Journal of Management Science and Engineering 8 (2023) 430–452

Science Press

Contents lists available at ScienceDirect

Journal of Management Science and Engineering

journal homepage: www.keaipublishing.com/en/journals/journal-of-management-science-and-engineering/

Economic uncertainty, central bank digital currency, and negative interest rate policy

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ARTICLE INFO

Article history:
Received 6 October 2022
Received in revised form 24 March 2023
Accepted 3 April 2023
Available online 17 July 2023

Keywords:
Economic uncertainty
Zero lower bound (ZLB)
Central bank digital currency (CBDC)
Negative interest rate policy (NIRP)

ABSTRACT

The COVID-19 outbreak has brought unprecedented social attention to economic uncertainty and negative interest rate policy (NIRP). How does uncertainty affect economic activity, and how effective is a NIRP based on central bank digital currency (CBDC)? To answer the two questions, we constructed a dynamic stochastic general equilibrium (DSGE) model that accommodates sticky prices and wages. The results indicated: (i) Economic uncertainty has substantially reduced investment, output, wage, and loans, which increases unemployment risk. In the short term, it has triggered impulsive consumption by households, while consumption has fallen into a slump in the long run. (ii) After suffering an uncertainty shock, the economy entered short-term stagflation and long-term deflation. The short-term stagflation was mainly caused by resident wage adjustment, and the long-term deflation was due to the decline in effective demand caused by unemployment risk. (iii) CBDC could eliminate the zero lower bound (ZLB) constraint, thereby improving the effectiveness of NIRP. Compared with traditional currency, CBDC-based NIRP could more effectively smooth macroeconomic fluctuations and alleviate the negative impact of an uncertainty shock, which is more conducive to restoring market confidence and promoting economic recovery.

1. Introduction

The COVID-19 pandemic has swept the world and brought massive risk changes (Hasan et al., 2022). Exogenous emergencies increase market uncertainty, which causes severe damage to the global economy (Bloom, 2009). Shortly after the COVID-19 outbreak, the World Bank projected that the global economy would shrink by 5.2% in 2020, possibly leading to the worst recession since World War II. While the COVID-19 pandemic has led to the collapse of global economic activity, people's lives have been dramatically changed by the control measures of the pandemic (Zhou et al., 2022). Until now, the pandemic has remained highly uncertain, and the economy still faces downward risks such as the COVID-19 persistence, financial turmoil, and further disruption of global trade and supply chains.

Many governments have resorted to unconventional economic stimulus measures to mitigate the negative impact of economic uncertainty (Hu and Liu, 2021), such as a negative interest rate policy (NIRP). According to the Bank for International Settlements (BIS), major economies have made interest rate cuts mandatory to reduce the corporate debt burden,

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https://doi.org/10.1016/j.jmse.2023.04.001

ensure the security of the capital chain, and mitigate the impact of uncertainty on economic and financial operations. The economic uncertainty has accelerated the formation of a low-interest rate environment around the world, which significantly reduces the effectiveness of traditional monetary policies (Ulate, 2021). Therefore, central banks in many countries have introduced extraordinary monetary policies, including NIRP, and have used monetary and interest rate policy tools to stimulate economic growth. NIRP has been widely influential (Goodfriend, 2016; Sims and Wu, 2021) and has gradually been adopted by many central banks in recent years. Given that the global economy is unlikely to pull out of this slump in the short term, we cannot rule out the possibility that NIRP will continue to expand worldwide.

However, the effect of NIRP is limited by the zero lower bound (ZLB) constraint (Boungou and Mawusi, 2023). While the NIRP is theoretically feasible, the government cannot reduce the nominal interest rate to negative because of the objective hoarding cost of cash (Agarwal and Kimball, 2015; Davoodalhosseini, 2022). To continuously stimulate inflation and economic growth, central banks need to eliminate the ZLB constraint and achieve negative nominal interest rates (Ulate, 2021). This is essential in expanding the operating space and improving the effectiveness of negative interest rates.

It is a general trend for central banks to issue digital currencies, which is conducive to eliminating the ZLB constraint by replacing cash (Grasselli and Lipton, 2019). For example, the People's Bank of China is building a digital currency and electronic payment (DC/EP) system (Wang et al., 2019). Central bank digital currency (CBDC) can monitor the use of funds, trace the flow of funds, and effectively prevent money laundering and other financial risk behaviors. In addition, CBDC interest rates can be developed into a new monetary policy tool (Wilkins, 2022) to promote CBDC effectiveness (Oh and Zhang, 2022). Many policy attempts, which can only be theoretically assumed in the traditional monetary system, can be realized in the digital currency system. When an uncertainty shock does not hit the macroeconomy, the central bank can adjust the interest rate of digital currency in the same way as that of traditional currency. When the macroeconomy suffers from an uncertainty shock, the central bank can modify the digital currency interest rate negatively, thereby implementing NIRP and promoting economic growth. We can see that the issuance and use of CBDC have the advantages of traditional currency and make up for its shortcomings. The NIRP can be implemented more effectively in the digital currency system.

While some countries experienced deflation subject to the pandemic uncertainty, China's inflation has shown a short-term upward trend with insufficient demand since February 2020 (Zhang et al., 2021). So how does uncertainty affect economic activity? What is the mechanism of its influence? Can NIRP improve its effectiveness in the CBDC system? This study constructs a six-sector dynamic stochastic general equilibrium (DSGE) model to solve these problems, including households, final and intermediate product firms, commercial banks, the central bank, and the government. Based on impulse response analysis, we explore the impact of economic uncertainty and the effectiveness of CBDC-based NIRP.

The possible contributions of this study are reflected in the following three aspects.

First, this study enriches the economic impact of uncertainty shocks. How uncertainty affects inflation has yet to be thoroughly studied in the literature. Some scholars have proposed that the impact of uncertainty shocks on the economy is deflation (Haque and Magnusson, 2021; Leduc and Liu, 2016), stagflation (Cross and Nguyen, 2018; Mumtaz and Theodoridis, 2015; Zhang et al., 2021), or no significant effect (Carriero et al., 2018; Katayama and Kim, 2018). Moreover, existing studies rarely mention the role of resident wage adjustments and unemployment risks in the economic impact of uncertainty shocks. This study proposes that wage adjustment causes short-term inflation and long-term deflation when subjected to an economic uncertainty shock.

Second, this study promotes theories related to negative interest rates. There needs to be more research on negative interest rates, especially in combination with CBDC. Scholars hold different views on the relationship between NIRP and economic growth, such as positive (Chen, 2020; Fukuda, 2018; García-Herrero, 2016; Goodfriend, 2016; Honda and Inoue, 2019; Schelling and Towbin, 2022; Sims and Wu, 2021), negative (Baars et al., 2020; Heider et al., 2019; Kay, 2018; Molyneux et al., 2019; Swanson and Williams, 2014) and undefined (Boungou, 2020; Carbó-Valverde et al., 2021; López-Penabad et al., 2022; Nucera et al., 2017). It is worth exploring the impact direction of CBDC-based NIRP on economic growth.

Third, this study excavates the impact mechanisms of CBDC-based NIRP on economic growth. Scholars have begun trying to combine the CBDC with NIRP and conducted theoretical analysis around the role of CBDC in NIRP. However, most studies are limited to qualitative analysis, which may not be convincing, and only some scholars have performed numerical simulations to clarify the problem. We will describe the behavior of households, final and intermediate product firms, commercial banks, the central bank, and the government through the utility function and constraints of the DSGE model and explore its impact mechanisms in detail.

The remainder of this study is organized as follows: Section 2 provides the literature review; Section 3 constructs a DSGE model; Section 4 represents the parameter calibration; Section 5 analyzes the results; and Section 6 describes the conclusions. The logical framework of this study is shown in Fig. 1.

2. Literature review

2.1. The impact of uncertainty on the macroeconomy

In recent years, there have been some research results about the impact of uncertainty on the macroeconomy. Before the COVID-19 outbreak, scholars mainly focused on the uncertainty of economic policies, financial markets, and energy markets. Carriero et al. (2018) proposed a new framework to conclude that financial uncertainty significantly impacts the macroeconomy. Wen et al. (2019) concluded that economic policy uncertainty might lead to inflation asymmetry as financial market

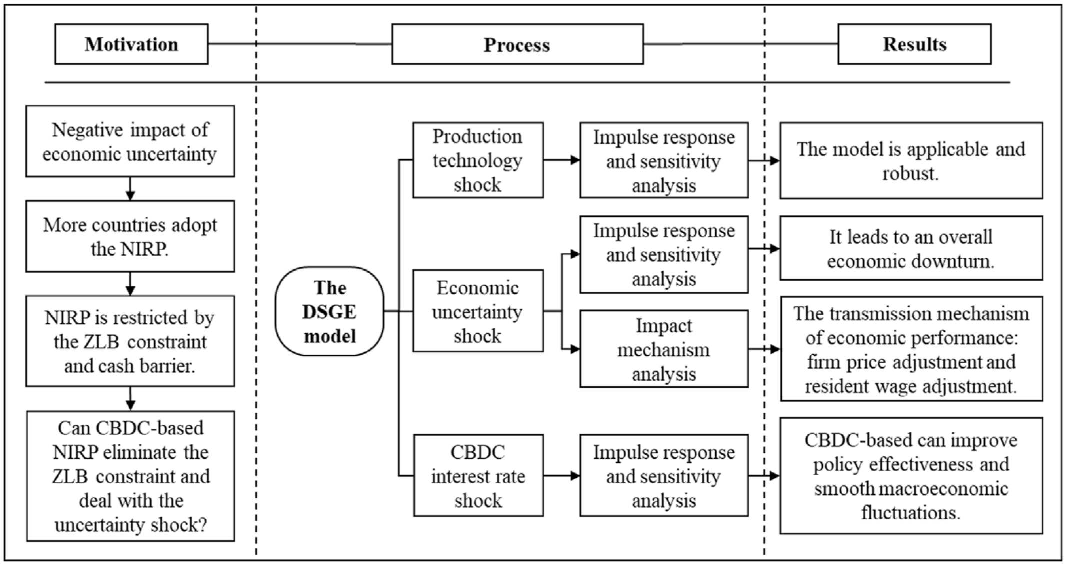

Fig. 1. Logical framework.

uncertainty plays a decisive role in China's macroeconomy, and energy uncertainty may increase the money supply by a nonlinear autoregressive distributed lag (NARDL) model. Trung (2019) studied the spillover effect of US economic policy uncertainty and its impact on world business cycle fluctuations. Benhabib et al. (2019) constructed a model in which financial markets and the real economy learn from each other and analyzed uncertainty shock with overall economic activities in the same framework.

After the COVID-19 outbreak, scholars have focused on the economic impact and policy response to uncertain events, especially the pandemic shock. Altig et al. (2020) analyzed the negative effects of economic uncertainty on variables, such as stock prices, unemployment, and industrial production during the COVID-19 pandemic. Rossi and Miescu (2021) extracted COVID-19-related indicators through statistical identification and found that the COVID-19 uncertainty shock would severely impact industries that need to meet and interact. Peňáková (2021) constructed a DSGE model to explore the role of different tax policies in Slovakia and the Czech Republic to compensate for losses from the COVID-19 uncertainty shock. Hu and Liu (2021) analyzed the impact mechanism of COVID-19 uncertainty shock on China's export volatility and proposed corresponding policy countermeasures. Ngo et al. (2022) constructed a TVP-VAR model to compare the adverse effects of uncertainty shocks caused by the financial crisis and COVID-19 on consumption, investment, and exports. Dietrich et al. (2022) explored the short-term economic impact of COVID-19 on inflation and output based on survey data from the United States and proposed appropriate policy response mechanisms.

Scholars have concluded that uncertainty shocks can inhibit output growth, but how uncertainty affects inflation is yet to be concluded. Some scholars consider that the impact of uncertainty shocks on the economy is deflation. For example, using a calibrated DSGE model, Leduc and Liu (2016) showed that price stickiness leads to economic deflation following an uncertainty shock with US data. Haque and Magnusson (2021) estimated a time-varying parameter VAR using US data and found the response of inflation to be negative in the Post World War II period. Other scholars argue that the uncertainty shock has no significant effect on inflation. For example, Katayama and Kim (2018) and Carriero et al. (2018) only found that uncertainty shock negatively affects output and employment and has no noticeable impact on inflation based on US data. However, Mumtaz and Theodoridis (2015) used an extended SVAR model and DSGE model to estimate the effect of an increase in the volatility of shocks to US real activity on the UK economy. They pointed out that uncertainty can lead to significant periods of stagflation due to the effects of price and wage adjustments. Cross and Nguyen (2018) examined the impact of world energy price shocks on China's macroeconomy. They concluded that uncertainty energy price shocks could lead to a decline in real GDP and an increase in inflation, thus causing stagflation. Zhang et al. (2021) identified and decomposed uncertainty shock into level and volatility effects based on China's data, where volatility shock produces a stagflation effect. A literature summary on the impact of uncertainty is shown in Table 1.

2.2. *The effect of NIRP*

Many scholars have done a lot of research on NIRP, and many countries have put it into practice. Relevant research points out that NIRP can play a role in fighting deflation and boosting the economy. Goodfriend (2016) found that the United States tried implementing NIRP during the Great Depression, promoting economic growth. After exploring the effect of NIRP in Japan, some scholars found that the NIRP expanded the scale of overseas investment (García-Herrero, 2016) and caused a

Table 1
Impact of uncertainty on the macroeconomy.

Classification	Content	Literature source
Before the COVID-19 outbreak	The uncertainty of economic policies	Wen et al. (2019) Trung (2019)
	The uncertainty of financial markets	Carriero et al. (2018) Wen et al. (2019) Benhabib et al. (2019)
	The uncertainty of energy markets	Wen et al. (2019)
After the COVID-19 outbreak	The economic impact	Altig et al. (2020) Rossi and Miescu (2021) Hu and Liu (2021) Ngo et al. (2022) Dietrich et al. (2022)
	The policy response	Peňáková (2021) Hu and Liu (2021) Dietrich et al. (2022)
The impact on inflation	Deflation	Leduc and Liu (2016) Haque and Magnusson (2021)
	No significant impact	Katayama and Kim (2018) Carriero et al. (2018)
	Short-term stagflation and long-term deflation	Mumtaz and Theodoridis (2015) Cross and Nguyen (2018) Zhang et al. (2021)

significant increase in the Nikkei index, especially in the real estate industry (Honda and Inoue, 2019). NIRP is a powerful policy with the following functions: (i) promoting economic growth as conventional monetary policy (Sims and Wu, 2021); (ii) making up for the shortcomings of open market operations (Goodfriend, 2016) and the quantitative easing approach (Fukuda, 2018); (iii) expanding the credit scale of commercial banks; (iv) improving the financing difficulty of small and medium-sized enterprises; (v) stimulating investment to boost the economy. In addition, Chen (2020) proposed that a negative interest rate would reduce liquidity risks and improve the capital utilization rate of commercial banks. Schelling and Towbin (2022) proved that the NIRP in Switzerland could stimulate banks to take more risks and provide easier loan conditions.

However, there have been many objections since the implementation of NIRP, such as Swanson and Williams (2014), Molyneux et al. (2019), Heider et al. (2019), Kay (2018), and Baars et al. (2020). Scholars have conducted extensive studies on NIRP's impact on the macroeconomy and financial markets. Relevant studies have found that NIRP has the following macroeconomic impacts: (i) reducing the sensitivity of interest rate decline (Swanson and Williams, 2014); (ii) inhibiting the credit activities and monetary policy transmission of commercial banks (Molyneux et al., 2019); (iii) increasing the risk preference of banks; (iv) causing severe capital shrinkage (Heider et al., 2019), which has a profound negative impact on the economy. In terms of the effects on the financial market, NIRP may discourage the enthusiasm of the market to hold cash and market liquidity, aggravate the market volatility (Kay, 2018), and significantly increase the preference under risk premium (Baars et al., 2020), which is not conducive to the financial market development.

Other scholars emphasize that whether NIRP is effective cannot be defined unilaterally and is related to many factors. Boungou (2020) concluded that the effect of NIRP on bank risk-taking depends on the capitalization level and size of the banking system by using the bank data in several countries. Carbó-Valverde et al. (2021) proposed that the impact of NIRP on the economy is related to the current assets, the capitalization degree, the central bank reserves, and the customer deposits in the country's banking industry. In addition, Nucera et al. (2017) proved that the business model is an essential factor affecting negative interest rate risk and bank security. Likewise, López-Penabad et al. (2022) applied a static modeling method to measure the impact of NIRP on banks' net interest margin and return on capital and also pointed out that the effect of NIRP on the banks' profit and risk-taking depends on their business model. A literature summary on the impact of NIRP is shown in Table 2.

2.3. *The impact of digital currency on NIRP*

The NIRP, which is theoretically feasible, is constrained by the ZLB and cannot adjust the interest rate to negative in reality. Many scholars have pointed out that the ZLB constraint on interest rate affects the regulatory effect of NIRP. Basu and Bundick (2015) showed that monetary policy could reduce the negative impact of uncertainty. Hall (2016) proposed that a negative real interest rate may restore full employment, while the ZLB limits this possibility and leads to high unemployment. Still, the ZLB constraint may lead to the limited role of monetary policy, thus exacerbating its negative impact. Chen (2020) applied the dynamic equilibrium model and found that the interest rate is close to zero in the Japanese foreign exchange market, but being unable to enter the negative value would increase the liquidity risk. Dotsis (2020) indicated that the ZLB constraint induces the uncertainty of interest rates, which leads to an asymmetric effect on investment decisions. Heider et al. (2021)

Table 2
Effect of NIRP.

Classification	Literature source	View
The positive impact	Goodfriend (2016)	Promoting economic growth and making up for the shortcomings of open market operation
	García-Herrero (2016)	Expanding the scale of overseas investment
	Honda and Inoue (2019)	Causing a significant increase in the real estate industry
	Sims and Wu (2021)	Promoting economic growth
	Fukuda (2018)	Making up for the shortcomings of quantitative easing policy
	Chen (2020)	Reducing liquidity risks and improving the capital utilization rate of commercial banks
	Schelling and Towbin (2022)	Stimulating banks to take more risks and provide easier loan conditions
The negative impact	Swanson and Williams (2014)	Reducing the sensitivity of interest rate decline
	Molyneux et al. (2019)	Inhibiting the credit activities and monetary policy transmission of commercial banks
	Heider et al. (2019)	Causing serious capital shrinkage
	Kay (2018)	Aggravating market volatility
	Baars et al. (2020)	Increasing the preference under risk premium
Whether NIRP is effective cannot be defined	Boungou (2020)	Depending on the capitalization level and size of the banking system
	Carbó-Valverde et al. (2021)	Relating to the current assets, the capitalization degree, the central bank reserves, and the customer deposits
	Nucera et al. (2017)	Depending on the business model
	López-Penabad et al. (2022)	Business model affecting the banks' profit and risk-taking

analyzed the impact of negative interest rates on the banking system and concluded that the ZLB hindered the spread of retail deposit interest rates among banks.

The CBDC is the key to eliminating the ZLB constraint (Chen and Siklos, 2022). In recent years, scholars began trying to combine the CBDC with NIRP and conducted theoretical analyses around the role of CBDC in the regulation process of NIRP. Rogoff (2017) pointed out that negative interest rates on electronic money can subtly eliminate the ZLB barrier. Grasselli and Lipton (2019) indicated that replacing physical cash with CBDC is the key to eradicating the ZLB constraint and giving full play to the NIRP. With proper issuance arrangements, CBDC policy rules can significantly improve central banks' ability to minimize risks and stabilize the business cycles (Barrdear and Kumhof, 2022). Echarte Fernández et al. (2021) focused on monetary policies to boost the economy after the COVID-19 outbreak and found that issuing CBDC is an effective way to improve the effectiveness of NIRP. Shen and Hou (2021), Chen and Siklos (2022), and Yang and Zhou (2022) all agreed that digital currency is a new monetary operation tool for the central bank, which is conducive to the implementation of NIRP to stimulate the economy and raise inflation. Wilkins (2022) also held the same view that after an excellent digital currency design, the central bank could realize accurate control of it, which is conducive to the directional regulation of NIRP. Xin and Jiang (2023) argued that the CBDC could eliminate the ZLB constraint and stabilize the economic fluctuations caused by NIRP. In addition, CBDC plays a vital role in reducing time delay and leakage in the process of monetary policy transmission (Fegatelli, 2022), enhancing financial stability (Kim and Kwon, 2023), and increasing social welfare (Minesso et al., 2022). The literature summary is shown in Table 3.

2.4. Literature summary

In summary, scholars have made many achievements in multi-perspective and multi-level research on economic uncertainty, CBDC, and NIRP. However, most existing studies are limited to theoretical analysis, and model deduction and empirical simulation are few. In particular, the research on CBDC and NIRP is still focused on empirical feasibility discussion. Only a few scholars have researched the impact mechanism of uncertainty shock on the macroeconomy and the regulation effect of NIRP in digital currency. Given this, we construct a new Keynesian DSGE model to explore the impact of economic uncertainty and the effectiveness of CBDC-based NIRP to provide literature support and enlightenment for subsequent research.

3. Model construction

In this section, we assumed that CBDC is not only an interest-bearing asset but also a payment instrument that can completely replace cash. Then we constructed a six-sector DSGE model including households, final and intermediate product firms, commercial banks, central bank, and government. When an uncertainty shock hits the economy, the central bank can impose NIRP by lowering the interest rate on digital currency to negative. The framework of the DSGE model is shown in Fig. 2.

Table 3
Impact of CBDC on NIRP.

Classification	Literature source	View
The ZLB constrains the NIRP	Basu and Bundick (2015)	Limiting the contribution to reducing the negative impact of uncertainty
	Hall (2016)	Limiting the contribution to restoring full employment
	Chen (2020)	Increasing the liquidity risk
	Dotsis (2020)	Inducing the uncertainty of interest rates and leading to an asymmetric effect on investment decisions
	Heider et al. (2021)	Hindering the spread of retail deposit interest rates among banks
The CBDC is the key to eliminating the ZLB constraint	Chen and Siklos (2022)	The key to removing the ZLB constraint
	Rogoff (2017)	Electronic money can subtly eliminate the ZLB barrier
	Grasselli and Lipton (2019)	The key to eliminating the ZLB constraint and giving full play to the NIRP
	Barrdear and Kumhof (2022)	Improving central banks' ability to minimize risks and stabilize the business cycles
	Echarte Fernández et al. (2021)	An effective way to improve the effectiveness of NIRP
	Shen and Hou (2021) Chen and Siklos (2022) Yang and Zhou (2022)	A new monetary operation tool of the central bank and stimulating the economy and raising inflation
	Wilkins (2022)	Depending on the capitalization level and size of the banking system
	Xin and Jiang (2023)	Eliminating the ZLB constraint and stabilizing the economic fluctuations caused by NIRP.
	Fegatelli (2022)	Reducing time delay and leakage in the process of monetary policy transmission
	Kim and Kwon (2023)	Enhancing financial stability
	Minesso et al. (2022)	Increasing social welfare

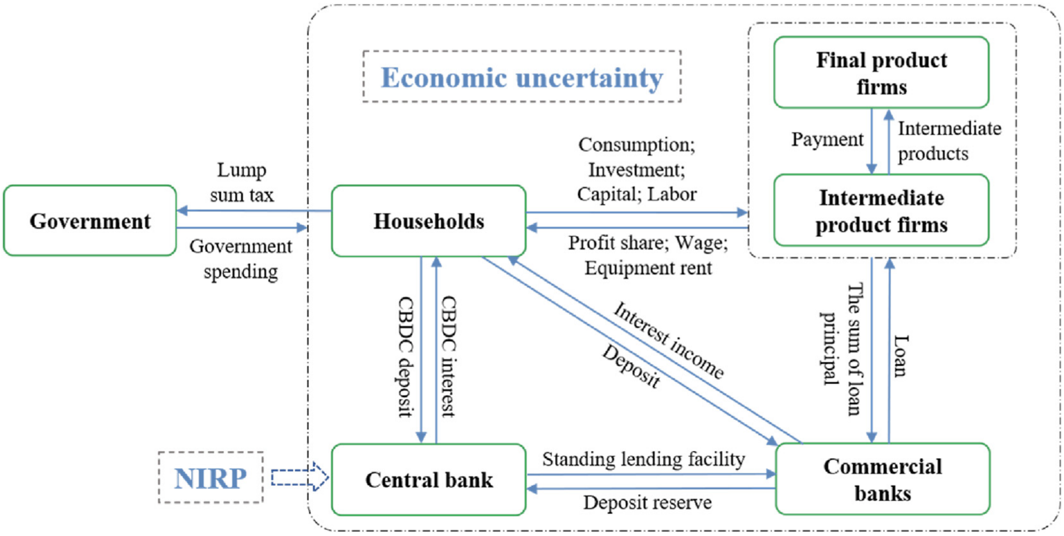

Fig. 2. Schematic diagram of the model frame.

3.1. Households

3.1.1. Heterogeneous labor

We assumed that households provide heterogeneous labor and have some wage bargaining power, thereby introducing wage stickiness into the model. The labor $l_t(n)$ provided by a single household is packaged into final labor l_t, where $n\in(0,1)$. The final unemployment rate can be expressed as $1-l_t$, where l_t satisfies the following form.

$$l_t=\left(\int_0^1 l_t(n)^{\frac{\in_w-1}{\in_w}}\mathrm{d}n\right)^{\frac{\in_w}{\in_w-1}}, \tag{1}$$

where, $\in_w$ represents the elasticity of substitution between heterogeneous labors, which satisfies $\in_w>1$. We assumed that the final labor producer faces full competition, and its profit maximization problem is as follows.

$$\max_{l_t(n)} \quad w_t l_t - \int_0^1 w_t(n) l_t(n) \mathrm{d}n\,, \tag{2}$$

where, $w_t(n)$ and w_t are the corresponding wage and total wage of single labor, respectively. According to the constraint condition (1), the first-order condition can be obtained as follows.

$$l_t(n) = (w_t(n)/w_t)^{-\in_w} l_t. \tag{3}$$

The final labor producer satisfies the zero-profit condition, so the wage evolution can be expressed as follows.

$$w_t = \left(\int_0^1 w_t(n)^{1-\in_w} \mathrm{d}n \right)^{\frac{1}{1-\in_w}}. \tag{4}$$

3.1.2. Representative household

The assumption of labor heterogeneity makes households heterogeneous, which makes it quite challenging to solve the utility maximization problem in the household sector. To simplify the model, we assumed that households have the same consumption and money holdings and differ only in wages and labor. The latter model $n \in (0,1)$ only represents the labor of a family, which does not mean that households are heterogeneous.

The representative household maximizes its expected utility by choosing consumption, labor, and CBDC balances.

$$E_t \sum_{t=0}^{\infty} \beta^t U(c_t, l_t(n), dc_t), \tag{5}$$

where E_t is the conditional expectation operator, β is the discount factor, c_t and dc_t represents the consumption and CBDC balance of the representative household, respectively.

In addition, the utility function $U(\bullet)$ has the following form.

$$U(c_t, l_t(n), dc_t) = \log(c_t - \alpha c_{t-1}) - \chi_l l_t(n)^{1+\delta_l} \Big/ (1+\delta_l) + \chi_{dc} (dc_t)^{1-\delta_{dc}} \Big/ (1-\delta_{dc}), \tag{6}$$

where, α represents the consumption habit coefficient of representative household; δ_l and δ_{dc} denote the reciprocal of labor supply's Frisch elasticity and money demand's interest elasticity, respectively; χ_l and χ_{dc} represent the marginal contribution of labor and CBDC balance to the household utility, respectively.

We assumed that the household assets are bank deposits and CBDCs. That is, CBDCs will replace all physical cash. The interest rate of CBDC is R_t. We defined d_t and inv_t to represent the bank deposits and investments, respectively; $R_{k,t}$, φ_t and k_t respectively represent the return on capital, capital utilization rate and capital stock; $R_{d,t}$, tax_t and UC_t represent deposit interest rate, lump sum tax and capital utilization cost, respectively. When there is a ZLB on the deposit interest rate, the deposit interest rate can be expressed as $R_{d,t} = Max \quad (0, R_{d,t})$. Thus, the budget constraint of the representative household can be expressed as follows.

$$w_t(n)l_t(n) + R_{k,t}\varphi_t k_t + (1+R_{d,t})d_t + (1+R_{t-1})dc_{t-1} + \left(\prod\nolimits_t - tax_t\right) \begin{array}{l} \big/ P_t - UC_t \\ = c_t + d_{t+1} + dc_t + inv_t, \end{array} \tag{7}$$

where $\varphi_t k_t$ and $\prod_t$ represent the adequate capital stock and the profit dividends households receive from the manufacturer, respectively. We defined $\varphi_t = 1$ when capital is fully utilized. That is, the adequate capital stock is equal to the real capital stock. In other cases, the representative household will incur a capital utilization cost, expressed as follows.

$$UC_t = \frac{k_t}{\psi_t} \left(\gamma_1(\varphi_t - 1) + \frac{\gamma_2}{2}(\varphi_t - 1)^2 \right), \tag{8}$$

where, both γ_1 and γ_2 are capital utilization parameters.

According to Christiano et al. (2014), the investment return risk of firms is the most critical factor in the economic cycle, which exacerbates cyclical volatility by changing the resource allocation of various economic sectors. Likewise, Li et al. (2021) indicated that uncertainty directly affects investment return. Economic uncertainty shock ψ_t follows a stochastic process.

$$\log \psi_t = \rho_\psi \log \psi_{t-1} + \varepsilon_{\psi,t}, \tag{9}$$

where, the autoregressive coefficient $|\rho_\psi| < 1$, and the random disturbance term $\varepsilon_{\psi,t} \sim N(0, \sigma_\psi^2)$.

We defined η and ν to represent the capital depreciation rate and investment adjustment coefficient, respectively. Then the capital accumulation equation is as follows.

$$k_{t+1} = \psi_t \left(1 - \frac{\nu}{2}\left(\frac{inv_t}{inv_{t-1}} - 1\right)^2\right) inv_t + (1-\eta)k_t. \tag{10}$$

$\lambda_{1,t}$ and $\lambda_{2,t}$ are Lagrange multipliers of two constraints, respectively. The Lagrange equation of the representative family can be expressed as follows.

$$L_{1,t} = E_t \sum_{t=0}^{\infty} \beta^t \left\{ \begin{array}{l} \log(c_t - \alpha c_{t-1}) - \chi_l l_t(n)^{1+\delta_l} \Big/ (1+\delta_l) + \chi_{dc}(dc_t)^{1-\delta_{dc}} \Big/ (1-\delta_{dc}) \\ +\lambda_{1,t}\left(k_{t+1} - \psi_t\left(1 - \frac{\nu}{2}\left(\frac{inv_t}{inv_{t-1}} - 1\right)^2\right) inv_t - (1-\eta)k_t\right) \\ +\lambda_{2,t}\left(\begin{array}{l} c_t + d_{t+1} + dc_t + inv_t - w_t(n)l_t(n) - R_{k,t}\varphi_t k_t \\ -(1+R_{d,t})d_t - (1+R_{t-1})dc_{t-1} - \left(\prod_t - tax_t\right) \Big/ P_t + UC_t \end{array}\right) \end{array} \right\}. \tag{11}$$

The first-order conditions for maximization can be obtained through the Lagrange solution.

$$\lambda_{2,t} = \frac{1}{c_t - \alpha c_{t-1}} - \beta\alpha \frac{1}{c_{t+1} - \alpha c_t}, \tag{12}$$

$$\lambda_{2,t} = \beta E_t \lambda_{2,t+1}(1 + R_{d,t}), \tag{13}$$

$$\chi_{dc}(dc_t)^{-\delta_{dc}} + \lambda_{2,t} = \beta E_t \lambda_{2,t+1}(1 + R_t), \tag{14}$$

$$R_{k,t} = \frac{1}{\psi_t}(\gamma_1 + \gamma_2(\varphi_t - 1)), \tag{15}$$

$$\begin{aligned} \lambda_{2,t} = \lambda_{1,t}\psi_t &\left(\left(1 - \frac{\nu}{2}\left(\frac{inv_t}{inv_{t-1}} - 1\right)^2\right) - \nu\left(\frac{inv_t}{inv_{t-1}} - 1\right)\frac{inv_t}{inv_{t-1}}\right) \\ &+ \beta E_t \lambda_{2,t+1}\psi_{t+1}\nu\left(\frac{inv_{t+1}}{inv_t} - 1\right)\left(\frac{inv_{t+1}}{inv_t}\right)^2, \end{aligned} \tag{16}$$

$$\lambda_{1,t} = \beta E_t\left(\lambda_{2,t+1}\left(R_{k,t+1}\varphi_{t+1} - \frac{1}{\psi_{t+1}}\left(\gamma_1(\varphi_{t+1} - 1) + \frac{\gamma_2}{2}(\varphi_{t+1} - 1)^2\right)\right) + \lambda_{1,t+1}(1-\eta)\right). \tag{17}$$

3.1.3. Wage stickiness setting

In this part, we introduced wage stickiness by solving wage determination in the household sector. Referring to Calvo (1983), we do not consider indexation adjustment. We assumed that households could adjust wages to the optimum with the probability of $1 - \varphi_w$ in each period and cannot adjust wages optimally with the probability of φ_w. Among them, φ_w determines the degree of wage stickiness. We assumed that households can optimally adjust wages in period t, and cannot adjust wages in subsequent periods, i.e., $w_{t+j}(n) = w_t(n), j > 0$.The maximum utility of households comprises the disutility brought by labor and the positive utility generated by labor wage.

$$max \quad E_t \sum_{j=0}^{\infty} (\beta\varphi_w)^j \left(-\chi_l l_t(n)^{1+\delta_l} \Big/ (1+\delta_l) + \lambda_{2,t+j} w_{t+j}(n) l_{t+j}(n)\right) dn, \tag{18}$$

where j is a sum of numbers, and its constraints can be expressed as follows.

$$l_{t+j}(n) = \left(\frac{w_{t+j}(n)}{w_{t+j}}\right)^{-\in_w} l_{t+j}. \tag{19}$$

The first-order condition of the optimal wage can be expressed as follows.

$$\left(w_t^*\right)^{1+\in_w\delta_l} = (w_t(n))^{1+\in_w\delta_l} = \frac{\in_w}{\in_w - 1}\frac{E_t\sum_{j=0}^{\infty}(\beta\varphi_w)^j\chi_l\left(w_{t+j}\right)^{\in_w(1+\delta_l)}\left(l_{t+j}\right)^{1+\delta_l}}{E_t\sum_{j=0}^{\infty}(\beta\varphi_w)^j\lambda_{2,t+j}\left(w_{t+j}\right)^{\in_w}l_{t+j}}. \tag{20}$$

3.2. Final product firms

The firm sector in the simulated economy is divided into final and intermediate product firms. $P_t(i)$ is the price of intermediate products, $y_t(i)$ is the input of intermediate products to produce the final products, and κ is the elasticity of demand for the intermediate products. The production function of final product firms can be expressed as follows.

$$y_t = \left(\int_0^1 y_t(i)^{\frac{\kappa-1}{\kappa}}\mathrm{d}i\right)^{\frac{\kappa}{\kappa-1}}. \tag{21}$$

The profit maximization problem of final product firms can be expressed as follows.

$$\max_{y_t(i)} \quad P_t y_t - \int_0^1 P_t(i)y_t(i)\mathrm{d}i. \tag{22}$$

For an intermediate good *i*, its first-order condition is as follows.

$$y_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\kappa} y_t. \tag{23}$$

The final product firms face perfect competition and meet the following zero-profit condition.

$$P_t y_t - \int_0^1 P_t(i)y_t(i)\mathrm{d}i = 0. \tag{24}$$

The determining equation of the aggregate price level index is as follows.

$$P_t = \left(\int_0^1 P_t(i)^{1-\kappa}\mathrm{d}i\right)^{\frac{1}{1-\kappa}}. \tag{25}$$

The inflation rate is expressed as follows.

$$\pi_t = \frac{P_t(i)}{P_{t-1}(i)}. \tag{26}$$

3.3. Intermediate product firms

Unlike the final product firms in the perfect competition market, the intermediate product firms are in the monopolistic competition market. The intermediate product firms solve the two-stage problems, which is also a crucial part of the model to introduce price stickiness. In the first stage, the intermediate product firms solve the cost minimization problem to determine their marginal cost. In the second stage, we introduced price stickiness to solve the profit maximization problem in the dynamic pricing strategy.

We defined μ and $1-\mu$ to represent the output elasticities of capital and labor, respectively. Then the production function of intermediate product firms can be expressed as follows.

$$y_t(i) = A_t(\varphi_t k_t)^{\mu}(l_t)^{1-\mu}. \tag{27}$$

We assumed that the production technology shock A_t follows a stochastic process.

$$\log A_t = \rho_A \log A_{t-1} + \varepsilon_{A,t}, \tag{28}$$

where, the autoregressive coefficient $|\rho_A| < 1$, and the random disturbance term $\varepsilon_{A,t} \sim N(0, \sigma_A^2)$.

3.3.1. Cost minimization problem

The first stage determines the marginal cost of intermediate product firms to prepare for the second stage problem. We assumed that the intermediate product firms need to pay employee wages and equipment rents by borrowing from the commercial bank, and the loan ϖ_t is expressed as follows.

$$\varpi_t = R_{k,t}\varphi_t k_t + w_t l_t. \tag{29}$$

The sum of principal to be repaid by the intermediate product firms is $(1 + R_{\varpi,t})\varpi_t$, and its cost minimization equation is as follows.

$$min \quad (1 + R_{\varpi,t})\varpi_t \, . \tag{30}$$

$\lambda_{3,t}$ represents the Lagrange multiplier of the Constraint condition (27), from which the Lagrange function can be expressed as follows.

$$L_{2,t} = -(1 + R_{\varpi,t})\varpi_t + \lambda_{3,t}\left(A_t(\varphi_t k_t)^{\mu}(l_t)^{1-\mu} - \left(\frac{P_t(i)}{P_t}\right)^{-\kappa} y_t\right), \tag{31}$$

where $\lambda_{3,t}$ means the actual cost that must be paid for each additional unit of product produced. Therefore, $\lambda_{3,t}$ it can be interpreted as marginal cost, that is, $mc_t = \lambda_{3,t}$.

The first-order condition of labor is as follows.

$$w_t = \frac{\lambda_{3,t}(1-\mu)A_t(\varphi_t k_t)^{\mu}(l_t)^{-\mu}}{(1 + R_{\varpi,t})}. \tag{32}$$

The first-order condition of capital is as follows.

$$R_{k,t} = \frac{\lambda_{3,t}\mu A_t(\varphi_t k_t)^{\mu-1}(l_t)^{1-\mu}}{(1 + R_{\varpi,t})}. \tag{33}$$

The marginal cost can be expressed as follows.

$$mc_t = \lambda_{3,t} = \frac{w_t(1 + R_{\varpi,t})}{(1-\mu)A_t}\left(\frac{\varphi_t k_t}{l_t}\right)^{-\mu}. \tag{34}$$

3.3.2. Profit maximization problem and price stickiness setting

This part considers the profit maximization problem in the second period. The actual profit of intermediate product firms in period t is as follows.

$$\prod\nolimits_t \begin{aligned} / P_t &= \frac{P_t(i)y_t(i)}{P_t} - (1 + R_{\varpi,t})(R_{k,t}\varphi_t k_t + w_t l_t) \\ &= \frac{P_t(i)y_t(i)}{P_t} - (\mu mc_t y_t(i) + (1-\mu)mc_t y_t(i)) \\ &= \frac{P_t(i)y_t(i)}{P_t} - mc_t y_t(i) \\ &= P_t(i)^{1-\kappa}P_t^{\kappa-1}y_t - mc_t P_t(i)^{-\kappa}P_t^{\kappa}y_t. \end{aligned} \tag{35}$$

We assumed that intermediate product firms have specific pricing power, thus introducing price stickiness. φ_P is the price adjustment parameter. We assumed that firms can adjust product price to the optimum with the probability of $1 - \varphi_P$ in each period, and cannot adjust price optimally with the probability of φ_P. The firms can optimally adjust product price to $P_t(i)$ in period t, and cannot modify the price in subsequent periods, that is, $P_{t+j}(i) = P_t(i)$. The maximum utility of intermediate product firms can be expressed as follows.

$$max \quad E_t \sum_{j=0}^{\infty} (\beta \varphi_P)^j \frac{u'(C_{t+j})}{u'(C_t)} \left(P_t(i)^{1-\kappa} P_t^{\kappa-1} y_t - mc_t P_t(i)^{-\kappa} P_t^{\kappa} y_t \right). \tag{36}$$

The first-order condition of the optimal price can be obtained as follows.

$$P_t^* = P_t(i) = \frac{\kappa}{\kappa - 1} \frac{E_t \sum_{j=0}^{\infty} (\beta \varphi_P)^j u'(C_{t+j}) mc_{t+j} P_{t+j}^{\kappa} y_{t+j}}{E_t \sum_{j=0}^{\infty} (\beta \varphi_P)^j u'(C_{t+j}) P_{t+j}^{\kappa-1} y_{t+j}}. \tag{37}$$

We defined π_t^* as the repriced inflation rate, which satisfies the following form.

$$\pi_t^* = \frac{P_t^*}{P_{t-1}}. \tag{38}$$

The optimal pricing equation for intermediate product firms is as follows.

$$\pi_t^* = \frac{\kappa}{\kappa - 1} \pi_t \frac{N_{1,t}}{N_{2,t}}, \tag{39}$$

where, auxiliary variables $N_{1,t}$ and $N_{2,t}$ can be expressed as follows.

$$N_{1,t} = \lambda_{2,t} mc_t y_t + \varphi_P \beta N_{1,t+1} \pi_{t+1}^{\kappa}, \tag{40}$$

$$N_{2,t} = \lambda_{2,t} y_t + \varphi_P \beta N_{2,t+1} \pi_{t+1}^{\kappa-1}. \tag{41}$$

3.4. Commercial banks

We assumed that there is an interest rate corridor mechanism, with the upper limit being the interest rate $R_{f,t}$ on commercial banks' loans to the central bank, which is the Standing Lending Facility (SLF) f_t, and the lower limit being the interest rate $R_{h,t}$ paid by commercial banks on their excess deposit reserves h_t at the central bank. In addition, commercial banks lend ϖ_t to firms and take deposits d_t from representative households.

Commercial banks meet the following conditions.

$$\varpi_t + h_t = d_t + f_t. \tag{42}$$

θ and ϑ are the loan cost parameters and the risk management capability coefficient, respectively. The profit maximization problem of commercial banks is as follows.

$$max \quad E_t \sum_{t=0}^{\infty} \beta^t \left(\varpi_t R_{\varpi,t} + h_t R_{h,t} - d_t R_{d,t} - f_t R_{f,t} - \theta \varpi_t - \vartheta \frac{d_t}{h_t} \right), \tag{43}$$

where, $\theta \varpi_t$ represents the cost of a commercial bank's loan business; $\vartheta \frac{d_t}{h_t}$ is the risk cost of commercial banks.

The optimal first-order conditions of commercial banks are as follows.

$$R_{\varpi,t} - R_{f,t} = \theta, \tag{44}$$

$$R_{f,t} - R_{h,t} = \vartheta \frac{d_t}{h_t^2}, \tag{45}$$

$$R_{f,t} - R_{d,t} = \frac{\vartheta}{h_t}. \tag{46}$$

3.5. Central bank

Central banks' liabilities are the base currencies, consisting of the CBDC dc_t and the excess deposit reserves h_t of commercial banks. The assets are loans f_t to commercial banks. The central bank maintains the following balance sheet equilibrium.

$$dc_t + h_t = f_t. \tag{47}$$

We introduced an interest-paying asset CBDC with an interest rate of R_t, which means it can be used as a new monetary policy tool. The monetary policy obeys the Taylor rule and R_t can be expressed as follows.

$$R_t = (1 - \rho_R)(R_0 + \xi_\pi(\pi_t - \pi) + \xi_Y \log(Y_t - Y)) + \rho_R R_{t-1} + \varepsilon_{R,t}, \tag{48}$$

where, ρ_R, γ_π and ξ_Y represent the interest rate smoothing parameter, Taylor formula inflation parameter, and Taylor formula output parameter, respectively. R_0, π and Y represent the steady-state values of CBDC interest rate, inflation, and output, respectively. $\varepsilon_{R,t}$ represents the monetary policy interest rate shock, which follows the normal distribution with mean 0 and standard deviation σ_R.

Both CBDC and excess deposit reserves of commercial banks are the liabilities of the central bank and highly liquid assets, so we assumed that their interest rates are equal, that is, $R_t^m = R_t$. The assets of representative households are allocated only to deposits and CBDCs. Moreover, CBDCs, which are supported by national credit, are safer than bank deposits, so the deposit interest rate set by commercial banks will be higher than the CBDC interest rate. We assumed that the risk premium part of the deposit rate relative to the CBDC interest rate is Z_t, then the interest rate pricing equation is as follows.

$$R_{d,t} = R_t + Z_t, \tag{49}$$

where the risk premium Z_t follows the process of $\log Z_t = \rho_Z \log Z_{t-1} + \varepsilon_{Z,t}$.

3.6. Government

The government expenditure satisfies the following relation.

$$g_t = \varsigma_t y_t, \tag{50}$$

where ς_t is the proportion of government expenditure in output, subject to the following stochastic process.

$$\log \varsigma_t = \rho_\varsigma \log \varsigma_{t-1} + \varepsilon_{\varsigma,t}, \tag{51}$$

where $|\rho_\varsigma| < 1$, $\varepsilon_{\varsigma,t} \sim N(0, \sigma_\varsigma^2)$.

The government's revenue comes mainly from taxation, that is:

$$g_t = tax_t. \tag{52}$$

3.7. Market clearing

When the market reaches equilibrium, it will satisfy the following condition.

$$y_t = c_t + inv_t + g_t + \frac{k_t}{\psi_t}\left(\gamma_1(\varphi_t - 1) + \frac{\gamma_2}{2}(\varphi_t - 1)^2\right) + \theta\varpi_t + \vartheta\frac{d_t}{h_t}. \tag{53}$$

4. Parameter calibration

In this section, we estimated the parameters by calibration. First, the endogenous variables in the DSGE model have few observable values and short sample time series. The parameter values calibrated according to the references have clearer economic meaning and stronger feasibility, which can improve the robustness of model estimation results. Second, we can better simulate the real macroeconomic environment by directly assigning values to some parameters.

β is the discount factor of households, which is set as 0.993 based on the relevant research of Brzoza-Brzezina et al. (2018). According to Chetty et al. (2011) and Sims and Wu (2021), we calibrated the inverse of labor supply's Frisch elasticity δ_l to 1. The inverse of money demand's interest rate elasticity δ_{dc} and the investment adjustment coefficient ν are both 2. χ_l is the contribution of labor to household utility, which is calibrated to 1 based on Huang et al. (2021). According to the actual macro data, the contribution of CBDC balance χ_{dc} to household utility is taken as 0.012; The capital utilization parameter γ_2 and capital depreciation rate η are calibrated to 0.01 and 0.025 (Hodbod et al., 2020), respectively. The salary adjustment parameter φ_W and the price adjustment parameter φ_P are both 0.75 (Yin et al., 2022). We set the demand elasticity of intermediate products κ and the output elasticity of capital μ to be 6 and 0.333, respectively, which is consistent with the study of Ulate (2021). ρ_A represents the autoregressive coefficient of a production technology shock, which is set to 0.89 according to the research of Nückles (2020), and the autoregressive coefficient of other shocks is set to 0.9. Combined with the public data of the Chinese Bank, the commercial bank loan business cost parameter θ and risk management capability coefficient ϑ are calibrated to 0.006 and 0.2, respectively. The interest rate smoothing parameter ρ_R, the Taylor formula inflation parameter ξ_π, and the Taylor formula output parameter ξ_Y are calibrated to 0.8, 3.5, and 0.2, respectively, consistent with Ulate (2021). In addition, the standard deviations of exogenous shocks are all set to 0.01. The specific calibration results of the model parameters are shown in Table 4.

5. Results analysis

Based on the above calibration and estimation, this section further discusses the impact of uncertainty shock on the macroeconomy and the effectiveness of CBDC-based NIRP. First, we applied a negative production technology shock to test the model's applicability. Then we compared the impulse response of the main variables with other existing literature, thereby analyzing the extent to which the model reflects the real economy.

5.1. Model applicability analysis

Fig. 3 shows the impulse response of primary variables in the model affected by a one-unit negative production technology shock. Fig. 4 shows the sensitivity analysis results of negative production technology shock.

We found that the total output of firms is directly affected and significantly declines with the reduction of production technology level, which indirectly leads to a decrease in wages paid to employees. For the representative household, decreasing wage income limits household members' consumption and investment and causes the unemployment rate to rise. The government tightens monetary policy and reduces spending to lower aggregate demand in response to a rise in inflation caused by the shock. In addition, banks also raise interest rates accordingly. There is a cyclical exchange between inflation and deflation (Stock and Watson, 2020). In the later stage, with the declining wages and the rising unemployment (Rhee and Song, 2020), the decreases in consumption willingness and production investment are more significant than the decrease in output, which affects the decline of prices and causes deflation (Harding et al., 2022). To further test the robustness of impulse response results, the sensitivity analysis results of the main variables in the model are shown in Fig. 4 after the magnitude of negative production technology shock fluctuates by 15%. With the increase of negative production technology shock, its negative effects on output, employee wage, household consumption and investment, government expenditure, and medium and long-term inflation rate gradually increase. The positive impact on deposits and the initial inflation rate have also steadily increased.

Table 4
Calibration results of model parameters.

Department	Parameter	Calibration value	Economic significance
Households	$\in_w$	11	The elasticity of substitution between heterogeneous labor
	β	0.993	Discount factor
	α	0.7	Consumption habit coefficient
	δ_l	1	The inverse of labor supply's Frisch elasticity
	δ_{dc}	2	The inverse of money demand's interest rate elasticity
	χ_l	1	The contribution of labor to household utility
	χ_{dc}	0.012	The contribution of actual CBDC balance to household utility
	γ_2	0.01	Capital utilization parameter
	ρ_ψ	0.9	The autoregressive coefficient of the uncertainty shock
	σ_ψ	0.01	The standard deviation of the uncertainty shock
	η	0.025	Capital depreciation rate
	ν	2	Investment adjustment coefficient
	φ_w	0.75	Wage adjustment parameter
Final product firms	κ	6	The demand elasticity of intermediate products
Intermediate product firms	μ	0.333	The output elasticity of capital
	ρ_A	0.89	The autoregressive coefficient of production technology shock
	σ_A	0.01	The standard deviation of production technology shock
	φ_P	0.75	The price adjustment parameter
Commercial banks	θ	0.006	The loan business cost parameter
	ϑ	0.2	The risk management capability coefficient
Central bank	ρ_R	0.8	The interest rate smoothing parameter
	σ_R	0.01	The standard deviation of CBDC interest rate shock
	ξ_π	3.5	Taylor formula inflation parameter
	ξ_Y	0.2	Taylor formula output parameter
	ρ_Z	0.9	The autoregressive coefficient of risk premium shock
	σ_Z	0.01	The standard deviation of risk premium shock
Government	ρ_ς	0.9	The autoregressive coefficients of government expenditure shock
	σ_ς	0.01	The standard deviation of government expenditure shock

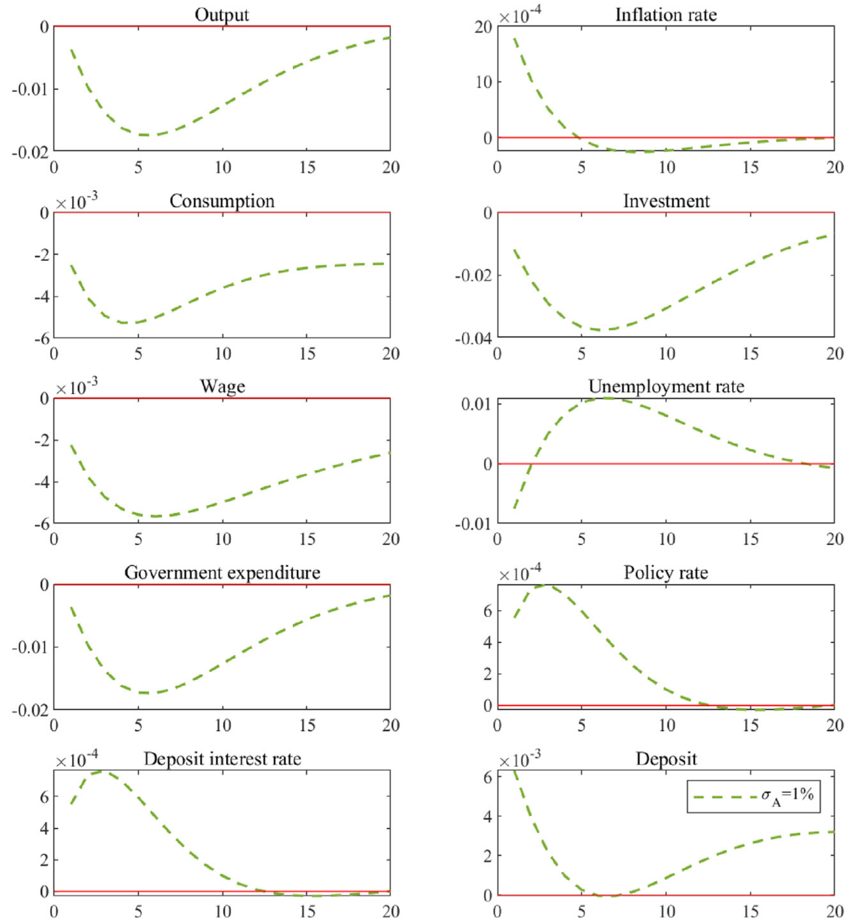

Fig. 3. Impulse response of negative production technology shock.

From the performance of the main variables in Figs. 3 and 4, the DSGE model constructed in this study better fits the actual data. Moreover, the findings are consistent with the study by Xiao et al. (2018) and Lang and Yang (2019), they showed that the model is applicable and robust.

5.2. The effect of an economic uncertainty shock

5.2.1. Impulse response of an economic uncertainty shock

Fig. 5 shows the impulse response of the main variables affected by an economic uncertainty shock, and the shock magnitude is 1% of ψ in the steady state.

When there is an uncertainty risk, residents' investment is significantly reduced, and residents' consumption increases rapidly in a short period and then gradually enters a state of reduction. We considered that residents panic in the initial stage of an economic uncertainty shock, resulting in many hoarding and irrational consumption behaviors. The firms' output has decreased dramatically due to investment and consumption constraints. The employee wages have also been reduced accordingly, which has led to an increase in unemployment to a certain extent. The inflation rate has risen and then fallen, which means the economy has fallen into short-term stagflation and long-term deflation. It is consistent with the study of Zhang et al. (2021) and fits the specific fact that China's economy first entered a state of stagflation and then turned into deflation after the COVID-19 outbreak. The government adopted austerity policies and significantly reduced fiscal expenditures in response to the economic fluctuations caused by an uncertainty shock. In addition, banks also lowered interest rates accordingly, resulting in a substantial reduction in short periods and a gradual increase of long periods in loan scale as the economy recovers.

To further test the robustness of impulse response results, we made a sensitivity analysis of economic uncertainty shock. Specifically, we made the negative uncertainty shock fluctuate by 15%. The impulse response is shown in Fig. 6. As the negative uncertainty shock increases, its negative effects on manufacturer output, employee wage, household investment,

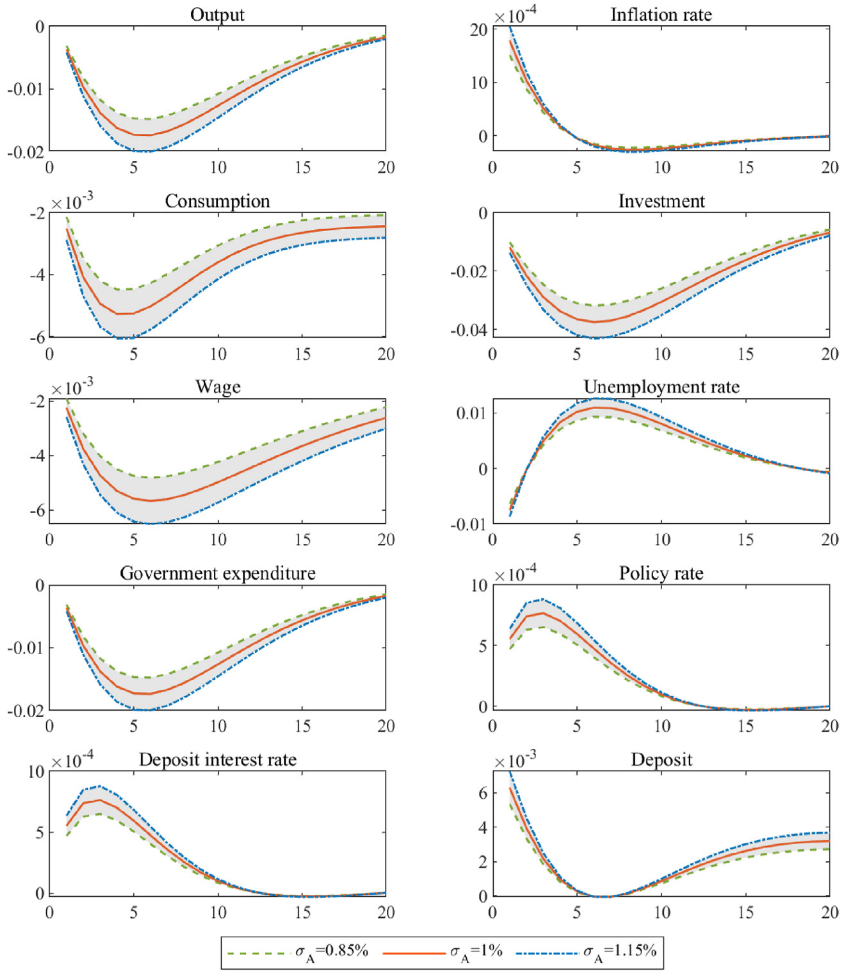

Fig. 4. Sensitivity analysis results of negative production technology shock.

government expenditure, policy interest rate, deposit interest rate, long-term consumption and loan scale, and medium to long term inflation rate gradually increase. The positive effects on the scale of a long-term loan, short-term consumption, and inflation gradually also increase.

5.2.2. The impact mechanism of an economic uncertainty shock

When the economy suffers from an uncertainty shock, inflation rises and then falls, which means the economy has gone through a process from stagflation to deflation. What are the reasons and internal mechanisms of short-term stagflation and long-term deflation caused by uncertainty? Next, we analyzed the influencing mechanisms from two aspects: firm price adjustment and resident wage adjustment.

To analyze the role of firm price adjustment in the uncertainty's impact on the macroeconomy, we simulated the impulse response of an uncertainty shock when the price stickiness coefficient is 0.35 and 0.75, respectively. Two impulse response curves for inflation rates with different price stickiness intersect, as shown in Fig. 7. Stagflation refers to the economic phenomenon in which economic stagnation, high inflation, unemployment, and depression coexist (Bruno and Sachs, 1985). High inflation is caused by increasing consumption, decreasing output, increasing prices, etc. Economic stagnation is caused by increasing unemployment and decreasing wages, etc. Before the two curves intersect, the impulse response of inflation at high price stickiness is below that at low price stickiness. It indicates that as price stickiness increases, the effect of uncertainty on raising the inflationary effect becomes weaker, and the stagflation effect decreases. The reason is that price stickiness amplifies the inflation-reducing effect of insufficient effective demand caused by economic stagnation. In the medium to long term, the impulse response curve of inflation at high price stickiness is above that at low price stickiness. In summary, the price adjustment mechanism is not the reason for short-term stagflation and long-term deflation after an economic uncertainty shock. Otherwise, inflation would be higher in the beginning after the increase in price viscosity, and the deflationary effect would be more pronounced in the long run.

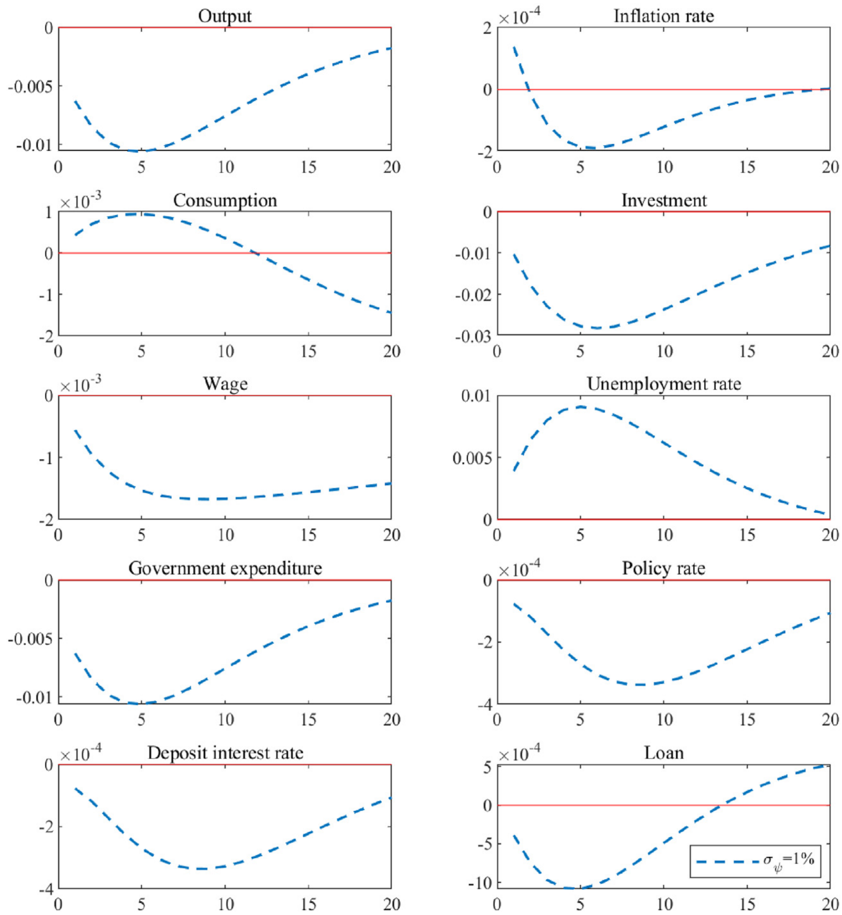

Fig. 5. Impulse response of economic uncertainty shock.

To verify the role of household wage adjustment in the uncertainty's impact on the macroeconomy, Fig. 8 further simulates the impulse response of an uncertainty shock when the wage stickiness coefficient is 0.35 and 0.75, respectively. Unlike price stickiness, the impulse response curve of inflation with high wage stickiness crosses the impulse response curve of inflation with low wage stickiness. The inflation rate is higher at the beginning. The deflationary effect is also more pronounced in the long run. In addition, after an uncertainty shock, the unemployment rate rises with the increase in wage stickiness, leading to a shortage of aggregate demand and deflating the economy. However, the mechanism of wage stickiness also plays a crucial role in economic recovery. The wage stickiness makes the market wage lower than the equilibrium wage in the recovery stage, thus speeding up the process of economic recovery. The short-term stagflation after an economic uncertainty shock is mainly caused by resident wage adjustment. The long-term deflation is due to the decline in effective demand caused by unemployment risk (Basu and Bundick, 2017).

5.3. The macroeconomic effect of a CBDC interest rate shock

The preceding provides a suitable economic environment for simulating NIRP by introducing an uncertainty shock into the model. To further explore the effectiveness of CBDC-based NIRP, we adjusted the CBDC interest rate to a negative value. Then we added a one-unit negative CBDC interest rate shock to the model and analyzed its impact on the macroeconomy by observing the impulse response results. In addition, banks cannot cut deposit rates negatively due to the ZLB constraint. Therefore, we constructed a model with a ZLB constraint on deposit rate to compare with the benchmark model, which can better understand the transmission mechanism of CBDC-based NIRP affecting the macroeconomy. Specifically, referring to Guerrieri and Iacoviello (2015), we constructed a model targeting interest rates for a limited period. The deposit interest rate remains at zero in the first 20 periods and follows the classical Taylor rule after the end of 20 periods. Fig. 9 compares the impulse response of CBDC interest rate shock in the presence and absence of the ZLB constraint, represented by ZLB and No ZLB, respectively.

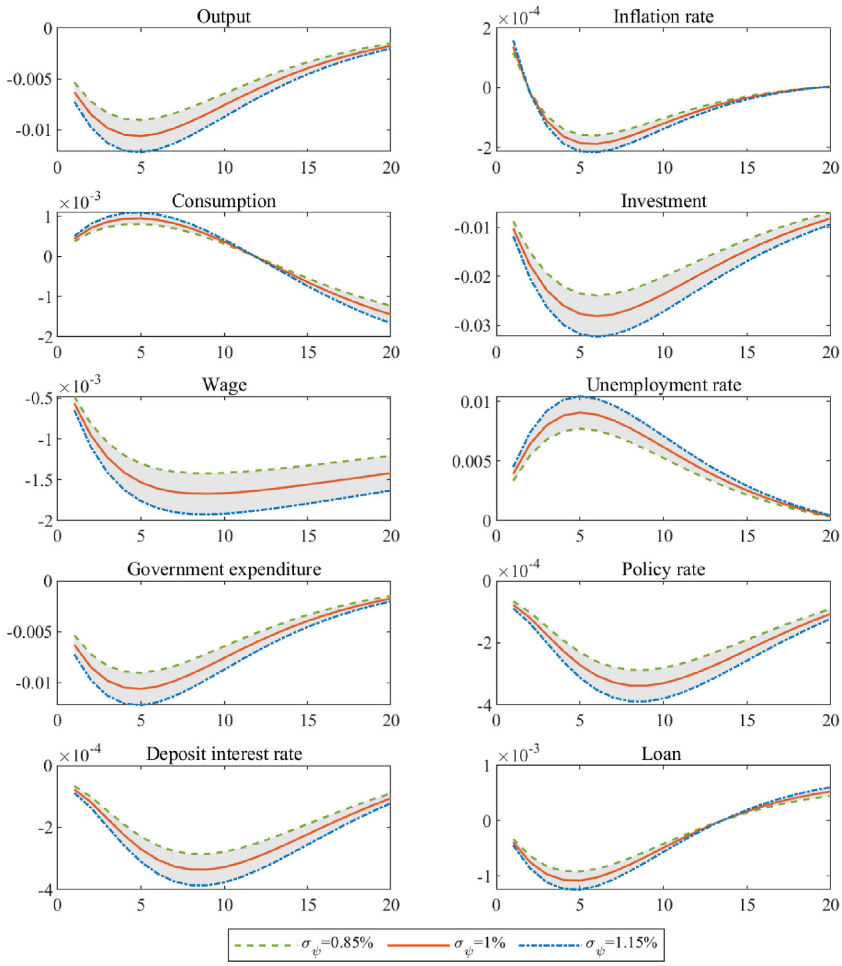

Fig. 6. Sensitivity analysis results of economic uncertainty shock.

As shown in Fig. 9, the consumption and investment of residents have increased rapidly after the implementation of CBDC-based NIRP. Meanwhile, banks expand their loan scale, which solves the problem of banks reluctant to lend. The financing cost of firms has been dramatically reduced, and the output scale has been continuously expanded with the increasing consumption and investment demand of residents, which leads to the increase in employee wages and the consequent reduction of the unemployment rate. The fiscal expenditure of the government increases, and the inflation rate increases accordingly, which alleviates the short-term stagflation and long-term deflation caused by the adjustment of the resident wage after an uncertainty shock, and the economic recovery shows apparent signs. However, it should be noted that the reduction of deposit interest rate may lead to the crowding out effect of CBDC on bank deposits.

Compared to NIRP under cash (ZLB), small increases in output, investment, and wages under CBDC (No ZLB) would boost the economy and financial stability. Moreover, NIRP under CBDC (No ZLB) restrains a sharp unemployment decline, preventing economic turbulence. Therefore, NIRP under CBDC (No ZLB) effectively smooths the fluctuations of macroeconomic variables and is more conducive to financial stability and economic development. In addition, it plays a vital role in stabilizing the production and operation activities of the real economy (such as banks and firms), which is more conducive to reviving market confidence and promoting economic recovery.

To further test the robustness of CBDC-based NIRP's effectiveness, we conducted a sensitivity analysis of CBDC interest rate shock in the benchmark model. Specifically, we imposed the negative CBDC interest rate shock fluctuation by 15% and obtained the impulse response of the main variables, as shown in Fig. 10. With the increase of CBDC interest rate shock, its positive effects on output, inflation rate, household consumption and investment, employee wage, government expenditure, and loan scale gradually increase. Its negative impacts on the unemployment rate and deposit interest rate increase progressively. Therefore, NIRP based on CBDC can eliminate the ZLB constraint of traditional cash deposit interest rate, effectively alleviate the negative impact of uncertainty shock on the economy, re-boost market confidence, and play a crucial role in accelerating the real economic recovery.

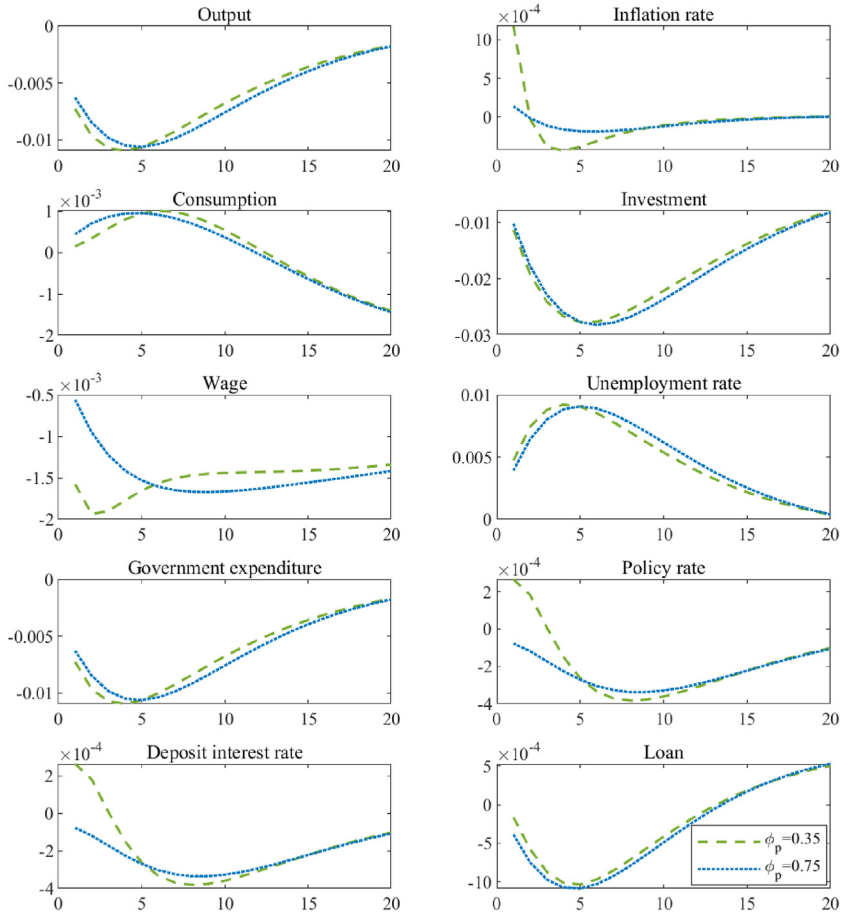

Fig. 7. Impulse response of main variables with different price stickiness.

6. Conclusions

6.1. Main findings

Based on the mainstream economic models, this study establishes a DSGE model including households, final and intermediate product firms, commercial banks, the central bank, and government departments, which aims to analyze the impact of economic uncertainty and the effectiveness of CBDC-based NIRP. In addition, we introduced price stickiness and wage stickiness into the model to explore the impact mechanisms of economic uncertainty. The main conclusions of this study are as follows.

First, the uncertainty shock significantly negatively impacts the macroeconomy. It has substantially reduced investment, output, wages, and loans, increasing unemployment risks. In the short term, it has also triggered impulsive consumption by households, while consumption falls into a slump in the long run. The government has sharply reduced fiscal spending, banks have cut interest rates, and the amount of loans has been sharply decreased and then gradually increased as the economy recovers.

Second, after suffering an uncertainty shock, the economy enters short-term stagflation and long-term deflation. The short-term stagflation is mainly caused by resident wage adjustment, and the long-term deflation is due to the decline in effective demand caused by unemployment risk. However, the mechanism of wage stickiness also plays a crucial role in economic recovery, which makes the market wage lower than the equilibrium wage in the recovery stage, thus speeding up the process of economic recovery.

Third, CBDC can eliminate the ZLB constraint, thereby improving the effectiveness of NIRP. Compared with traditional currency, CBDC-based NIRP can more effectively alleviate the negative impact of economic uncertainty and smooth macroeconomic fluctuations, which is more conducive to restoring market confidence and promoting economic recovery.

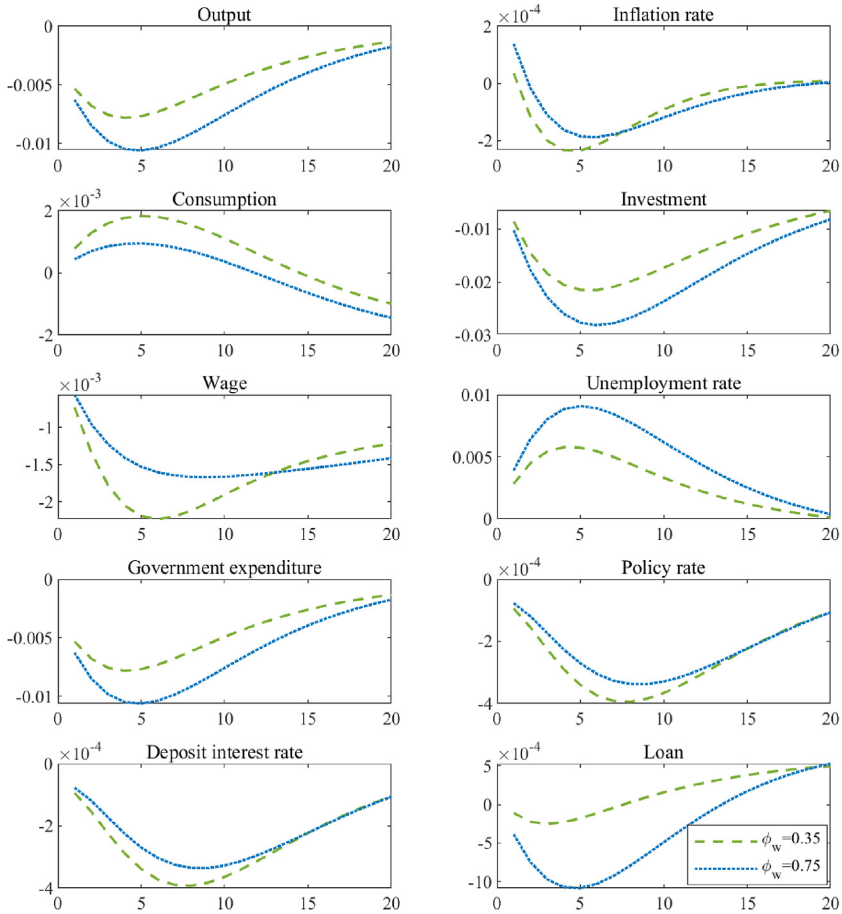

Fig. 8. Impulse response of main variables with different wage stickiness.

6.2. Theoretical implications

This study analyzed the relationship between economic uncertainty, digital currency, and NIRP, which has significant theoretical implications in different aspects:

First, this study innovatively expands and refines the macroeconomic impact of an uncertainty shock. Existing research has not reached a unified opinion on the economic state after uncertainty shocks. However, our research shows that the inflation rate rises rapidly after the uncertainty shock, and the economy falls into stagflation in the short term and turns to deflation in the long time, which is consistent with the short-term upward trend of China's inflation since February 2020 after the COVID-19 pandemic (Zhang et al., 2021).

Second, this study enriches the impact mechanisms of economic uncertainty shocks. Existing studies rarely mention the role of resident wage adjustments and unemployment risks in the impact of economic uncertainty shocks. We introduced a stickiness mechanism to focus on its role in influencing inflation when subjected to an economic uncertainty shock.

Third, this study promotes the development of theories related to negative interest rates. There is limited research on negative interest rates and even less research in combination with CBDC. Moreover, most studies are restricted to theoretical analysis, and few scholars use model deduction and empirical simulation to clarify the problem. We constructed a DSGE model for policy analysis, which provides a reference for implementing and improving NIRP.

6.3. Practical implications

This study has great practical significance for the response to economic uncertainty and the implementation of CBDC-based NIRP, and its actual impact is reflected in the following aspects.

6.3.1. Government

It is necessary to establish a sound policy system to prevent uncertain risks. On the one hand, the government should learn from the fruitful practical experience of NIRP in various countries to enrich the monetary policy toolbox for emergencies. On

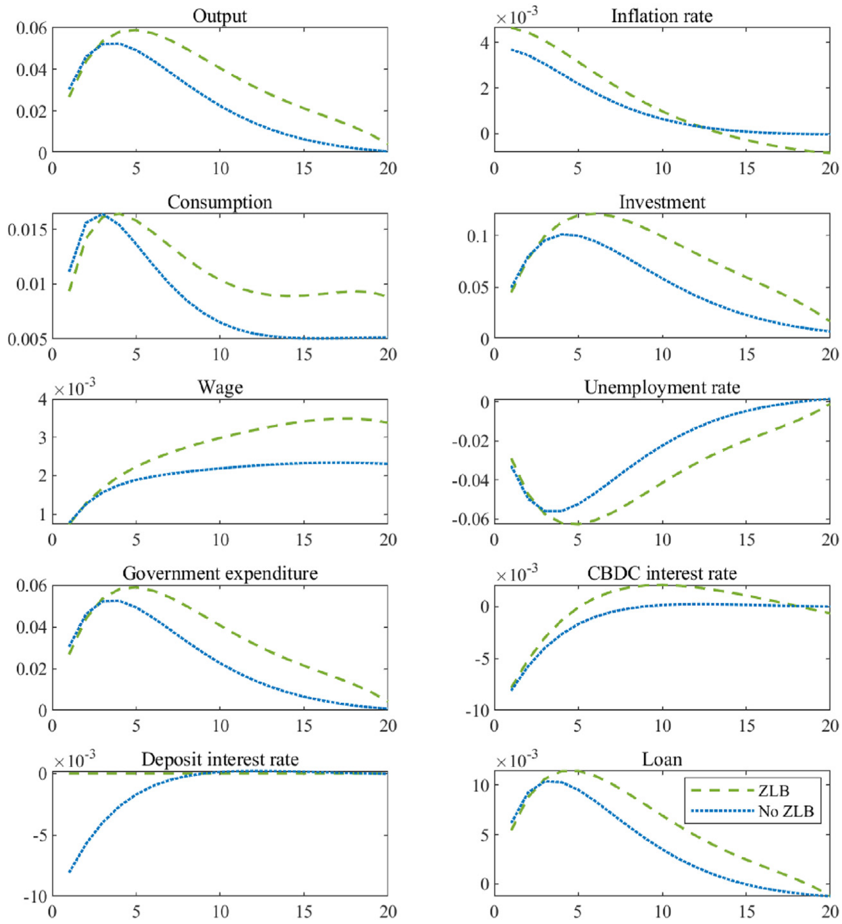

Fig. 9. Impulse response of CBDC interest rate shock.

the other hand, we had better adhere to a prudent monetary policy with a cautious attitude and awareness of risk prevention and should not blindly follow suit.

6.3.2. Central bank

The central bank had better accelerate the CBDC construction and improve the effectiveness of monetary policy through precise and targeted regulation of CBDC. In addition, the central bank can combine conventional and unconventional monetary policies to stabilize the confidence of market players and reduce the negative impact of economic uncertainty shock.

6.3.3. Commercial banks

When confronted with the uncertainty shock, commercial banks had better cooperate with the relevant policies of the government and the central bank, such as timely reduction of reserve ratio and interest rate to solve the problems of firms' reluctance to lend and financing difficulties. We can achieve economic recovery by stimulating production, investment, and consumption.

6.3.4. Firms

The economy will fall into stagflation due to the adjustment of resident wages after an economic uncertainty shock. Firms should cooperate with the government and banks to solve the reluctance to lend and financing difficulties and reduce the motivation for wage adjustment through the wage decision-making mechanism to stabilize inflation.

6.3.5. Households

On the one hand, households should plan long-term wages and dividend income, thereby improving the ability to resist uncertainty risks. On the other hand, it is indispensable for households to consume and invest prudently when facing an economic uncertainty shock.

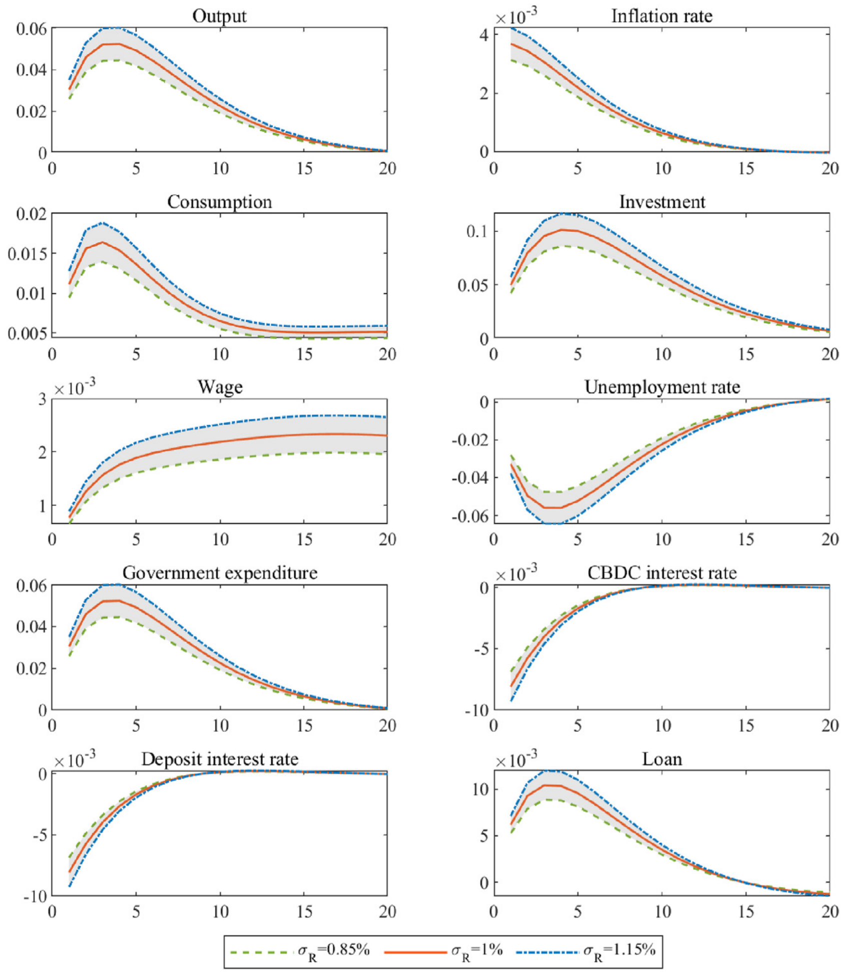

Fig. 10. Sensitivity analysis results of CBDC interest rate shock.

6.4. Future work

Our study still has many deficiencies, which need to be continuously improved in the future. First, we can consider the economic effects of other uncertainty shocks, such as economic policy uncertainty, price uncertainty, etc. Second, this study analyzed the mechanism of an economic uncertainty shock on inflation. In the future, we can explore how uncertainty affects other economic variables such as output, consumption, and investment. Third, the study of related issues is not limited to a DSGE model. We can use other economic models to analyze our research question, such as a computable general equilibrium (CGE) model (Du et al., 2020) and a rational expectations (RE) model.

Consent

All authors have approved the manuscript.

Data availability

Data are available on request.

Data transparency

All data support published claims.

CRediT authorship contribution statement

Baogui Xin: Conceptualisation, Methodology, Investigation, Writing-review & editing, Supervision, Validation, Resources. **Kai Jiang:** Methodology, Formal analysis, Software, Data processing, Writing-original draft, Investigation.

Declaration of competing interest

The authors have no interests to disclose.

Acknowledgments

This work was supported by the National Planning Office of Philosophy and Social Science of China (Grant No. 21BJY206).

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