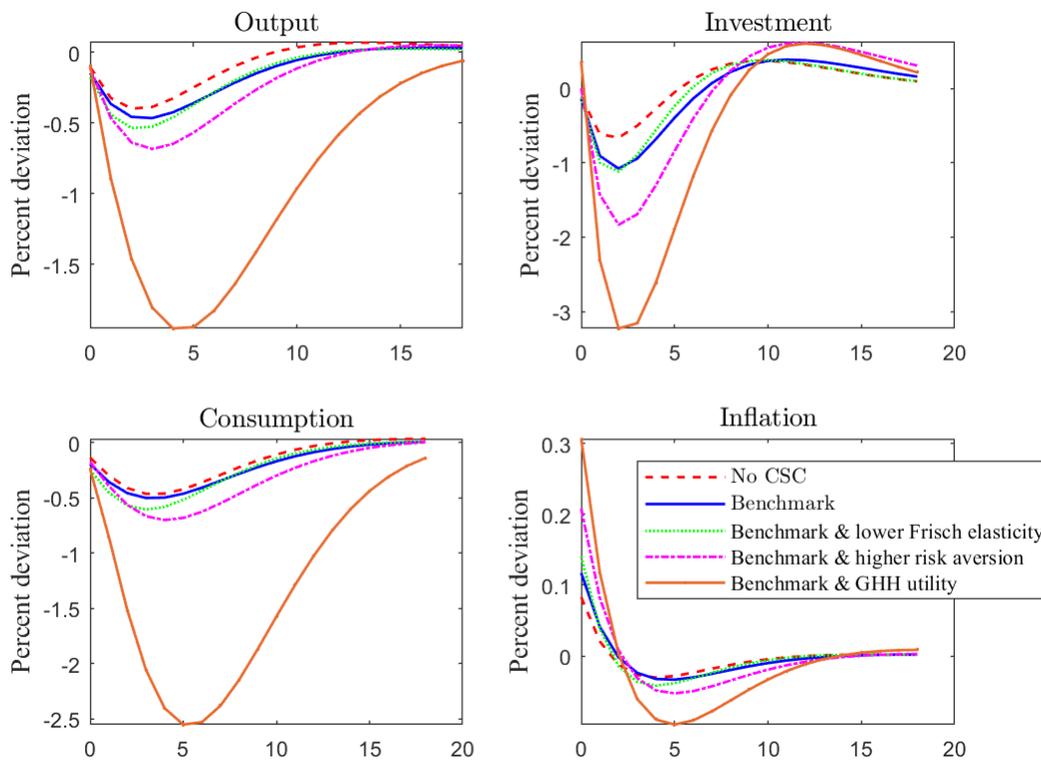


Figure 6.5: Impulse response functions to TFP uncertainty shock – aggregate variables.

Conclusion

In this paper I showed that aggregate uncertainty has a heterogeneous impact on employment and wages of skilled in comparison with unskilled workers. On the empirical side, I documented that while generating a contraction in aggregate economic activity, heightened macroeconomic uncertainty induces a fall in relative wages and a rise in relative employment of skilled vs. unskilled labor. On the theoretical side, I showed that considering differences across skill levels of labor inputs and their different degrees of complementarities and (or) substitutabilities with physical capital in a New-Keynesian model allows better understand the transmission mechanism of elevated uncertainty to the real economy. A macroeconomic uncertainty shock increases disparities in labor earnings of skilled vs. unskilled workers since it generates a decline in the relative wage but raises relative employment of skilled workers. I find that the interaction of capital-skill complementarity and precautionary labor supply is crucial in delivering this result. The presence of capital-skill complementarity amplifies the responses of relative labor demand and relative labor supply. As

such, it is important to highlight this mechanism in addition to existing propagation channels of uncertainty shocks, namely aggregate demand and precautionary motives, in order to have a deeper understanding of the implications of macroeconomic uncertainty shocks.

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Appendix

C Empirical Robustness

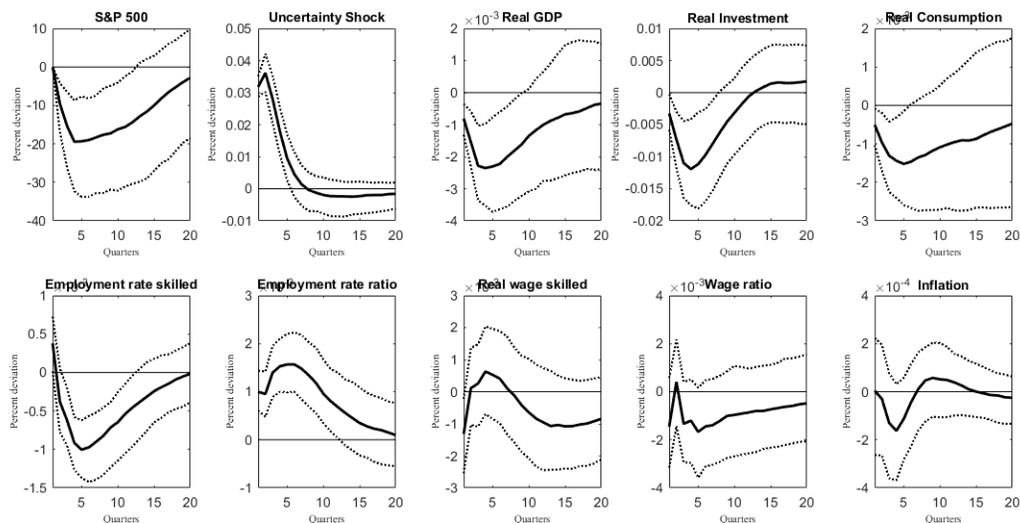
The benchmark SVAR presented in Section 2 revealed two stylized facts – a 1-sd uncertainty shock diminishes the skill premium as well as it raises the employment rate ratio. In this section, I examine the robustness of the benchmark empirical model along several dimensions. I show that the main results regarding the behavior of the aggregate variables, the skill premium and employment rate ratio hold, if I include stock prices in the SVAR, order uncertainty last in the SVAR, use higher frequency estimation, restrict analysis to the pre-2007 financial crisis sample period.

C.1 Control for the Stock Market

I re-estimate the benchmark specification of the SVAR and include the Standard & Poor’s 500 Stock Price Index ordering it first, which allows to control for the movements in the stock market⁴¹. 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 Budnick (2017), Bonciani and Oh (2020). Figure 6.6 shows that skill premium declines and employment ratio increases after an uncertainty shock, which is consistent with the baseline results. Including stock prices in the SVAR produces a slightly larger decline in investment, consumption and skilled employment, and a slightly smaller increase in employment rate ratio and a steeper decline in the skill premium. Overall, the results are very similar to the baseline specification.

⁴¹It is common practice to include stock prices in such empirical specifications, see other studies, for example, Bloom (2009), Basu and Budnick (2017), Bonciani and Oh (2020)

Figure 6.6: Empirical 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 14th and 86th 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. Variables enter with two lags, selected according to the Akaike criterion.

C.2 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 the 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 1979M1 to 2018M12. The monthly SVAR-(p) model reads as follows:

$$AY_t = B \sum_{p=1}^P B_p Y_{t-1} + \epsilon_t$$

where p is the number of lags, 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 $Y_t = [\sigma_t^z \ y_t \ i_t \ c_t \ n_t^s \ (\frac{n^s}{n^u})_t \ w_t^s \ (\frac{w^s}{w^u})_t \ \pi_t]'$ is a vector comprising the following variables: σ_t^z the macroeconomic uncertainty measure – JLN index from Jurado et al. (2015), y_t – Industrial Production (IP) Index, i_t – real gross private

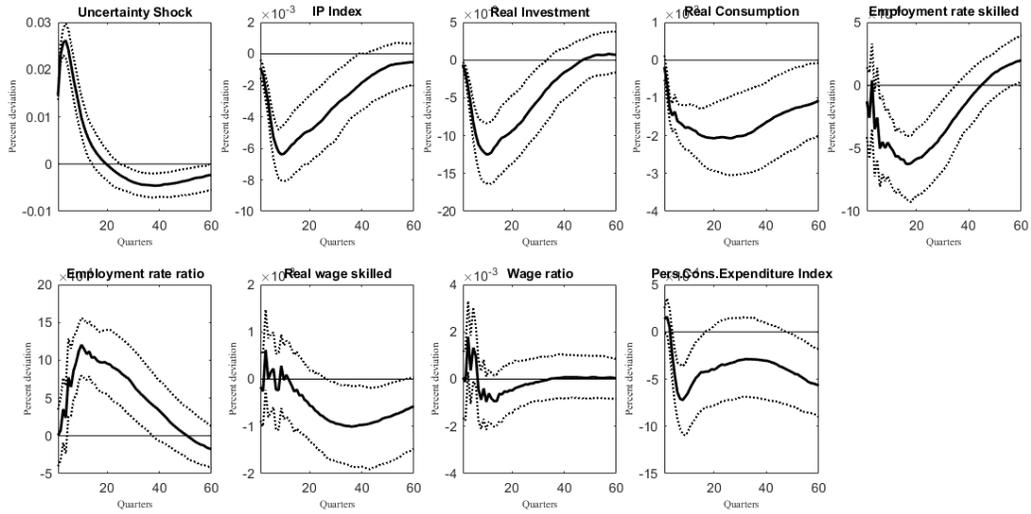
domestic investment⁴², c_t – personal consumption expenditures, n_t^s the skilled employment rate defined as the share of skilled employed workers in the skilled labor force, $\frac{n_t^s}{n_t^u}$ the employment rate ratio⁴³, w_t^s weighted average of real hourly wage of employed in the skilled category⁴⁴, $\frac{w_t^s}{w_t^u}$ 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; <https://fred.stlouisfed.org/series/>. 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. I include six lags in the monthly SVAR, as suggested by the Akaike Information Criterion.

Figure 6.7a shows the results of the monthly SVAR. Figure 6.7b 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. In particular, in both of these specifications with and without *S&P500* a 1-sd shock to the uncertainty measure triggers a decline in real economic activity and a rise in the employment rate ratio and a fall in the wage ratio confirming the baseline intuition.

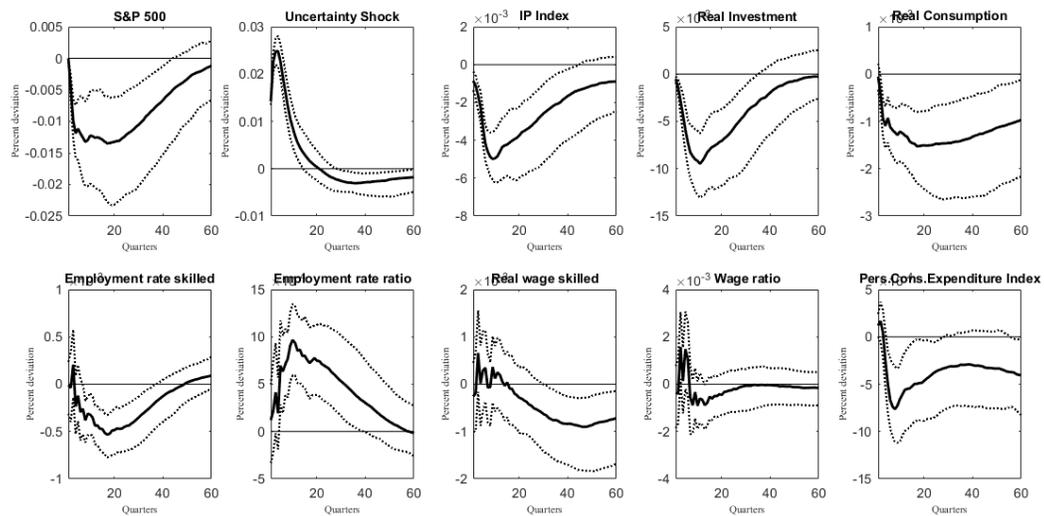
⁴²Since monthly series are not available, I temporally disaggregate quarterly time series of real gross private domestic investment into monthly series with Chow-Lin method using software JDemetra+ version 2.2.1. Figure 6.8 displays impulse responses without disaggregated private investment. The Figure 6.8 shows that not including private investment series does not change the results. 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).

⁴³Inclusion 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.

⁴⁴Aggregated real hourly wage of employed in skilled category combines the usual hourly earnings for hourly workers (excluding otc), and nonhourly workers (including otc) in the usual hourly earnings.



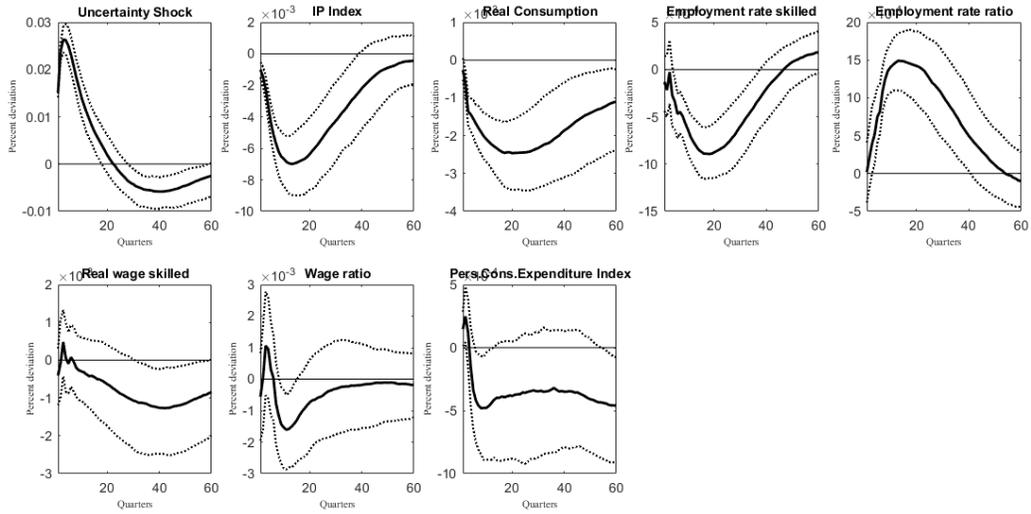
(a) Empirical impulse response functions to 1-sd uncertainty shock with monthly frequency of the data.



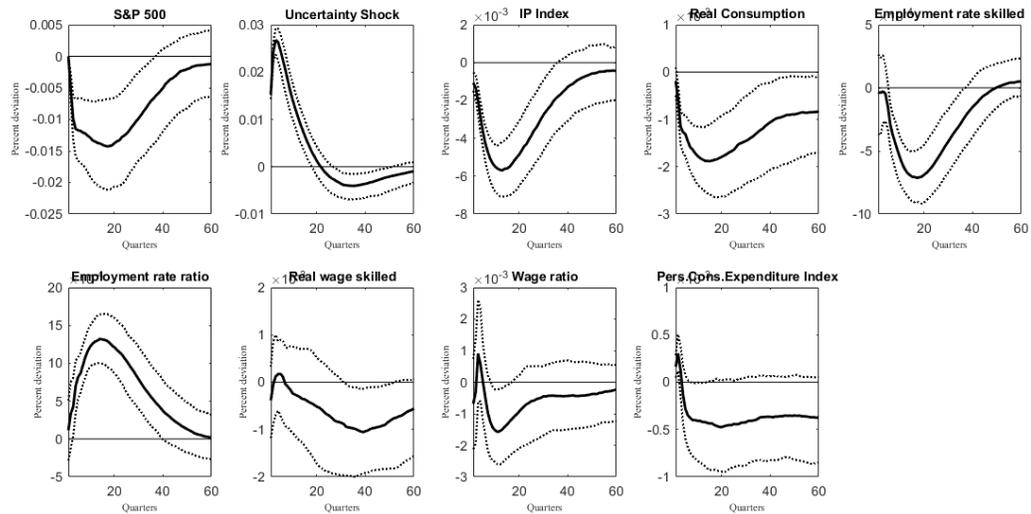
(b) Empirical impulse response functions to 1-sd uncertainty shock with monthly data frequency and controlling for the stock market.

Figure 6.7: Empirical impulse response functions to 1-sd uncertainty shock with monthly data frequency.

Note: Solid lines correspond to the median IRFs while the dashed lines are the 14th and 86th percentiles. Horizontal axes indicate quarters. Variables enter with six lags, selected according to the Akaike criterion.



(a) Empirical impulse response functions to 1-sd uncertainty shock with monthly data frequency.



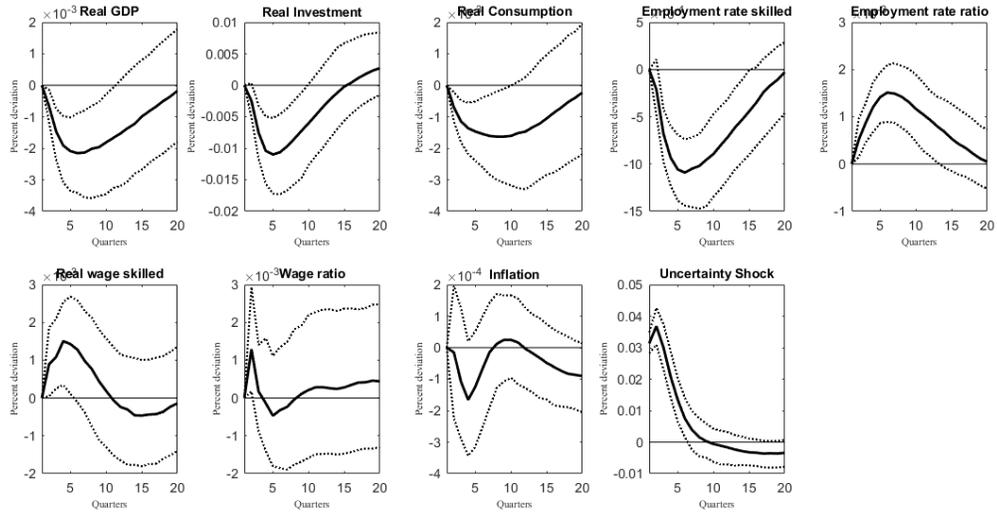
(b) Empirical impulse response functions to 1-sd uncertainty shock with monthly data frequency and controlling for the stock market.

Figure 6.8: Empirical impulse response functions to 1-sd uncertainty shock with monthly data frequency without private investment.

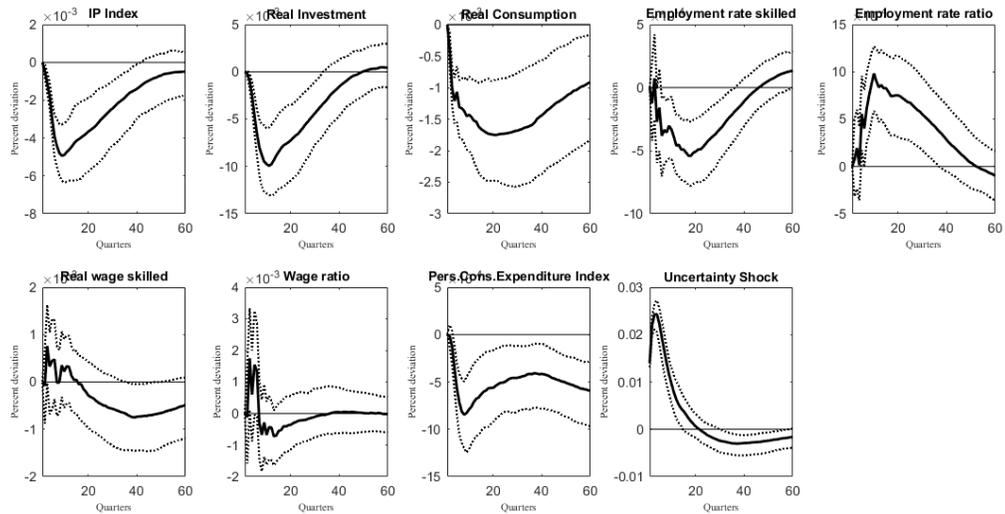
Note: Solid lines correspond to the median IRFs while the dashed lines are the 14th and 86th percentiles. Horizontal axes indicate quarters. Variables enter with six lags, selected according to the Akaike criterion.

C.3 Uncertainty Ordered Last

I check 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 6.9 also shows that the baseline results hold. I conduct this robustness check using both quarterly and monthly data in Figure 6.9a and Figure 6.9b respectively, both produce similar findings.



(a) Empirical impulse response functions to 1-sd uncertainty shock with uncertainty shock ordered last in the quarterly SVAR.



(b) Empirical impulse response functions to 1-sd uncertainty shock with uncertainty shock ordered last in the monthly SVAR.

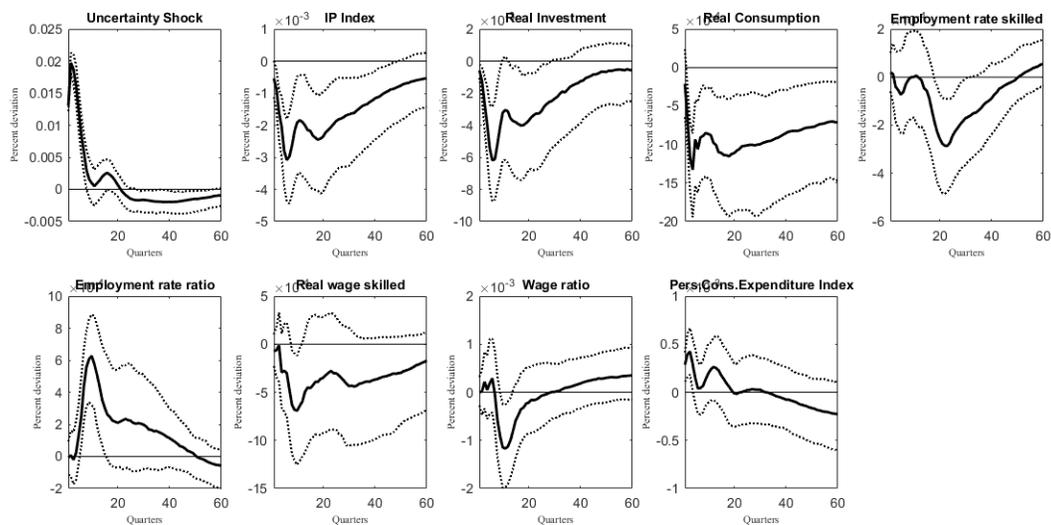
Figure 6.9: Empirical impulse response functions to 1-sd uncertainty shock with uncertainty ordered last.

Note: Solid lines correspond to the median IRFs while the dashed lines are the 14th and 86th 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.

C.4 Period Prior to 2007

I reduce the sample until 2007M12 in order to exclude the financial crisis. I conduct this robustness check using monthly data in order to preserve sufficient length of the model. Figure 6.10 shows that the results hold if I exclude the post-2007 financial crisis years.

Figure 6.10: 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 14th and 86th percentiles. Horizontal axes indicate quarters. Variables enter with six lags, selected according to the Akaike criterion.