Central bank digital currencies in open economies: A new Keynesian DSGE approach

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CENTRAL BANK DIGITAL CURRENCIES IN OPEN ECONOMIES: A NEW KEYNESIAN DSGE APPROACH

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"We'd rather have Stanley Fischer than a DSGE model, but we'd rather have Stanley Fischer with a DSGE model than without one."

Christiano et al. (2018)

1. Acknowledgement

First I would like to sincerely thank **Dr. Thomas Lejeune** for agreeing to supervise my research thesis as well as my internship report, and whose expertise, help and guidance, both academically and professionally, have been invaluable. Your insightful feedback pushed me to sharpen my thinking and brought my work to higher levels.

In addition, I am keen to express my deepest gratitude to my readers, **Dr. Pierrick Clerc** and **Dr. Markus Kontny**, for their time and expertise. Dr. Clerc has shown himself available, flexible and thoughtful, especially in light of a tight schedule. In addition, I would like to single out Dr. Kontny who taught me the necessary foundations and provided me with opportunities to develop a hands-on understanding of, and experience with DSGE models.

I would also like to acknowledge my ex-colleagues from the European Commission for their wonderful collaboration on central bank digital currencies. More specifically, it is with a great sense of pleasure that I would like to personally thank my former mentor, **Mr. László Butt**, for his flexibility, numerous in-depth explanations and for sharing his expertise on the topic.

It is with great gratitude that I acknowledge the help and support of these dear individuals. At last, I am indebted to my beloved parents and friends for their sympathetic ear.

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List of Abbreviations

AD	Aggregate Demand curve.
AS	Aggregate Supply curve.
BIS	Bank for International Settlements.
CBDC	Central Bank Digital Currencies.
CES	Constant Elasticity of Substitution.
CPI	Consumer Price Index.
DSGE	Dynamic Stochastic General Equilibrium.
ECB	European Central Bank.
ELB	Effective Lower Bound.
Fed	Federal Reserve Bank.
GDP	Gross Domestic Product.
IMF	International Monetary Fund.
IRF	Impulse Response Function.
LRAS	Long-Run Aggregate Supply curve.
NK	New Keynesian.
QE	Quantitative Easing.
SOE	Small Open economy.
SR	Sveriges Riksbank.
SRAS	Short-Run Aggregate Supply curve.
TEM	Two-Economy Model.
TFP	Total Factor Productivity.

2. Preface

In partial fulfillment of the graduation requirements for my Dual Master's degree in Economics with specialisation Macroeconomics and Finance at HEC Liège | University of Liège and Universität Hohenheim, I was enthusiastically engaged in researching and writing this research Thesis from May 3^{rd} 2022 to June 22^{nd} 2022 for which I would like to make a few preliminary remarks about the research topic developed in this work.

The topic of central bank digital currencies came first in the limelight when exchanging with **Prof. Dr. Michael P. Evers**, which was my academic mentor during the academic year 2020-2021. His state-of-the-art interest in research arose my curiosity for the topic, which led to a growing and exponential passion. Nonetheless, my blooming interest falls short at keeping up with this nascent and transdisciplinary field, advancing at lightning speed. Far from being understood, CBDCs are unquestionably a multidisciplinary theme, and locates at the crossing of monetary economics, politics, technology and finance among others. In addition, this work demanded a thorough understanding of its economic and financial intricacies as well as sound modelling skills, in particular related to MATLAB and DYNARE.

This topic is extremely technical and challenging provided its intrinsic novelty within scientific literature notwithstanding the fact that DSGE models do not easily lend themselves to analysing effects from CBDCs. In that light, I am keen to bring my current knowledge developed throughout years of personal analyses, academic experience and policy drafting know-how to the forefront of the ongoing and exciting research.

Finally, I wanted to emphasize the importance of conducting research as it contributes to the backbone of tomorrow's future policy decisions regarding central bank digital currencies.

I hope you enjoy reading it as much as I enjoyed writing it!

Maxime Polis

3. Introduction

Interest from central banks, international financial institutions, academics and regulators alike around Central Bank Digital Currencies (CBDC) is growing considerably in recent years. The Bank for International Settlements (BIS) estimated in May 2022 that nine out of ten central banks worldwide are engaging with CBDCs although their stage of maturity - research, development, pilot or launch - depends greatly on the country (BIS (2022b)). The International Monetary Fund (IMF) estimated that over 100 countries representing more than 95 percent of global Gross Domestic Product (GDP) are exploring CBDCs with already 10 countries having already fully launched a digital currency and more than half are developing or running concrete experiments. In addition, over two thirds of central banks are considering launching a CBDC in the short or medium term (IMF (2022)). In parallel, many countries are exploring alternative international payment systems whereby CBDCs would become ideally fully interoperable. Furthermore, the BIS envisioned CBDCs - retail and wholesale - to represent a key branch of the future monetary system which will "help to make money and payments fit for the decades to come" (BIS (2022a)).[1] Central bank money becomes the scaffolding of a diverse and multi-layered ecosystem of actors and nodes where the payment service providers will be able to exploit the technological convenience of CBDCs, and turn their ingenuity and imagination into virtuous added-value services for consumers.[2] In such a world, CBDCs harness and build upon new capabilities such as programmability, composability and tokenisation.

In short, a CBDC is defined as "a digital payment instrument, denominated in the national unit of account, that is a direct liability of the central bank" (Group of Central Banks (2020)), thus benefiting from the intrinsic credit risk-free characteristic of central bank money. The European Central Bank (ECB) makes the distinction between a retail CBDC, being a central bank liability issued in digital form for use by the general public (e.g. citizens, businesses and government entities), and a wholesale CBDC that is only of use by eligible entities (e.g. financial intermediaries) for wholesale payments (ECB (2022)).[3] It is further argued that the plumbing behind wholesale CBDCs and central bank reserves operates in a similar fashion, the real revolution is expected to come from the retail side, thereby challenging cash's monopoly as central bank money available to the general public (BIS (2021a)). While this idea was evidently emitted decades ago by James Tobin, which suggested the Federal Reserve Bank (Fed) to make widely accessible a "medium with convenience of deposits and safety of currency", technological possibilities were then admittedly more limited, rendering this idea noble and purely hypothetical at the time (Tobin (1987)).

While coins and banknotes have all been innovations of their own day (Giannini (2011)), it is hard to imagine that their underlying technology is eternal in an increasingly digitalising world where the role of cash is declining. CBDCs are expected to update central bank money supplied to citizens, i.e. coins and banknotes, which underlying technology dates back to the 17^{th} century when the Bank of Amsterdam began issuing bills to merchants against cash deposits (Quinn and Roberds (2006)). Although

[1] See Figure (D.1).
[2] Such use cases would e.g. increase the instantaneous availability of funds domestically and internationally, streamline its reconciliation, foster digital innovation etc.
[3] See Figure (D.2) .

great heterogeneity prevails between advanced and emerging economies, several drivers are leading amongst the key explanations behind this unprecedented surge in attitude from central bankers, i.e. the increasing reliance on digital means of payment, the declining role of cash, especially in advanced economies where the COVID-19 pandemic is said to have accelerated this trend, and the emergence of stablecoins and cryptocurrencies which pose risks to financial stability (BIS (2021b)). The burgeoning interest behind CBDCs is also being motivated by the wide array of arguments in its favour ranging from maintaining the monetary anchor and the access to a credit risk-free medium of exchange, to preventing illicit payments and fostering monetary policy among others (Bindseil (2022)).

Despite the seemingly clear and luminous potential of retail CBDCs, academicians and central bankers remain curious and cautious, often endorsing a so-called "staggered approach". Depending on its precise design features, CBDCs could prompt changes in the demand for bank deposits, with likely knock-on consequences for bank lending and resilience of the banking sector. By inducing bank disintermediation, fears are that CBDCs could become a source of financial disruption, altering the transmission of monetary policy and impacting adversely financial stability. Provided that commercial banks rely on deposits to fund their credit allocation, seamless conversion from risky bank deposits to credit risk-free retail CBDCs is expected to lead, *ceteris paribus*, to a deterioration of loan volume, investment and bank profitability among others (Group of Central Banks (2021)). Henceforth central bankers are studying the implications of safeguards such that retail CBDCs are *successful enough* to generate added-value for its users, but not *too successful* in order to avoid crowding out financial intermediation. For instance, quantitative limits on individual holdings and a two-tiered remuneration are often brought forward.[4]

With academic research on CBDCs at full steam, a growing consensus comes to the conclusion that financial stability risks could be manageable under various take-up scenario's (ECB (2022)). Yet, with no advanced economy having issued a CBDC, further research remains welcome on the implications for financial stability and monetary policy in open economies, presently still poorly understood. In this paper, we contribute to contemporaneous research in numerous ways. First, we review the cutting-edge arguments of CBDCs alongside three dimensions. In addition, we gap existing and prominent frameworks within two tractable New Keynesian (NK) Dynamic Stochastic General Equilibrium (DSGE) models including CBDC in a remarkable simplistic form, one for the Small Open economy (SOE) and one for the Two-Economy Model (TEM). Finally, we review the case of Sweden, which is on the verge of making History and constitutes a prime example to our TEM, and we present avenues for future work.

The remainder of the paper is organised as follows. Section 4 outlines a comprehensive and thorough stream of research in regard to financial and monetary implications of CBDCs. Section 5 introduces the baseline model and Section 6 considers its calibration. Section 7 present the results, and Section 8 examines the case of Sweden. Finally, Section 9 concludes.

[4]The two-tiered remuneration refers to the application of less attractive rates for larger holdings, thereby disincentivising remuneration above a certain threshold. (See Bindseil (2020).)

4. Related literature

This paper can be seen as complementary to the exciting literature on the financial and monetary implications of CBDCs which can intuitively be divided into three strands: (i) papers focusing on financial stability; (ii) papers focusing on monetary policy and its transmission; (iii) and papers embedding dynamic models (e.g. DSGE). Although it certainly does not cover the whole state of research, it provides the latest and most complete overview in light of financial and monetary implications. We will review sequentially each strand of literature in turn.

4.1. Financial Stability Implications

While often being overshadowed in academic debates, CBDCs could present numerous potential benefits for financial stability.

A recent study by Haldane (2021) argued that a widely-used digital currency would facilitate the division between the safe payment-based banking activities - narrow banking - and the risky credit-provision activities, thereby potentially reducing the fragility of the current banking system and thus improving financial stability. In addition, Keister and Monnet (2020) study how the introduction of CBDCs could become useful crisis management tools by monitoring the flow of funds - and hence information - into digital currency, in particular in order to alleviate markets before a banking crisis unravels. The authors evaluate that this additional information increases "the effectiveness of the central bank's regulatory policy and can thereby improve financial stability". This latest finding is being complemented by Kumhof and Noone (2021) which indicate that CBDCs could be of help in avoiding banking crises, contrary to the widely believed argument against CBDCs that it may trigger, or even exacerbate, a bank run. The arguments in favour are that it would ease bank resolution, diminish contagion effects of bank failures and limit *ex-ante* the risk for banks by holding higher capital buffer stocks (Bindseil (2022)).

On the grounds of competition, Andolfatto (2021) shows that the introduction of CBDCs is expected to lead to greater levels of competition within the existing monopolistic deposit market, thereby improving prices (deposit rates) and services for consumers with little effects on intermediation. In a similar vein, Chiu et al. (2019a) who also study the impact of CBDCs on bank lending, go beyond Andolfatto (2018) in the sense that they analyse the case where banks are allowed to hold CBDCs to meet their reserve requirements. In doing so, and calibrating their model to the U.S., Chiu et al. (2019b) found that providing a viable outside option to depositors increase lending and investment by as much as 7 percent if a properly remuneration rate (on CBDCs) is chosen. This surprising "crowd-in effect" on bank intermediation nonetheless comes at the cost of a floor on deposit rates, eroding banks' monopoly profits and inciting them to increase lending.

Brunnermeier and Niepelt (2019) argue that the presumed downsides of bank disintermediation - and hence financial stability - would fully depend on the monetary policy following the introduction of CBDCs and on the commitment and credibility of the central bank to act as a lender of last resort. Accompanied by strong commitment, a natural substitution between commercial bank funding (i.e. bank deposits) and central bank funding would arise as a consequence of the introduction of CBDCs on competition.

However, ongoing debates are legitimately more verbal when it comes to the possible and serious risks to financial intermediation, especially so in times of crisis where CBDCs could become more attractive *relative* to bank deposits. The most sensitive argument is that CBDCs could crowd out bank deposits, especially if left unconstrained (Group of Central Banks (2021)).

Piazzesi and Schneider (2022) explore this avenue and study the welfare effects of introducing a CBDC with a focus on the modern payment systems. The main result is that "even if a central bank that is better at producing deposits than the private sector, it need not improve welfare since it interferes with commercial banks' ability to cheaply provide credit lines funded with deposits". In other words, CBDCs could make funding more volatile and costly, reduce lending and bank profitability.

Subsequent research from Fernandez-Villaverde et al. (2021) feed into this lively debate with their study based on the benchmark Diamond and Dybvig (1983) model for bank runs and liquidity crises. During times of distress, the rigidity of the central bank's contract with the investment banks has the capacity to deter runs, providing central banks a more stable image than the commercial banking sector. Depositors will internalize this feature *ex-ante* and the central bank will arise as deposit monopolist, drawing all deposits away from the commercial banking sector, thereby threatening the maturity transformation function. Within the Diamond and Dybvig (1983) model, Fernandez-Villaverde et al. (2020) had already studied the CBDC trilemma that central bank would face whereby a socially efficient solution, i.e. price stability and financial stability, cannot be simultaneously achieved. Popescu (2022) pushed this frontier of research in the case of cross-border CBDCs and capital flows in a similar setting for bank runs augmented by its SOE dimension. Importantly, an account-based, and interest bearing CBDC is made available to non-residents. Their findings are closely related to Fernandez-Villaverde et al. (2021) to the extent that a foreign CBDC would emerge as an international safe asset with likely contagion effects to financial stability in the domestic banking sector, leading to greater, and more volatile capital flows.

Kumhof and Noone (2021) nuance their optimistic findings by emphasizing that CBDCs, as safe asset, could potentially be held in large volumes, and that in the absence of safeguards, "digital bank runs" could be self-fulfilling, driving savers to increase CBDC holdings at the expense of bank deposits, thereby deepening volatility and distress. Finally, Cecchetti and Schoenholtz (2017) doubt about the ability for the central bank to act efficiently at the retail level and its potential for cost savings. Their primary concern is that CBDCs could promote financial instability since it offers a quickly accessible "flight-to-safety" instrument.

4.2. Monetary Policy Implications

Research on the effects of CBDCs on monetary policy proves to be far less understood. In the vein of the financial stability debate, findings often contrast within literature: on the one hand, CBDCs could impair the transmission of monetary policy, especially in the absence of safeguards, and on the other hand, CBDCs could actually strengthen and speed up monetary policy transmission.

Left unconstrained, CBDCs would allegedly alter the funding structure of banks, with serious implications for financing conditions. Garratt et al. (2022) explore its effects through heterogeneous commercial banks. The authors focus solely on two design features, namely the interest rate ("store of value") and the payment convenience ("medium of exchange"), where it is argued that a trade-off arises. On the one hand, raising interest rates would enhance monetary policy but at the cost of negative consequences on market composition and, on the other hand, raising its convenience value fosters equal opportunities for competition between banks, but weakens the transmission of monetary policy. Surprisingly, it is only if CBDCs have a high convenience value that the transmission could be strengthened. The magnitude of the effects all depends on the effective take-up of the "store of value" and "medium of exchange" features, and the effects are different according to the size of banks.

Jiang and Zhu (2021) study how CBDCs, as perfect substitute for bank deposits, can affect the pass-through of the traditional monetary policy instrument. The new policy instrument, the CBDC remuneration rate, and its accompanying policy both affect the demand for CBDC holdings and bank deposits. For instance, digital currencies tend to "weaken the pass-through of the interest on reserves", especially if the deposit market is not in full competition, whilst the CBDC remuneration rate has a stronger pass-through to the loan market. Coordination between the CBDC remuneration rate and the interest rate for central bank reserves is required to achieve policy goals (e.g. boost lending with a higher CBDC rate *relative* to the reserve rate, *ceteris paribus*).

In addition, Böser and Gersbach (2020) consider the short and long run implications of CBDCs and monetary policy. In essence, central banks, fearing digital runs, enforces tighter collateral requirements and penalties to increase bankers' monitoring activities in light of CBDCs. While it leads to higher aggregate productivity in the short run, the preference for households to gradually shift bank deposits towards CBDCs steadily cause additinal liquidity risks for banks, which in turn "renders banking non-viable and prompt the central bank to abandon such policies." Ultimately, CBDCs are expected at best to generate short-term welfare gains.

In contrast, Meaning et al. (2021) investigate throughout a stylized model its potential impact on the monetary transmission mechanism and studied how CBDCs could affect its various stages, from markets for central bank money to the real economy. Their main finding presents that monetary policy would likely operate similarly as it currently does, i.e. piloting the economy by varying the policy rate. Despite great uncertainty, a potential consequence would be an improvement of the monetary policy toolkit.

Dyson and Hodgson (2016), Mancini-Griffoli et al. (2018) and Bindseil (2020), among others, go further and argue that CBDCs could be effective in providing substantial monetary stimulus during severe economic downturns, and in the absence of cash, the Effective Lower Bound (ELB) could be overcome and negative interest rates on CBDCs could be implemented as additional monetary policy instrument. The idea of "helicopter money" is also increasingly being discussed as its feasibility (and implementability) has improved, Dyson and Hodgson (2016) claim that it could become more effective than conventional monetary policy in the long run. Mancini-Griffoli et al. (2018) propose a conceptual framework regarding the transmission of monetary policy. While CBDCs are unlikely to significantly affect the main channels of monetary policy transmission, the classical interest rate channel and bank lending channel are expected to strengthen the transmission, while others are unlikely to be affected. The impact of CBDCs on the interest channel corresponds exactly to the focus of Kahn et al. (2022), which argued that its introduction within the payment landscape is unlikely to be of first-order importance in shaping economic activity in a country. Yet, this global innovation could come at the expense of changes in spreads between funding costs and lending rates, and the effects are deemed to be of greater magnitude if the monetary authority explicitly targets monetary aggregates.

To our knowledge, Fraschini et al. (2021) are the first to tackle the interactions of CBDCs with the monetary policy including both the standard policy and Quantitative Easing (QE). Surprisingly, they find that the economic effects differ according to the interaction between the current monetary policy and the type of CBDC launched: it can reduce lending under QE and be neutral under standard monetary policy. In addition, the timing of the introduction is important in the sense that its impact depends on the "amount of excess reserves" available while the central bank conducts QE. The larger the reserves, the smaller the impact up to a threshold where banks lose their cheap source of funding. In turn, to avoid such access to cheap funding, the central bank may decide to render the QE policy quasi-permanent.

Finally, Davoodalhosseini et al. (2020) acknowledge some of the above findings that CBDCs could allow monetary policy to break the ELB provided that cash is being fully supplanted by its digital ally. In addition, CBDCs could improve the effectiveness of monetary policy by "reducing the incentives to adopt alternative means of payment" such as cryptocurrencies which could, if widely adopted, imperil the central bank's ability to fulfill monetary policy objectives.

4.3. Dynamic Modelling

In absence of empirical data, dynamic modelling proves to be most effective to assess the impact of CBDCs on financial stability and monetary policy.

Pioneers in this endeavor are Barrdear and Kumhof (2021), who propose a DSGE model calibrated on pre-crisis U.S. data to study the macroeconomic implications of CBDCs. Under the assumption that the digital monies are exchanged at par with government debt, they found that issuance of CBDCs, against government bonds, would permanently raise GDP by as much as 3 percent, and improve the central bank's ability to stabilize the business cycle by giving policymakers access to a second macroeconomic and monetary policy tool which could either control the quantity or the price of CBDCs. Insofar the optimal quantity, Burlon et al. (2022) shed light among others on its welfare implications within a bank-based economy. While great uncertainty remains, their model recommends a "welfare-maximizing amount of CBDCs in circulation" to spread between 15 percent and 45 percent of quarterly real euro area GDP.

Gross and Schiller (2020) also developed a medium-sized New Keynesian DSGE model with a particular focus on the financial sector and the effects of interest- and non-interest-bearing CBDCs during times of financial distress at the ELB. The authors show the existence of a serious threat to financial stability: "CBDCs crowd out bank deposits." Nonetheless, this effect could be mitigated if the central bank compensates losses in deposits by providing additional central bank funds, or if it reduces the appeal for CBDC accumulation (e.g. in a crisis) through low CBDC remuneration rates as to counteract disintermediation.

Turning to the open-economy setting, George et al. (2020) study a small economy where bank deposits and CBDCs are assets competing, as media of exchange, with domestic and foreign bonds. This first open-economy model sheds light on the improvement in domestic welfare with a flexible CBDC remuneration rate, provided that CBDCs are imperfect substitute of bank deposits. In addition, parity conditions between the digital currency and its competing assets emerge, which suggest that "the effectiveness of adjustable CBDC interest rate as a monetary policy instrument." This tool provides a window for the central bank to achieve simultaneously monetary autonomy and exchange rate stability.

Ferrari et al. (2020) explores the transmission of monetary policy in an open economy in greater details. A standard two-country DSGE model with financial frictions and where CBDCs represent another instrument within the monetary assets available is investigated. Findings report that the existence of this digital instrument significantly amplifies the size of international spillover shocks, and the magnitude thereof depends crucially on its intrinsic design. In addition, the authors argue that a domestically-issued CBDC can decrease monetary policy autonomy abroad given increasing asymmetries in the international monetary system.

Within the family of dynamic general equilibrium model, Assenmacher et al. (2021) consider a unified framework for CBDC design to assess its macroeconomic effects. Welfare gains are shown to depend on "the degree by which collateral or quantity constraints are binding, as well as on the spread between the CBDC deposit and lending rate." Intuitively, relaxing collateral or CBDC quantity constraints and smaller spreads are strictly welfare improving, as it always reduces frictions in credit provision. However, a certain disintermediation of banks takes place as for the provision for CBDCs reduce commercial bank credit. Yet, an appropriate increase in interest rate on CBDCs can mitigate this downside.

Keister and Sanches (2019) show within a dynamic general equilibrium model in the spirit of Lagos and Wright (2005) the existence of an essential policy trade-off. CBDCs, on the one hand, could could enhance the allocation of capital by facilitating access to payments and reducing transaction costs. Nonetheless, it may crowd out bank deposits and decrease investment throughout higher bank funding costs. In addition, they show that if CBDCs are widely used for exchanges, buyers will accumulate more of it and trade will increase, leading to higher consumption. At the same time, holding more CBDCs comes at the expense of lower deposit balances and hence lower lending by banks, thereby reducing investment. The welfare effects of introducing the digital currencies depend on whether the consumption effect is larger than the investment effect.

This paper speaks to the uprising debate at the crossing of all three strands of literature, with a particular focus on the open economy set-up. Whilst some degree of understanding is observed on the financial and monetary front of closed economies, only a handful of models deal with CBDCs in its international aspect. Accordingly, this paper contributes to the development of DSGE-based models embedding CBDCs in open economies.

5. Model

The baseline model builds on the NK framework for the SOE of Galí and Monacelli (2005) and a stylized banking sector in the spirit of Gertler and Karadi (2011). In contrast to Galí and Monacelli (2005), a stock of physical capital is introduced. Similarly to Gertler and Karadi (2011), CBDCs are offered as interest-bearing central bank money available to households and utility enhancing. However, CBDC interest rate is not directly the specific instrument used by the central bank to adjust its demand and/or supply.

The baseline model postulates that the world economy is modelled by a continuum of SOEs represented within a unit interval, with each SOE being too small to have an impact on the world economy and where the law of one price holds for simplicity. Households consume, save and supply labour. They consume homogeneous domestic and foreign consumption bundles of two final goods, which are then aggregated within a final consumption good. Similar to Gertler and Karadi (2011), households can save by lending funds to competitive banks or potentially by lending funds to the government. In addition, each household is made up of two different profiles: workers and bankers. The first one supplies labor in exchange of wages, while bankers own banks which collect deposits from households. Deposits are lent out to firms to finance capital, useful for producing the final consumption good sold to households. Importantly, nominal rigidities are introduced whereby intermediate goods producers must pay adjustment costs à la Rotemberg (1982) when they change prices. Three forms of central bank money exist: QE, cash and CBDCs. QE is activated in times of financial distress, when bank spreads widen, and is not accessible to households. In contrast, cash and CBDCs represent the essence of the money-in-utility specification which are used as media of transaction by households, rendering the case where it is used as a store of value irrelevant.[5]

In Sections 5.1 to 5.6, we characterize the essential ingredients of the baseline model. In Section 5.7, we enlarge it to a fully-fledged two-economy version of the SOE model of Galí and Monacelli (2005) with the banking sector of Gertler and Karadi (2011), and the distinctive characteristic that CBDCs only exist within the home economy. Finally, we also later consider the case where CBDCs are accessible to foreign households as alternative to bonds.

5.1. Households

Households face both an intertemporal and intratemporal maximization problem. Starting with the latter, the classical SOE is inhabited by a continuum of homogeneous households within the unit interval seeking to maximize their consumption bundle

$$c_t = \left[(1-\gamma)^{\frac{1}{\eta}} \, c_{H_t}^{\frac{\eta-1}{\eta}} + \gamma^{\frac{1}{\eta}} \, c_{F_t}^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}}, \tag{1}$$

[5] Central banks worldwide seek to promote CBDCs as a means of exchange rather than a store of value, which could be a direct threat to financial stability.

where $c_{H_t} = [\int_0^1 c_{H_t}(z)^{\frac{\epsilon-1}{\epsilon}} dz]^{\frac{\epsilon}{\epsilon-1}}$ and $c_{F_t} = [\int_0^1 c_{F_t}(z)^{\frac{\epsilon-1}{\epsilon}} dz]^{\frac{\epsilon}{\epsilon-1}}$ are Constant Elasticity of Substitution (CES) indices of domestic and foreign consumption goods respectively, $\epsilon > 1$ is the elasticity of substitution between differentiated goods within any given country, $\gamma \in [0, 1]$ is a parameter of trade openness[6] and η the elasticity of substitution of consumption bundles between countries.[7] The intratemporal problem consists in maximizing Equation 1 subject to the cost of purchasing the consumption bundles, i.e.

$$\int_0^1 P_{H_t}(z)\, c_{H_t}\, dz + \int_0^1 P_{F_t}(z)\, c_{F_t}\, dz = X_t, \tag{2}$$

where P_{H_t} is the price of the home good expressed in home currency, P_{F_t} is the price of the foreign good expressed in home currency and X_t is a given level of expenditure. In addition, by the law of one price, we have to adjust foreign good prices by its nominal exchange rate e_t

$$P_{F_t} = e_t\, p_t^\star, \tag{3}$$

where $p_t^\star$ is the foreign Consumer Price Index (CPI) deflator.[8] We assume that prices are set in the currency of the producer's country. Applying the Lagrangian, we obtain the optimal allocation of expenditures between home and foreign goods

$$c_{H_t} = (1-\gamma)\left(\frac{P_{H_t}}{p_t}\right)^{-\eta} c_t, \tag{4}$$

$$c_{F_t} = \gamma\left(\frac{P_{F_t}}{p_t}\right)^{-\eta} c_t, \tag{5}$$

where $p_t \equiv [(1-\gamma)\, P_{H_t}^{1-\eta} + \gamma\, P_{F_t}^{1-\eta}]^{\frac{1}{1-\eta}}$ is the home CPI. In the scenario where $\eta = 1$, the parameter γ now measures the share of home consumption allocated to imported goods, in addition to its natural index of openness. A similar endeavor holds for investment i in Equations 4 and 5 as well as in the home CPI where c becomes i with its respective subscripts.

In the spirit of Galí and Monacelli (2005), let us define the real exchange rate $rexr_t$ as the ratio between foreign and home CPI adjusted by the nominal exchange rate e_t

$$rexr_t = e_t\, \frac{p_t^\star}{p_t}, \tag{6}$$

and the terms of trade tot_t as the ratio between the price of imports and exports

$$tot_t = \frac{rexr_t}{p_{H_t}}. \tag{7}$$

[6]Correspondingly, $1-\gamma$ measures the degree of home bias. This parameter is necessary such that households do not attach infinitesimally small weight to local consumption.

[7]In contrast to the famous paper of Obstfeld and Rogoff (1995), we will focus on the case where $\eta \neq \epsilon$, meaning that we allow a different degree of substituability of goods *within* and *across* countries.

[8]A distinctive feature between the CPI and the inflation is that the former includes the price of imported goods.

At last, the total consumption expenditures entering the budget constraint can be written as

$$P_{H_t}\, c_{H_t} + P_{F_t}\, c_{F_t} = p_t\, c_t. \tag{8}$$

Henceforth, in line with the intertemporal problem, one can write the specific separable money-in-utility function, reworked for the purpose of integration of CBDCs as

$$U(c_t, h_t, CBDC_t, M_t) \equiv \frac{c_t^{1-\sigma}}{1-\sigma} - \zeta_L\, \frac{h_t^{1+\phi}}{1+\phi} + \Upsilon\, \frac{\left(\frac{CBDC_t}{p_t}\right)^{1-\Gamma}}{1-\Gamma} + \mu^M\, \frac{\left(\frac{M_t}{p_t}\right)^{1-\vartheta}}{1-\vartheta}, \tag{9}$$

where parameters σ, ϕ, ζ_L, Υ, and Γ are respectively the inverse of the intertemporal elasticity of substitution of consumption, the inverse Frisch elasticity of labor supply,[9] the labor preference parameter, the utility weight of CBDC and its elasticity.[10] The variables h_t, $CBDC_t$ and M_t feature labor, digital monies and cash. We thus extend Gross and Schiller (2020) by adding cash with its parameters μ^M and ϑ, which are the utility weight on cash and its elasticity. Observe that CBDCs enter as a utility enhancing variable, thereby suggesting the perceived added-value for households as it is sought after by central banks worldwide. We assume that households have the monopoly on CBDC holdings, as opposed to current endeavors.[11] Representative households are all facing the following intertemporal budget constraint[12]

$$\begin{aligned} p_t\, c_t + p_t\, i_t + d_{H_t} + e_t\, d_{F_t} + CBDC_t + M_t \leq p_t\, w_t\, h_t + r_t^k\, p_t\, k_{t-1} + r_{t-1}\, d_{H_{t-1}} + \\ e_t\, r_{t-1}^{\star}\, d_{F_{t-1}} + r_{t-1}^{cbdc}\, CBDC_{t-1} + \xi^M\, M_{t-1} - p_t\, t_t + p_t\, \Pi_t - \frac{\zeta_D}{2}\, e_t\, p_t^{\star} \left(\frac{d_{F_t}}{p_t^{\star}} - \overline{d_F}\right)^2, \end{aligned} \tag{10}$$

where d_{H_t} is the sum of one-period public bonds $d_{H_t}^p$ and bank deposits dep_t while d_{F_t} defines holdings of one-period foreign bond denominated in foreign currency, both of which pay a nominal interest rate r_t or $r_t^{\star}$. The foreign interest rate $r_t^{\star}$ is assumed to be following an exogenous process

$$r_t^{\star} = (1-\rho^p)\, \frac{1}{\beta} + \rho^p\, r_{t-1}^{\star} + \epsilon_{fmp_t}, \tag{11}$$

[9] It measures *ceteris paribus* the substitution effect of a change in the wage rate on labour supply. However, note that the Frisch elasticity does not capture its total effect as aggregate wealth effects (from wage changes) are ignored. (See Kimball and Shapiro (2008).)

[10] The utility weight of CBDC Υ and the elasticity of liquidity Γ are taken from Gross and Schiller (2020) who introduced CBDC within a money-in-utility specification. While very tractable, this shortcut for getting money valued in equilibrium depends heavily on the arbitrary specification of utility, which in turn affects the results. (See Sidrauski (1967)). Another famous specification to include money within DSGE models is the cash-in-advance constraint, whereby it is assumed that households hold enough cash from previous periods to finance current nominal consumption expenses. (See Lucas and Stokey (1987).)

[11] Retail CBDC projects aim at offering free access to individuals, merchants, and in some instances, government entities, hence our model underestimates CBDC holdings.

[12] This comes from the implicit assumption that all households within a country work for all the firms and they all earn a similar wage, thereby also sharing profits in equal proportion.

and $\epsilon_{fmp_t} \sim N(0, \sigma^2_{fmp})$ is a foreign shock in the interest rate. In addition, we can interpret ξ^M as storage costs, linearly increasing.[13]

The remuneration on CBDCs r_t^{cbdc} is lower than the remuneration earned on bonds or deposits and equates to the simple equation

$$r_t^{cbdc} = \Big[1 + (r_t^b - r_t)\Big], \tag{12}$$

where r_t^b is the loan rate. Should CBDCs become interest-bearing, this prior assumption is not far off from the broad academic consensus, which endorses a lower remuneration rate *relative* to bonds and deposits in order to avoid bank disintermediation. In contrast to Gross and Schiller (2020), we assume that deposits and bonds are equivalently remunerated. The last term of Equation (10) is a quadratic adjustment cost for domestic households if they adjust their financial position with the rest of the world.[14] The rest of the notation is standard.[15] In addition, capital is also bound by the following equality

$$k_t = (1-\delta)\, k_{t-1} + \left[1 - \frac{\zeta_I}{2}\left(\frac{i_t}{i_{t-1}-1}\right)^2\right] i_t. \tag{13}$$

The second term within brackets of Equation (13) is also a quadratic investment adjustment cost with ζ_I being its main dictating parameter and δ is the depreciation rate. Altogether, the representative household solves the following problem:

$$\max_{\{c_t, i_t, h_t, k_t, d_{H_t}, d_{F_t}, CBDC_t, M_t\}_{t=0}^{\infty}} E_0 \sum_{t=0}^{\infty} \beta^t\, U(c_t, h_t, CBDC_t, M_t) \tag{14}$$

subject to the constraints of Equations 10 and 13 and where E is the expectation operator. Applying its Lagrangian function yields the following first order conditions for the variables $\{c_t, i_t, h_t, k_t, d_{H_t}, d_{F_t}, cbdc_t, m_t\}$

$$\lambda_t = c^{-\sigma}, \tag{15}$$

$$\frac{1}{q_t} = \beta\, \zeta_I\, E_t \left\{ q_{t+1} \frac{\lambda_{t+1}}{\lambda_t} \left(\frac{i_{t+1}}{i_t} - 1\right) \left(\frac{i_{t+1}}{i_t}\right)^2 \right\} + \left[1 - \frac{\zeta_I}{2}\left(\frac{i_t}{i_{t-1}} - 1\right)^2 - \zeta_I \frac{i_t}{i_{t-1}} \left(\frac{i_t}{i_{t-1}} - 1\right)\right], \tag{16}$$

$$\zeta_L\, h_t^{\phi} = w_t\, \lambda_t, \tag{17}$$

$$\lambda_t = \beta\, E_t \Bigg\{ \lambda_{t+1} \frac{({r^k}_{t+1} + (1-\delta)\, q_{t+1})}{q_t} \Bigg\}, \tag{18}$$

$$\lambda_t = \beta\, E_t \left(\lambda_{t+1} \frac{r_t}{\pi_{t+1}} \right), \tag{19}$$

[13] In the baseline model, we assume that no storage costs exist for simplicity, i.e. $\xi^M = 1$.

[14] According to Schmitt-Grohé and Uribe (2003), this assumption guarantees the existence of a steady state and a stationary solution.

[15] Following conventions, r_t^k is the rental rate on capital, w_t is the wage, t_t is a lump-sum tax raised by the government to finance its public expenditure g_t and Π represents profits.

$$\lambda_t = \beta\, E_t \frac{\left(\lambda_{t+1}\, r_t^{\star}\, \frac{rexr_{t+1}}{rexr_t}\right)}{\left[1-\zeta_D\,(d_{f_t}-\overline{d_f})\right]}, \tag{20}$$

$$cbdc_t^{-\Gamma} = \frac{1}{\Upsilon}\,\beta\, E_t\left(\frac{r_t^{cbdc}\,\lambda_{t+1}}{\lambda_t\,\pi_{t+1}}\right), \tag{21}$$

$$\mu^M\, m_t^{-\vartheta} = \lambda_t - E_t\,\beta\,\xi^M\left(\frac{\lambda_{t+1}}{\pi_{t+1}}\right) \tag{22}$$

where λ_t and q_t are the Lagrangian multipliers. It is common to interpret q_t as Tobin's *q*.[16] Note that the budget constraint has been re-expressed in terms of domestic CPI.[17]

5.2. Final Goods Firms

The small open economies are producing CES differentiated intermediate goods indexed on the unit interval by a continuum of identical monopolistically competitive firms[18] using the following technology

$$y_{H_t} = \left(\int_0^1 y_{H_t}(z)^{\frac{\epsilon-1}{\epsilon}}\, dz\right)^{\frac{\epsilon}{\epsilon-1}}, \tag{23}$$

where $y_{H_t}(z)$ denotes the quantity of domestic intermediate input produced at date t. In addition, $\epsilon > 1$ is the elasticity of substitution among different intermediate goods and can be understood as mark-up in the goods market. Final good firms seeks to maximize profits subject to their production constraint

$$\max_{y_{H_t}} P_{H_t}\, y_{H_t} - \int_0^1 P_{H_t}(z)\, y_{H_t}(z)\, dz, \tag{24}$$

subject to Equation (23). The first order conditions come from taking the derivative of each $y_{H_t}(z)$ and setting it to zero, yielding the demand for each intermediate good

$$y_{H_t}(z) = \left(\frac{p_{H_t}(z)}{p_{H_t}}\right)^{-\epsilon} y_{H_t}. \tag{25}$$

Equation (25) says that the demand for each intermediate good depends positively on production and negatively on its relative price. We know that final good firms are competitive such that profits are zero. The aggregate price index is given by

$$P_{H_t} = \left(\int_0^1 P_{H_t}(z)^{1-\epsilon}\, dz\right)^{\frac{1}{1-\epsilon}}. \tag{26}$$

The same analysis holds for the foreign economy case where the subscript H is replaced by F.

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[16]Within his *Theory of Investment*, James Tobin attempts to model features closer to the real world, such that the quadratic adjustment cost of Equation (13) better fits with the empirical finding that, in the short run, capital costs of firms are fixed costs.

[17]For instance, $d_{f_t} \equiv \frac{d_{F_t}}{p_t^{\star}}$, $d_{h_t} \equiv \frac{d_{H_t}}{p_t^{\star}}$, $m_t \equiv \frac{M_t}{p_t}$ and $cbdc_t \equiv \frac{CBDC_t}{p_t}$.

[18]See Dixit and Stiglitz (1977) who formalised this approach.

5.3. Intermediate Goods Producers

A continuum of intermediate goods firms produce output using the usual Cobb-Douglas production function

$$y_{H_t}(z) = a_t\,(kQ_t\,k_{t-1}(z))^{\alpha}\,(h_t\,(z))^{1-\alpha}, \tag{27}$$

where a_t is the Total Factor Productivity (TFP) and kQ_t features variation in the capital quality, both of which are assumed to be following autoregressive processes

$$log(a_t) = \rho_\alpha\,log(a_{t-1}) + (1-\rho_\alpha)\,log(\overline{a}) + \epsilon_{a_t}. \tag{28}$$

$$log(kQ_t) = \rho_s\,log(kQ_{t-1}) + \epsilon_{k_t}. \tag{29}$$

The last term of Equations (28) and (29) are i.i.d Gaussian technology- and capital quality shocks respectively. The motivation for introducing a capital quality shock is to capture economic obsolescence, analog to physical depreciation. In particular, the capital quality shock introduces an exogenous source of variation in the return to capital, fundamental for investment and loans as shown later. Given that firms operate in monopolistic competition, they produce as much output as is demanded (Equation (25)) at a given (and chosen) price (Equation (26)). The profit maximization problem[19] is given below, as expressed in terms of domestic prices p_t

$$\begin{aligned}\max_{\{y_{H_t}(z),k_{t-1}(z),h_t(z),P_{H_t}(z)\}_{t=0}^{\infty}} & E_0\Bigg\{\sum_{t=0}^{\infty}\beta^t\,\frac{\lambda_t}{\lambda_0}\Bigg[y_{H_t}(z)\,\frac{P_{H_t}(z)}{p_t} \\ & - w_t\,h_t(z) - r_t^k\,k_{t-1}(z) - \frac{P_{H_t}\,y_{H_t}}{p_t}\left(\frac{\zeta_P}{2}\,(\frac{P_{H_t}(z)}{P_{H_{t-1}}(z)} - \overline{\pi})\right)^2\Bigg]\Bigg\},\end{aligned} \tag{30}$$

subject to Equations (25) and (27). Note that the last term of the above equation corresponds to quadratic adjustment costs final goods firms must pay whenever they adjust their respective prices *relative* to $\overline{\pi}$, the inflation target.[20] In contrast to the classical NK, capital expenditure of firms must be fully financed by borrowing a certain amount $G_t(z)$ either from the government or from banks

$$G_t(z) = q_t\,k_t(z). \tag{31}$$

Applying the Lagrangian function gives the following first order conditions with respect to capital, labor and domestic prices

$$y_{H_t}\,\alpha\,mc_t = k_{t-1}\,{r^k}_t, \tag{32}$$

$$y_{H_t}\,(1-\alpha)\,mc_t = h_t\,w_t, \tag{33}$$

[19] Oftentimes, a cost minimization problem is featured for intermediate goods producers in lieu of its maximization counterpart. As expected, results are equivalent.

[20] Rotemberg (1982) and Calvo (1983) offer the most common ways to introduce sticky prices. In Rotemberg (1982), all firms choose identical prices given similar costs, while the staggered price setting approach of his peer allow firms to randomly update their prices, regardless of the previous 'price reset'. ζ_P measures the size of good z price stickiness in the domestic country. Although both price-setting assumptions imply similar reduced-form inflation dynamics, pricing à la Rotemberg (1982) proves to have a computational edge.

$$\pi_{Ht}\left(\pi_{Ht}-\overline{\pi}\right)=\beta\,E_t\left[\pi_{H_{t+1}}\left(\frac{\lambda_{t+1}}{\lambda_t}\right)\left(\frac{p_{H_{t+1}}\,y_{H_{t+1}}}{y_{H_t}\,p_{H_t}}\right)\left(\pi_{Ht+1}-\overline{\pi}\right)\right]+\frac{\epsilon}{\zeta_P}\left(\frac{mc_t}{p_{H_t}}-\frac{\epsilon-1}{\epsilon}\right), \quad (34)$$

where the Lagrange multiplier, mc_t, can be interpreted as the nominal marginal cost, i.e. how much do nominal costs increase if the firm has to produce one additional unit of output. The optimal pricing in Equation (34) is also called the (non-linear) Phillips curve and is found by rearranging aggregate domestic prices *conditionally* on the optimal choice of capital and labor.

5.4. Banking Sector

The banking sector is made up of one type of households, the finitely lived bankers, whereby during any period, a fraction $1-f$ of households are workers and a fraction f are bankers. Over time, profiles can switch: a banker in period t stays a banker in period $t+1$ with probability χ, independent of how long (s)he has been a banker. On average, bankers stay for $\frac{1}{1-\chi}$ periods. Similarly, a fraction $(1-\chi)\,f$ of workers randomly become bankers, thereby ensuring equal shares of both profiles across time.[21] It is worth noting that bankers exiting give their retained earnings to the respective household(s) which, in turn, provide new bankers with start-up funds.

The bank balance sheet is defined as

$$bankAss_t(z)=cbdc_t(z)+dep_t(z)+n_t(z)+m_t(z), \quad (35)$$

where $bankAss_t$ represents assets of bank z and $n_t(z)$ denotes its net worth or the banker's equity. Cash and CBDCs are liquidity services for households, but constitute liabilities to commercial banks in line with Bindseil (2020). The equation is a departure from Gertler and Karadi (2011), and depicts a more realistic balance sheet portrayal of a typical bank, which financial account representation can be found in Table (B.1). Households transfer its deposits to banks which pay a stochastic interest rate r_t and bank assets are remunerated at the non-contingent rate r_t^b. Bank net worth evolves according to its law of motion

$$n_t(z)=\frac{r_{t-1}}{\pi_t}\,n_{t-1}(z)+\left(r_t^b-\frac{r_{t-1}}{\pi_t}\,bankAss_{t-1}(z)\right), \quad (36)$$

meaning that the equity in period t is the sum of net earnings on assets and previous period net worth. It is insightful to identify that growth in the net worth depends on the premium $r_t^b-\frac{r_{t-1}}{\pi_t}$ and the quantity of assets $bankAss_t$. We now must ensure that banks do not expand their balance sheet indefinitely but remains willing to operate, if and only if, the following participation inequality holds

$$E_t\left[\beta\,\Lambda_{t,t+1+z}\left(r_t^b-\frac{r_{t-1}}{\pi_t}\right)\right]\geq 0 \quad \forall z\geq 0, \quad (37)$$

where $\beta\,\Lambda_{t,t+1+z}$ is the discount factor of households as we assumed that they make up bankers within the model. Gertler and Karadi (2011) inform us that in the class of models with perfect capital markets, the relation always holds with equality, meaning that the premium is zero. Nonetheless, in imperfect

[21]This assumption entails that no banks can accumulate infinite amount of wealth.

capital markets, the premium could be positive if banks are constrained in their ability to collect funds.

As long as bankers earn the premium that is greater than or equal to the return on deposits or bonds, they continue to accumulate assets until their days as bankers come to an end. Accordingly, its objective is to maximize the expected value of terminal wealth

$$V_{z,t} = \max\ E_t \left[\sum_{i=0}^{\infty} (1-\chi)\, \chi^i\, \beta^i\, \Lambda_{t,t+1+i}\, n_{t+1+i}(z) \right], \tag{38}$$

subject to Equation (36). A cost enforcement problem is initiated to avoid indefinite expansion of its assets: at the beginning of period t, bankers have two choices. One the one hand, they can divert the fraction θ of available assets and allocate them back to the household (s)he belongs to.[22] The reverse of the medal is that depositors have the capacity to force the banker into bankruptcy and claim anew their remaining fraction $1-\theta$ of assets. The bigger is the embezzlement parameter θ, the less are bankers trustworthy, and hence it becomes harder to collect funds from households. It is assumed in line with Gertler and Karadi (2011) that recovering diverted funds is too costly. In addition, lenders are willing to supply funds to banks if the incentive constraint is satisfied

$$V_{z,t} \geq \theta\, bankAss_t\,(z), \tag{39}$$

where the left hand side is the cost for the banker of diverting a fraction of assets, and the right hand side the gain from doing so. We follow Gertler and Karadi (2011) in the solution of V_{z_t} whereby the banker's terminal wealth can be expressed recursively as

$$V_{z,t} = \mu_{n,t}\, n_t(z) + \mu_{bA,t}\, bankAss_t(z). \tag{40}$$

The functions $\mu_{n,t}$ and $\mu_{bA,t}$ are often interpreted as the marginal value of holding (investing) one additional unit of net worth (bank assets).

In frictionless and complete competitive markets, bankers would expand their balance sheet up to the point where the premium is zero. The financial friction introduced could limit the arbitrage, and provided that the incentive constraint binds, bankers are restricted by the amount of net worth. We define the leverage ratio of bank z as follows

$$lev_{z,t} = \frac{bankAss_t(z)}{n_t(z)}. \tag{41}$$

Equation (41) constrains banks' leverage ratio such that the cost of cheating (bankruptcy) is exactly balanced out by its incentive to do so. Accordingly, rearranging Equation (41) and inserting it, together

[22] Bankers cannot actually divert funds in reality but this trick aims to create an upper limit based on bankers' equity and households' deposits.

with Equation (39), in Equation (40) yields

$$bankAss_t(z) = \frac{\mu_{n,t}}{\theta - \mu_{bA,t}}\, n_t(z). \tag{42}$$

Note that expressed under that light, the leverage ratio lev_t is increasing in $\mu_{bA,t}$. In other words, large positive deviations in $\mu_{bA,t}$ will induce greater cost to the banker to fall into bankruptcy. Relating to the characteristic of the banking sector, it is useful to break down the aggregate equity of bankers into the net worth of existing n_{e_t} and new bankers n_{n_t} as

$$n_t = n_{e_t} + n_{n_t}. \tag{43}$$

Given that the fraction χ of bankers in period $t-1$ remain until period t, the net worth of old banks is given by

$$n_{e_t} = \chi\left[\frac{r_{t-1}}{\pi_t}\, n_{t-1} + \left(r_t^b - \frac{r_{t-1}}{\pi_t}\, bankAss_{t-1}(z)\right)\right]. \tag{44}$$

Recall that young bankers are receiving start-up funds from households, amounting to a small fraction τ of the value of assets departing bankers possessed in their final operating period. Accordingly, the net worth of new bankers is defined as

$$n_{n_t} = \tau\, bankAss_{t-1}. \tag{45}$$

Combining Equations (44) and (45), we obtain the evolution of aggregate bank net worth

$$n_t = \chi\left[\frac{r_{t-1}}{\pi_t}\, n_{t-1} + \left(r_t^b - \frac{r_{t-1}}{\pi_t}\, bankAss_{t-1}(z)\right)\right] + \tau\, bankAss_{t-1}. \tag{46}$$

Finally, define the credit spread as follows

$$spr_t = E_t\left[r_{t+1}^b - \frac{r_t}{\pi_{t+1}}\right]. \tag{47}$$

5.5. Policy

In line with Gertler and Karadi (2011), the central bank and the government are equivalent. Its consolidated budget constraint reads as

$$m_t + cbdc_t + (d_{H_t}^{qe} - d_{H_t}^{p}) + g_t = \xi^M\, m_{t-1} + r_{t-1}^{cbdc}\, cbdc_{t-1} + (r_t^b\, d_{H_{t-1}}^{f} - r_{t-1}\, d_{H_{t-1}}^{p}) + t_t + \frac{\zeta_D}{2}\left(d_{f_t} - \overline{d_f}\right)^2, \tag{48}$$

where $d_{H_t}^{qe}$ represents bonds issued by firms, $d_{H_t}^{p}$ was the one-period public bonds[23], and the last term denotes the quadratic adjustment costs households pay when changing their financial positions. Exogenous government spending g_t follows an autoregressive process

$$log(g_t) = \rho_g\, log(g_{t-1}) + (1-\rho_g)\, log(\overline{g}) + \epsilon_{g_t}, \tag{49}$$

[23] See Equation (10).

and $\epsilon_{g_t} \sim N(0, \sigma_g^2)$ is a government spending shock. Note that we assume that the central bank could issue CBDCs in unlimited quantity; it depends on its demand by households. In addition, we assume that firm's bond demand $d_{H_t}^{qe}$ is fully met by one-period public bonds $d_{H_t}^{p}$, i.e.

$$d_{H_t}^{qe} = d_{H_t}^{p}. \tag{50}$$

For simplicity, we interpret $d_{H_t}^{qe}$ as some unconventional monetary policy such as QE. The rationale behind is that the central bank acts as an intermediary by borrowing funds from the government ($d_{H_t}^{p}$) and lending them. Unlike the banking sector, the central bank faces no financial frictions given that the central bank cannot default. To capture an effect of this unconventional monetary policy, we must assume that the Wallace neutrality breaks down.[24] We suppose that the central injects funds in times of financial distress, in response to movements in credit spreads, according to the QE rule

$$\frac{d_{H_t}^{qe}}{\overline{d_H^{qe}}} = \left[\left(\frac{spr_t}{\overline{spr}}\right)^{\phi_{qe}}\right]^{1-\rho_{qe}} \left(\frac{d_{H_{t-1}}^{qe}}{\overline{d_H^{qe}}}\right)^{\rho_{qe}} \exp(\epsilon_{qe_t}), \tag{51}$$

where $\epsilon_{qe_t} \sim N(0, \sigma_{qe}^2)$ is the QE shock. Following Equation (51), the central bank increases credit in response to deviations of the spread from its steady state value.

We suppose monetary policy to be characterized by the modified Taylor rule, whereby the short-term nominal interest rate is set according to following feedback rule

$$\frac{r_t}{\overline{r}} = \left[\left(\frac{\pi_t}{\overline{\pi}}\right)^{\phi_\pi} \left(\frac{gdp_t}{\overline{gdp}}\right)^{\phi_y} \left(\frac{nomdep_t}{\overline{nomdep}}\right)^{\phi_e}\right]^{1-\rho_m} \left(\frac{r_{t-1}}{\overline{r}}\right)^{\rho_m} \exp(\epsilon_{mp_t}), \tag{52}$$

where $nomdep_t$ is the nominal depreciation rate of domestic currency within the SOE framework, $gdp_t \equiv P_{t_t} y_{H_t}$ and $\epsilon_{mp_t} \sim N(0, \sigma_{mp}^2)$. The monetary authority gradually adjusts the short-term nominal interest rate r_t in view of deviations in the gross inflation, output and nominal exchange rate from their steady state values. The motivation for integrating the exchange rate comes from Scholl and Uhlig (2008), Gourinchas and Tornell (2004) and Bacchetta and van Wincoop (2010), who found that an increase in the short-term nominal interest rate is source to sustained exchange rate appreciation, and especially so if investors underestimate the stickiness of monetary shocks. Within open economies, it is also argued that the above modified Taylor rule has better performance.[25] The optimal rule would surely account for this distinction.

[24]The Wallace neutrality is a property of monetary economic models whereby differences in the government's overall balance sheet, in times of rock low nominal interest rate, have no general equilibrium effect on price level and real allocations in the economy, i.e. interest rates or non-financial economic activity. In other words, assuming the Wallace neutrality breaks down is equivalent to assuming that conventional open-market purchases of securities affects effectively monetary policy.

[25]See Chen et al. (2017) for greater details.

5.6. Market Clearing

Finally, the domestic- and aggregate goods market clear

$$y_{H_t} = (1-\gamma)\,(p_{H_t})^{-\eta}\,(c_t+i_t)+g_t+\gamma^\star\,y_t^\star\,tot_t^\eta+y_{H_t}\,\frac{\zeta_P}{2}\,(\pi_{Ht}-\overline{\pi})^2, \tag{53}$$

$$gdp_t = c_t+i_t+p_{H_t}\,g_t+rexr_t\,r_{t-1}^\star\,d_{f_{t-1}}-rexr_t\,d_{f_t}+\frac{\zeta_P}{2}\,(\pi_{Ht}-\overline{\pi})^2\,gdp_t+\frac{rexr_t\,\zeta_D}{2}\,(d_{f_t}-\overline{d_f})^2, \tag{54}$$

where $y_t^\star$ is the foreign demand for domestic good, which follows an autoregressive process

$$log(y_t^\star) = \rho_g\,log(y_{t-1}^\star)+\epsilon_{fy_t}, \tag{55}$$

where $\epsilon_{fy_t} \sim N(0,\sigma_{fy}^2)$ is a foreign output shock. In addition, define aggregate foreign (domestic) demand for domestic (foreign) good X_t (M_t) as

$$X_t = tot_t^\eta\,{y^\star}_t\,p_{H_t}\,\gamma^\star, \tag{56}$$

$$M_t = (c_t+i_t)\,\gamma\,rexr_t^{1-\eta}, \tag{57}$$

and the trade balance is defined by the difference between exports (X_t) and imports (M_t).
By the Walras Law,[26] we know that clearing the bond market implicitly imposes an equilibrium in the deposit market. Hence, clearing the bond market implies

$$q_t\,k_t = bankAss_t + d_{H_t}^{qe}. \tag{58}$$

This completes the baseline model description, and we call the curious reader to refer to the section in the Appendix (A.1) for the completion of all equilibrium equations used in the model.

5.7. Enlargement of Baseline Model

A first extension to the baseline scenario is made to the TEM symmetric in all but the size of the home country *relative* to the foreign country, the state of technology, the degree of openness, and the presence of CBDC which only prevails within the home economy at first. To make the paper self-contained, we invite the interested reader to delve into the overview of the additional ingredients of this model extension as well as its equilibrium equations in Appendix (A.2) and (A.3).

Home households are now able to allocate their wealth among two one-period risk-free bonds, one in domestic currency and one in foreign currency, in addition to deposits issued by banks. They transact using liquidity services such as CBDCs or cash. In contrast, we maintain the assumption that foreign households do not have access to CBDCs. Foreign households allocate their wealth among home and

[26] The Walras law states that within an economy of X markets, there can only be $X-1$ independent demand/ supply equations. Thus, when studying the general equilibrium dynamics of an economy with X goods, it is sufficient to analyse $X-1$ markets. In our application, the deposit clearing condition becomes redundant.

foreign bonds as well as deposits. Importantly, we consider quadratic transactions costs in trading bonds in the international markets. In a similar vein to the baseline, we assume that the producer of goods sets his prices in the currency of the country (s)he belongs to. That means that (s)he only sets one price, which is subsequently converted into the other currency using an exchange rate; hence the international law of one price continues to hold and the pass-through of nominal exchange rate movements into import prices remains complete and instantaneous.[27] As always, NK features are embodied by price stickiness in the form of adjustment costs and monopolistic competition.

[27] Also called Producer-Currency Pricing (PCP), it sheds light on sticky export prices in the currency of the producer. We refer the reader to Basu et al. (2020) for an extensive and detailed overview of the different pricing strategies, i.e. PCP, DCP and LCP.

6. Parameter Calibration

Provided that the baseline and its extension embody clean slates of workhorse models within the NK literature, it is important to know whether their collective adjacency within a tractable and natural model will accommodate to existing calibration. DeJong and Dave (2007) argue that calibration is the quickest manner to determine the usefulness of extensions in a model. Tables (B.2) and (B.3) summarize the calibration of the baseline.

The model period is a quarter. To calibrate the discount rate, we need a measure on the interest on money. From Bindseil (2020), we obtain the conventional quarterly stochastic discount factor β assuming 2003-2008 data on euro area bank funding costs whereby "10 percentage points of M3-deposits of banks are substitute with CBDCs". Setting β to 0.99 implies a risk-free annual return of 4 percent in the steady state. The labor preference parameter ζ_L is set at 10.15. In addition, we set the Armington elasticity η and the inverse of the elasticity of intertemporal substitution of consumption σ equal to 3.8 and 1.5 respectively in accordance to Bajzik et al. (2020) and Corbo and Strid (2020). By doing so, we assume that households strongly respond to changes in the real interest rate. We assume a fairly low level of trade openness, with γ set at 0.30. We take data from Sweden to assess the depreciation rate δ at 0.015 according to Corbo and Strid (2020). Regarding CBDC parameters, we follow Gross and Schiller (2020) for the utility weight of CBDC Υ and its elasticity of liquidity Γ.[28] Interestingly, we observe that the greater the elasticity Γ, the larger the IRF, and the smaller the utility weight Υ, the greater the IRF. The cash-related parameters follow Ferrari et al. (2020) at the exception of the elasticity of substitution ϑ, which was set at -1.7.

Concerning the banking sector augmentation, we fully follow Gertler and Karadi (2011) and from Galí and Monacelli (2005), we derive the elasticity of substitution between differentiated goods ϵ to be 6, implying a steady state markup of 20 percent. Finally, we set the monetary policy response to inflation ϕ_π and output ϕ_y equal to 1.5 and 0.125 respectively in accordance with Gross and Schiller (2020). We assume that the monetary authority equally responds to changes in the nominal exchange rate as to deviations in the output gap. All other parameters are kept at zero.

[28] In Appendix (C.1) through (C.4), we provide a glimpse on the importance of those parameters for the subsequent analysis of Impulse Response Function (IRF). In fact, the responses of CBDC demand are highly sensitive to the calibration of the utility weight of CBDC and its elasticity.

7. Results

In this section, we present a facet on monetary and financial implications of issuing CBDCs in the baseline SOE and its extended model based on IRF of TFP and monetary policy innovations.[29] In the interest of comparison, we highly encourage the reader to contrast the IRF of a capital quality shock given in the Appendix (C) with Gertler and Karadi (2011).[30]

7.1. Baseline Simulations

In Figure (C.5), we show the dynamic impulse responses to an expansionary technological innovation in the home SOE with, and without, of CBDCs.[31] In absence of CBDCs, the effects are fairly standard: the shock leads to a hump-shaped expansion of home output, consumption and investment given higher expected returns on capital. Nonetheless, all responses gradually - and sluggishly - return to their steady state value. Inflation falls in the face of more efficient production frontier and the decline in the nominal interest rate yields a depreciation in the nominal exchange rate, thereby leading to an increase in the real exchange rate and the trade balance.[32]

Moving to financial variables, the premium consistently jumps in the presence of financial frictions thereby increasing the response of investment as financial intermediaries give loans to firms. Hence, bank assets (capital) increase. To keep the equality respected, deposits expand, and simultaneously, a reduction in bank net worth is observable. Recall that households could save i.a. in deposits, which is positively affected by a general improvement of the production frontier, and reinforced by the fact that the banking sector is seen as more trustworthy, i.e. the leverage ratio increases. In turn, it allows bankers to expand their portfolios for a given level of equity. In light of a technological innovation, the mere existence of CBDCs accessible to the home SOE has marginal effects: a small shift from deposits to the digital monies is nonetheless made apparent in accordance with previous studies (Gross and Schiller (2020) and Assenmacher et al. (2021)).

The same cannot be said regarding a tightening in monetary policy whose IRF are plotted in Figure (C.6) which quarterly autoregressive factor is equal to 0.95.[33] In absence of CBDCs, a positive shock to the modified Taylor rule decreases consumption as households substitute future consumption for present consumption. Likewise, output and investment suffer the same fate as inflation falls. Observe

[29] In his seminal paper, Sims (1986) argued that monetary policy shocks are to be identified throughout disturbances or innovations in the monetary policy rule, also known as the Taylor rule. At the time of writing, researchers' latest strategy is to focus on movements of the key policy rate in a tight window around announcements made by central bankers to better capture its *pure* effect. (See Jarociński and Karadi (2020).)

[30] Akin to the authors, we generated a shock simulating a 5 percent decline in capital quality, with its quarterly autoregressive factor equal to 0.66.

[31] The technology shock is represented by a one percent increase in the TFP. While transitory, a fairly persistent weight is attached within its AR(1) equation. See Table (B.3).

[32] See Equations (A.36) and (A.38).

[33] The monetary shock is represented by an unanticipated twenty-five basis point increase in the short term nominal interest rate.

that the presence of financial frictions causes an amplification of the effects of the shock on investment, in line with the financial accelerator mechanism and most noticeable in the presence of the digital monies. The short-lived slowdown in economic activity is also felt upon impact on the trade balance and the real exchange rate, which briefly go into negative territory. For instance, for the trade deficit, we see that although both exports and imports fall, imports are boosted by expenditure switching towards foreign goods and thus fall *relatively* less. By the Philips Curve, a change in the exchange rate also affects inflation because it is directly transmitted onto import prices.[34] The effects of a tightening on financial variables remain largely limited. However, introducing CBDCs exacerbates the short-term responses across real and nominal variables, driven by the larger increase in the nominal interest rate, which spikes upon impact. Therefore, the economy appears to suffer from a steeper downturn, although recovering with a fast pace.

As such, the responses across all variables are amplified by the initial response of the central bank, which is greater in the case with CBDCs. For instance, the higher increase in deposits stems from the greater deterioration of bank assets, and bank net worth in the CBDC scenario, which traces back to larger spreads and risk premium (in absolute value). Naturally, an increase in the short-term nominal interest rate directly leads to an increase in deposits upon which it is remunerated. The effects are thus consistent with conventional Friedmanite wisdom, stating that monetary policy does not generate real effects in the long-run, but only in the short-run due to sticky prices.

The main consequence of the introduction of an interest-bearing CBDC depends on the nature of the shock the economy is facing. A monetary policy shock emerges as generating greater deviations from the steady state compared to the no-CBDC world, indicative of real and financial international spillovers. In particular, the economy experiences a steeper, yet short-lived downturn, and deposits increase considerably. A positive technology innovation generates little, if any, divergence from the no-CBDC scenario.

7.2. Comparison Baseline-Extension

Consider now the basic extension model where we start by comparing the effects of the TEM with the NK SOE of Galí and Monacelli (2005) embedded within the banking sector of Gertler and Karadi (2011).

Analogous to Figure (C.5), Figure (C.8) shows the dynamic impulse responses to an expansionary technological innovation when CBDCs exist in the home economy only. The responses of real variables are equivalent to the baseline setting, despite exhibiting somewhat smaller magnitudes for consumption and output, owing to the fact that the TEM is more intertwined with the foreign economy. The enhanced response of investment is a product of the decline in the spread. Extra production and lower marginal costs appear to generate equivalent dynamics on prices of domestically produced goods, driving down

[34]The conventional view is that the exchange rate channel is the quickest channel to respond from policy to inflation. See Equation (34).

inflation. In a similar fashion, the central bank reacts by declining its nominal interest rate although to a slightly lesser extent in the extension. Accordingly, nominal exchange rate declines, driving to a greater increase in the real exchange rate, and a smoothing of the trade balance.[35]

In the financial realm, both models share comparable dynamics consistent with their symmetric and simplistic structure. The general improvement of the economy drives down the spread, which diminishes the cost of capital and increases bank assets, deposits and CBDC equivalently.

Turning to a tightening in monetary policy, Figure (C.9) outlines interesting results: output increases lightly upon impact in the TEM, shortly before declining somewhat for a temporary period, thereby avoiding the sharp decline in aggregate production of the SOE. In addition, the short-term nominal interest rate is marginally greater in the extension than the baseline with knock-on effects on variables in the TEM, analogous to the finding that the presence of CBDCs called for a higher nominal interest rate in the SOE scenario. This difference in the monetary authority response generates ultimately comparable pricing dynamics. In both cases, the anti-Fisherian property is satisfied, i.e. inflation and the nominal interest rate move in contradictory directions following the transitory shock. Unsurprisingly, the real exchange rate inherits from the unexpected larger contraction, which in turn affect consumption and investment more heavily. The trade balance benefits from this slightly lower real exchange rate, which scales down its trade deficit due to the expenditure switching channel, as compared to the SOE.[36]

Household deposits are no exception: their departure from the SOE setup is partly attributable to the greater remuneration it earns. CBDC holdings briefly increase before quickly returning to its trend in both models. The deterioration of the economy impacts bank assets too, owing to the rise in the incentive to divert funds.

Altogether, the availability of digital currencies do not appear to substantially affect variables across the two models, indicating that the two frameworks yield qualitatively comparable results. The TEM generates in general somewhat smoother IRF, with the exception of the real exchange rate.

7.3. Extension Simulations

We now shift the focus exclusively on the TEM where we analyse whether domestically-grown CBDC affects open economies. Previous studies have already documented that the presence of a CBDC opens new channels through which it influence foreign economies (Ferrari et al. (2020) and George et al. (2020)). We enrich our extension by assuming that CBDCs are a safe asset in competition with domestic bonds available in the foreign economy. A new channel of exchange of capital is recorded: CBDCs held by

[35]The depreciation of the home currency limits the positive spillover effects in the TEM.

[36]The expenditure switching channel works as follows: the relative price between home and foreign goods is influenced by movements in the exchange rate. In turn, an appreciation of the nominal exchange rate for the home economy leads to expenditure switching away from domestically produced goods and towards goods produced in the foreign economy – i.e. towards imports.

foreigners represent capital inflows (outflows) for the home (foreign) economy. Altogether, we provide the reader with all necessary adjustments in Section (A.3). We discriminate the effects according to the origin of the shocks. To make the paper self-contained, only the foreign TFP and monetary policy shocks are discussed.[37]

Figure (C.11) shows the dynamic impulse responses to one standard deviation expansionary technological shock.[38] As expected, the response comes with positive supply shock effects: the decline in the marginal cost causes the foreign output, consumption and investment to expand. This shift of the aggregate supply reduces *ispo facto* the price level in the short run. Accordingly, the foreign monetary authority reacts to the deflationary pressures by accommodating its short-term nominal interest rate downwards, which amplifies the response of foreign aggregate demand and accommodates the deflationary pressures. The sustained foreign demand supports its domestic counterpart, and brings in positive momentum for the domestic production, which benefits domestic consumption and investment, yet on a smaller scale. Similarly, the domestic key interest rate is diminished, with all subsequent consequences on home inflation and supply. The appreciation of the home currency reduces the trade balance, consistent with economic textbooks, while the opposite is at play for the foreign economy.

On the financial front, foreign spreads improve somewhat the lending conditions for foreign households to consume and foreign firms to invest. Domestic spreads react strongly owing to the fact that the home economy is more heavily influenced by the foreign economy as its sheer size is assumed to be greater.[39] Given that loans are the ultimate source of financing investment, foreign bank assets increase substantially in line with the overall improvement of the economic landscape. Meanwhile, foreign households own more resources, driving the expansion of deposits. In contrast to a home shock, aggregate CBDC demand is relatively weak following a foreign productivity shock. It is interesting to notice that foreign variables are more responsive to a foreign shock than domestic variables are to a similar-sized domestic shock (e.g. output, consumption, investment etc...).

We close this Section with Figure (C.12), which depicts the IRF of a foreign monetary tightening. As usual in NK models, a positive foreign shock to the modified Taylor rule leads to an accute and sudden fall in foreign GDP, consumption and investment with foreign inflation decreasing *de facto*. Notice how home output drops by much less than foreign output. A reason often brought forward for such discrepancies is the reaction of the home monetary authority which strives to offset its key policy rate, driving the more muted response. The financial frictions present in the model trigger the financial accelerator mechanism. As the shock propagates into aggregate demand, financial conditions worsen for all bankers, *ceteris paribus*, which are more tempted to steal funds. In turn, bank assets drop upon impact. Surprisingly,

[37]The lines illustrate the responses of the domestic (black) and foreign (red) economies from a domestic shock, whilst the dashed lines do so for a foreign shock.

[38]We provide in Figure (D.3) an Aggregate Supply curve (AS)/Aggregate Demand curve (AD) representation of the productivity shock. In compliance with macroeconomic standards, AS is split into the Short-Run Aggregate Supply curve (SRAS) and the Long-Run Aggregate Supply curve (LRAS).

[39]We assumed the home economy to be relatively smaller to its foreign peer.

ephemeral domestic inflationary pressures are immediately observed upon impact in the home economy. Yet, the immediate increase in the domestic short-term interest rate promptly brings its level back to the steady state. We thus conclude that the anti-Fisherian property is no longer satisfied.

We observe that the greater tightening of foreign monetary policy *relative* to its domestic counterpart leads to a coherent decrease of the overall trade balance. Financial spillovers are also noteworthy: the foreign contractionary shock comes in tandem with a weakening of the exchange rate, both in real and nominal terms, and in line with Ferrari et al. (2020). We refer the reader to Section 7.2 for a complimentary analysis of financial variables, which reads analogously from a foreign standpoint. Although indistinguishable in the IRF, note that the demand for CBDCs is slightly smaller when an unanticipated foreign monetary policy shock arises. This is extremely logical given that for foreigners, the stronger appreciation of foreign currency *relative* to the domestic currency suggests that CBDCs lose somewhat in attractiveness, especially when considering that bonds are also highly remunerated.

Conceding CBDCs a more prominent role as an international safe asset from a foreign economy perspective yields an intuitive insight. Unsurprisingly, we found that the home-grown digital monies are of limited appeal for foreigners when acting as alternative for bonds. The reason is that with a higher remuneration rate, bonds are more popular than CBDCs which have limited added-value in the foreign economy. In other words, demand for digital currencies in the enriched TEM is related to its simpler version, where the digital monies are not accessible beyond borders.

8. The Case of Sweden

In this section, we start by providing a synopsis regarding the state of play of CBDC research in Sweden, after which we relate the relevance of our TEM to the country. We close with the limitations of our analysis and avenues to future work.

The Sveriges Riksbank (SR) started the e-krona project in 2017, making it the European trailblazer when it comes to central bank financial innovation, of which CBDC is the latest manifestation.[40] The rationale of the SR for engaging with the digital currencies is mostly driven by two parallel forces. One the one hand, cash usage is decreasing[41] which could potentially erode the monetary anchor.[42] On the other hand, the Swedish society is highly digitalised, making it a fertile ground to study the need for, and the effects of a CBDC on their economy. Their cash-to-GDP ratio has fallen to 1.3 percent, and the share of the adult population using the national mobile payment system Swish is reaching record highs (IMF (2021)).

Currently, the project is in Phase 3, which further investigates the technical solution as well as the fulfilment of the requirements for an issuable e-krona. Previous Phases have covered the project description, legal analyses, testing of the integration within banks' and payment service providers' own existing systems and the actual technical solution. At the time of writing, policy makers have not formally nor publicly made a decision regarding its introduction; the impacts are admittedly wide-ranging, with undeniable consequences on society as a whole. An inquiry into the state's role in the payment market and the need for CBDC is currently under way. It is expected that the results of the inquiry stage will be made public prior November 30^{th} 2022.[43] Should a favourable opinion be taken, the legislative process will move ahead and enter the referral stage.

The case of Sweden is of particular importance given its currency in the European landscape. Ferrari et al. (2020) unearthed, among others, that monetary policy is reduced in foreign economies following the domestic issuance of CBDCs owing to increased asymmetries in the global monetary system. In other words, the introduction of digital monies in a jurisdiction (or currency union) is likely to adversely impact other jurisdictions, especially so where a high degree of trade dependence can be reported. In addition, we know that strong, highly liquid and widely-used currencies in cross-border transactions such as the U.S. Dollar or the Euro are often considered as flight-to-safety currencies which would be sought after during times of generalized stress (ECB (2022)). As such, central banks and policymakers seeking to introduce CBDCs ought to consider its cross-border currency substitution implications.[44] In

[40] E-krona is defined as state money, but in digital form. See greater details here.
[41] From 40 percent in 2010, it has fallen to less than 10 percent a decade later.
[42] Acceptability of private means of payment such as bank deposits in commercial bank money, relies on the convertibility at par towards central bank money. Henceforth, as users know that they are able to convert at any time and under any circumstances money received through private means of payment into cash, it provides the necessary confidence for users to trust the private means of payment. Nonetheless, a reduced demand for cash carries the risk of weakening this link.
[43] A two-year period was granted to fulfill the assignment. See the Committee directive press release from the Swedish Ministry of Finance.
[44] For instance, cross-border currency substitution is expected to be greater for weak currencies with unstable economies.

regard to the Swedish krona, the currency is admittedly less widely used *relative* to the euro, making it prone for a certain degree of currency substitution. In turn, if a significant part of Swedish bank deposits are converted into an unrestricted digital euro, it would potentially affect the demand for the Swedish krona. In the extreme scenario where the digital euro becomes widely used in Sweden, banks may face a gradual change in their business model as direct consequence of a reduction in bank deposits, not to mention the financial stability risks it would create should Swedish citizens find it more attractive to hold digital euros. Nonetheless, the SR lies currently at a further stage of maturity compared to the ECB, which could grant itself "a significant first-mover advantage" (Ferrari et al. (2020)).

While this current work strives to encompass developments made by the SR on theoretical grounds, it goes without saying that the technicalities, and intricacies of the e-krona project go beyond the scope of this Master Thesis.

The Swedish economy is a small, open and competitive economy which participates actively in international trade, for which it displays a high degree of openness. It is strongly dependent on global economic developments upon which it has, if any, little influence on (Corbo and Strid (2020)). There exists a considerable body of literature on the synchronized Swedish and foreign business cycles, with financial variables (e.g. stock indices, interest rates, spreads...) empirically drawing the strongest relationships. In addition, a series of recent studies have indicated that the common SOE models tended to generate little international comovements (Justiniano and Preston (2010) and Alpanda and Aysun (2014)), and that cross-country spillovers and comovements are better captured by TEM. Sweden's government spending also accounts for a large share amounting over 50 percent of the country's GDP. Despite room for improvement in terms of adequacy of current models, the SR believe in structural models such as the recent DSGE model MAJA as being currently most appropriate.

Our TEM shares numerous features in line with the MAJA model.[45] While our extension model lacks several critical ingredients, it may provide a flexible starting point in future endeavors of analysing the impact of CBDCs within small economies. We leave such undertakings to future research.[46] In addition, our enriched TEM opens the door for curious minds to study the effects of CBDCs on QE, insofar negligible adjustments are made.

Finally, let us close this section by highlighting some serious caveats to our model, as well as avenues to future work. Our model turned a blind eye on habit formation in consumption, which is crucial for capturing various stylized facts in the fields of macroeconomics and finance. For instance, its absence entails that a decline in the key policy rate leads to a near immediate jump of consumption, which is at odds from empirical data. The latter suggest that habit formation in consumption better captures

[45]The MAJA model is a two-country model, where the foreign economy embodies the rest of the world. The two economies are made of firms which produce goods operating in monopolistic competition and maximizing profits, households which gain utility from consumption and leisure, and they offer their labor to firms, a government, and a central bank.

[46]It includes among others a welfare analysis, taking the model to the data, studying its properties, and measuring its forecast accuracy.

its hump-shape response. In addition, the Uncovered Interest Parity and the dynamic interlinkages between the CBDC rate and other interest rates have been to a large extent ignored. A CBDC interest rate rule would have better captured the idea that central banks are actively able to adjust the CBDC interest rate to disincentivize its accumulation, especially in times of financial distress. Furthermore, we followed Gross and Schiller (2020) for the CBDC parameters. Nonetheless, little to no benchmark exists thus far when it comes to the utility weight of CBDC and its elasticity, leading presumably to inaccurate and adventurous responses of CBDC demand at the very least.[47] The inclusion of quantitative limits on indiviudal holdings and a tiering remuneration rate should also constitute the core of future work. At last, we notice the reader that a more appropriate and rigorous parametrization is desirable if the case of Sweden were to be solely analysed.[48]

We invite future research to cover our omissions and audacious assumptions, and go beyond. For instance, the researcher should be interested in inserting a global interbank market, which could help explain the propagation (and implications) of global financial crises in open economies and in the presence of digital monies, expected to heighten such international spillovers (Ferrari et al. (2020)).[49] Another promising and uncharted territory relates to the synergies between CBDCs and macroprudential policies. A recent study by Srivastava (2021) concluded that "CBDCs could have a significant impact on the conduct of macroprudential policy." To the best of our knowledge, no DSGE model has ever captured such intriguing interdependences. Also of relevance is the modified Taylor rule. The latter could also be supplanted by the specification of McCallum (1988), wherein the stance of monetary policy is defined in terms of money supply growth in contrast to the usual policy rate. An advantage thereof relates to its compatibility with a policy regime that controls for stable inflation. In his own words, the rule is "designed to be insensitive to regulatory changes and technical innovations in the payments and financial industries" (McCallum (1988)).

[47] See Appendix (C.1) through (C.4).

[48] In exchange for calibration which relies on empirical micro literature, using formal econometric sampling theory to estimate parameters is nowadays standard. This endeavor goes beyond the scope of the present work.

[49] Nuguer (2016) developed a DSGE TEM with global banks, i.e. financial intermediaries of the country A are the lenders of country B and *vice-versa*. The author's main goal was to "capture the international transmission of a financial crisis through the balance sheet of the global banks (...)." In addition, the structure closely follows Gertler and Karadi (2011), which suggests little adjustments necessary to include such global banking sector in ours. See Technical Appendix for reproducibility.

9. Conclusion

Introducing CBDCs have significant economic and financial implications for the home and foreign economy, most apparent during an adverse monetary tightening. Real and financial international spillovers are amplified in light of the digital monies, in accordance with earlier findings of Ferrari et al. (2020). We also conclude that the IRF largely depends upon the assumptions made concerning the CBDC parameters: the greater the elasticity, the larger the IRF and the smaller the utility weight, the greater the IRF, *ceteris paribus*. In addition, we found that the two models yield qualitatively comparable results, despite somewhat smoother responses for the TEM. At last, we have shown that demand for the digital monies was left unchanged to the baseline extension when offered as lower remunerated alternative to bonds for the foreign economy.

Altogether, central banks are seeking to minimise by design the risks related to the introduction of the CBDCs, hence it does not come as a surprise that our results support the idea that monetary policy is likely to operate similarly as it currently does at first, consistent with contemporaneous academic literature.

Those main results are the outcome of (i) a simple SOE DSGE model, and (ii) its respective TEM enlargement, with an interest-bearing CBDC and with financial frictions in the banking sector. However, the conclusions should be viewed with a great amount of caution due to serious caveats and crucial omissions as cited earlier.

We close with the case of Sweden, which is expected to issue a CBDC in the medium term. Our enriched TEM provides a flexible starting point for future work on the impact of digital monies in open economies. Its micro-founded general-equilibrium structure is rich, easily adaptable to the country, and captures well the Friedmanite wisdom. The framework naturally lends itself to many extensions as shown above.

Overall, our paper speaks to academics and policymakersalike to whom (i) a clean slate for the analysis of CBDCs in open economies is outlined, and (ii) a thorough literature review of the monetary and financial implications of such digital currencies is summarized.

A. Appendix

In this Appendix, we present the reader with the equilibrium equations of the baseline model, the additional equations coming from its extension to the TEM and its respective equilibrium equations. At last, we expand on solving the model.

A.1. Equilibrium Equations of Baseline

A.1.1. Households

$$\lambda_t = c^{-\sigma} \tag{A.1}$$

$$\lambda_t = \beta\, E_t \left(\lambda_{t+1}\, \frac{r_t}{\pi_{t+1}} \right) \tag{A.2}$$

$$\lambda_t = \beta\, E_t \frac{\left(\lambda_{t+1}\, r_t^{\star}\, \frac{rexr_{t+1}}{rexr_t} \right)}{\left[1 - \zeta_D\, (d_{f_t} - \overline{d_f}) \right]} \tag{A.3}$$

$$\lambda_t = \beta\, E_t \left[\lambda_{t+1}\, \frac{\left(r_{t+1}^k + (1-\delta)\, q_{t+1} \right)}{q_t} \right] \tag{A.4}$$

$$\zeta_L\, h_t^{\phi} = w_t\, \lambda_t \tag{A.5}$$

$$1 = q_t \left[1 - \frac{\zeta_I}{2} \left(\frac{i_t}{i_{t-1}} - 1 \right)^2 - \zeta_I\, \frac{i_t}{i_{t-1}} \left(\frac{i_t}{i_{t-1}} - 1 \right) \right] + \beta\, \zeta_I\, E_t \left\{ q_{t+1}\, \frac{\lambda_{t+1}}{\lambda_t} \left(\frac{i_{t+1}}{i_t} - 1 \right) \left(\frac{i_{t+1}}{i_t} \right)^2 \right\} \tag{A.6}$$

$$cbdc_t^{-\Gamma} = \frac{1}{\Upsilon}\, \beta\, E_t \left(\frac{r_t^{cbdc}\, \lambda_{t+1}}{\lambda_t\, \pi_{t+1}} \right) \tag{A.7}$$

$$\mu^M\, m_t^{-\vartheta} = \lambda_t - E_t\, \beta\, \xi^M \left(\frac{\lambda_{t+1}}{\pi_{t+1}} \right) \tag{A.8}$$

A.1.2. Firms

$$y_{H_t} = a_t\, (k_{t-1}\, kQ_t)^{\alpha}\, h_t^{1-\alpha} \tag{A.9}$$

$$y_{H_t}\, (1-\alpha)\, mc_t = h_t\, w_t \tag{A.10}$$

$$y_{H_t}\, \alpha\, mc_t = k_{t-1}\, {r^k}_t \tag{A.11}$$

$$r_t^k = r_t^b\, q_{t-1} - (1-\delta)\, kQ_t\, q_t \tag{A.12}$$

$$k_t = (1-\delta)\, k_{t-1}\, kQ_t + i_t \left(1 - \frac{\zeta_I}{2} \left(\frac{i_t}{i_{t-1}} - 1 \right)^2 \right) \tag{A.13}$$

$$\pi_{Ht}\, (\pi_{Ht} - \overline{\pi}) = \beta\, E_t \left[\pi_{H_{t+1}} \left(\frac{\lambda_{t+1}}{\lambda_t} \right) \left(\frac{p_{H_{t+1}}\, y_{H_{t+1}}}{y_{H_t}\, p_{H_t}} \right) (\pi_{Ht+1} - \overline{\pi}) \right] + \frac{\epsilon}{\zeta_P} \left(\frac{mc_t}{p_{H_t}} - \frac{\epsilon - 1}{\epsilon} \right) \tag{A.14}$$

A.1.3. Banking Sector

$$lev_t = \frac{E_t\left[\beta\,\frac{r_t}{\pi_{H\,t+1}}\,\frac{\lambda_{t+1}}{\lambda_t}\,bdf_{\,t+1}\right]}{\theta - E_t\left[\beta\frac{\lambda_{t+1}}{\lambda_t}\,bdf_{\,t+1}\left(r^b{}_{t+1} - \frac{r_t}{\pi_{H\,t+1}}\right)\right]} \tag{A.15}$$

$$bankAss_t = cbdc_t + dep_t + n_t + m_t \tag{A.16}$$

$$n_t = n_{e_t} + n_{n_t} \tag{A.17}$$

$$n_{et} = \chi\left[\frac{r_{t-1}}{\pi_{H\,t}} + \left(r_t^b - \frac{r_{t-1}}{\pi_{H\,t}}\right) lev_{t-1}\right] n_{t-1} \tag{A.18}$$

$$n_{n_t} = \iota\, bankAss_{t-1} \tag{A.19}$$

$$bdf_{\,t} = 1 - \chi + \chi\,\beta\,E_t\left\{bdf_{\,t+1}\,\frac{\lambda_{t+1}}{\lambda_t}\left[\frac{r_t}{\pi_{H\,t+1}} + lev_t\left(r_{t+1}^b - \frac{r_t}{\pi_{H\,t+1}}\right)\right]\right\} \tag{A.20}$$

A.1.4. Market Clearing

$$y_{H_t} = (1-\gamma)\,(p_{H_t})^{-\eta}\,(c_t + i_t) + g_t + \gamma^\star\,y_t^\star\,tot_t^\eta + y_{H_t}\,\frac{\zeta_P}{2}\,(\pi_{H\,t} - \overline{\pi})^2 \tag{A.21}$$

$$gdp_t = c_t + i_t + p_{H_t}\,g_t + rexr_t\,r_{t-1}^\star\,d_{f_{t-1}} - rexr_t\,d_{f_t} + \frac{\zeta_P}{2}\,(\pi_{H\,t} - \overline{\pi})^2\,gdp_t + \frac{rexr_t\,\zeta_D}{2}\,(d_{f_t} - \overline{d_f})^2 \tag{A.22}$$

$$q_t\,k_t = bankAss_t + d_{H_t}^{qe} \tag{A.23}$$

A.1.5. Pricing

$$1 = \gamma\,rexr_t^{1-\eta} + (1-\gamma)\,(p_{H_t})^{1-\eta} \tag{A.24}$$

$$\pi_{H\,t} = \frac{p_{H_t}}{p_{H_{t-1}}}\,\pi_t \tag{A.25}$$

A.1.6. Policy

$$\frac{r_t}{\overline{r}} = \left[\left(\frac{\pi_t}{\overline{\pi}}\right)^{\phi_\pi}\left(\frac{gdp_t}{\overline{gdp}}\right)^{\phi_y}\left(\frac{nomdep_t}{\overline{nomdep}}\right)^{\phi_e}\right]^{1-\rho_m}\left(\frac{r_{t-1}}{\overline{r}}\right)^{\rho_m}\,\exp(\epsilon_{mp_t}) \tag{A.26}$$

$$\frac{d_{H_t}^{qe}}{\overline{d_H^{qe}}} = \left[\left(\frac{spr_t}{\overline{spr}}\right)^{\phi_{qe}}\right]^{1-\rho_{qe}}\left(\frac{d_{H_{t-1}}^{qe}}{\overline{d_H^{qe}}}\right)^{\rho_{qe}}\,\exp(\epsilon_{qe_t}) \tag{A.27}$$

A.1.7. Shocks

$$\log(a_t) = (1-\rho_a)\ \log(\overline{a}) + \rho_a\ \log(a_{t-1}) + \epsilon_{at} \tag{A.28}$$

$$\log(g_t) = (1-\rho_g)\ \log(\overline{g}) + \rho_g\ \log(g_{t-1}) + \epsilon_{g_t} \tag{A.29}$$

$$\log({y^\star}_t) = \rho_y\ \log({y^\star}_{t-1}) + \epsilon_{fy_t} \tag{A.30}$$

$$\log(kQ_t) = \rho_s\ \log(kQ_{t-1}) + \epsilon_{kt} \tag{A.31}$$

$${r^\star}_t = \left(\frac{1-\rho_p}{\beta}\right) + {r^\star}_{t-1}\,\rho_p + \epsilon_{fmp_t} \tag{A.32}$$

A.1.8. Others

$$r_t^r = \frac{r_t}{E_t\left[\pi_{t+1}\right]} \tag{A.33}$$

$$r_t^{cbdc} = \left[1 + (r_t^b - r_t)\right] \tag{A.34}$$

$$spr_t = E_t\left[{r^b}_{t+1} - \frac{r_t}{\pi_{H\,t+1}}\right] \tag{A.35}$$

$$\frac{rexr_t}{rexr_{t-1}} = \frac{nomdep_t}{\pi_t} \tag{A.36}$$

$$gdp_t = y_{H_t}\,p_{H_t} \tag{A.37}$$

$$tb_t = X_t - M_t \tag{A.38}$$

$$X_t = tot_t^\eta\,{y^\star}_t\,p_{H_t}\,\gamma^\star \tag{A.39}$$

$$M_t = (c_t + i_t)\,\gamma\,rexr_t^{1-\eta} \tag{A.40}$$

$$tot_t = \frac{rexr_t}{p_{H_t}} \tag{A.41}$$

In the baseline scenario, there are 41 equations for 41 endogenous variables, i.e. $[a_t, bankAss_t, bdf_t, c_t, cbdc_t, d_{H_t}^{qe}, d_{f_t}, dep_t, g_t, gdp_t, h_t, i_t, k_t, kQ_t, \lambda_t, lev_t, mc_t, M_t, m_t, n_t, n_{e_t}, n_{n_t}, nomdep_t, p_{H_t}, \pi_t, \pi_{H_t}, q_t, r_t, r_t^\star, r_t^{cbdc}, r_t^b, r_t^k, r_t^r, rexr_t, spr_t, tb_t, tot_t, w_t, X_t, y_{H_t}, y_t^\star]$. In addition, the model draws 7 exogenous shocks, i.e. $[\epsilon_a, \epsilon_{fy}, \epsilon_{fmp}, \epsilon_g, \epsilon_k, \epsilon_{mp}, \epsilon_{qe}]$.

A.2. Model Extension Overview

In the interest of space and simplicity, we solely focus on the domestic case for all equations unless otherwise specified. Thanks to the intrinsic symmetrical structure of this first TEM, all the following still hold within their foreign setting, unless otherwise stated, where variables would take a star symbol (*) to differentiate themselves from their home peers. We maintain common conventions where H symbolizes the home economy and F the foreign economy. In addition, we are following the identical red line from Section 5 and present the reader with the main technical changes of the extension.

A.2.1. Households

We build on Equations (1) and (2), and we replace Equation (3) by

$$P_{H_t} = e_t \, P^\star_{H_t}, \tag{A.42}$$

where $P^\star_{H_t}$ are domestic goods priced in foreign currency. Equations (4) through (10) continue to hold in the two-economy setting, with the exception of Equations (9) and (10) which see CBDCs fade in the foreign economy only. Equation (11) fully disappears from the extension at the expense of the introduction of a foreign Taylor rule similar to Equation (52) and Equation (12) only prevails within the home economy. In addition, Equations (13) through (19), (21) and (22) included remain identical with the exception of Equation (14) whose third term of the utility function clearly disappears from the foreign economy. The first order condition with regard to the one-period internationally traded home bond of Equation (20) is slightly adjusted to the foreign future inflation rate $\pi^\star_{t+1}$

$$\lambda_t = \beta \, E_t \frac{\left(\lambda_{t+1} \, \frac{r^\star_t}{\pi^\star_{t+1}} \, \frac{rexr_{t+1}}{rexr_t}\right)}{\left[1 - \zeta_D \left(d_{f_t} - \overline{d_f}\right)\right]}. \tag{A.43}$$

A.2.2. Firms

Home and foreign intermediate and final-good firms within the extension are identical to the SOE baseline framework. As such, Equations (23) to (34) remain unchanged.

A.2.3. Banking Sector

A banking sector exists in both economies, meaning that Equations (35) to (47) continue to rule in the extension of the baseline model.[50] Nonetheless, no CBDCs are issued in the foreign economy. The structure of the international financial markets is left to its minimum, i.e. citizens of each economies have mutual access to one-period state-contingent home and foreign bonds.

[50] We will assume at first that the home economy only issues and has access to CBDCs.

A.2.4. Policy

The home consolidated budget constraint of Equation (48) is identical to the SOE baseline but its foreign counterpart sees CBDCs disappear from it. Equations (49) and (52) hold for both economies.

A.2.5. Market Clearing

Within this section, solely Equation (58) holds for the both economies. The home and foreign goods clearing equations are

$$y_{H_t} = (1-\gamma)\, p_{H_t}^{-\eta}\, (c_{H_t} + i_{H_t}) + g_t + \frac{(1 - rPopH)}{rPopH}\, \gamma^\star\, p_{H_t}^{\star\,-\eta}\, (c_{H_t}^\star + i_{H_t}^\star) + \left[\frac{\zeta_P}{2}\left(\pi_{H_t} - \overline{\pi}\right)^2\right] y_{H_t}, \tag{A.44}$$

$$y_{F_t}^\star = (1-\gamma^\star)\, p_{F_t}^{\star\,-\eta}\, (c_{F_t}^\star + i_{F_t}^\star) + g_t^\star + \left(\frac{rPopH}{1 - rPopH}\right) \gamma\, p_{F_t}^{-\eta}\, (c_{H_t} + i_{H_t}) + \left[\frac{\zeta_P}{2}\left(\pi_{F_t}^\star - \overline{\pi^\star}\right)^2\right] y_{F_t}^\star, \tag{A.45}$$

where $rPopH$ is the relative home population parameter compared to its foreign counterpart. In addition to the bond market clearing condition stemming from the domestic and foreign banking sector, another twofold bond clearing conditions emerge from the simplistic structure of the international financial markets whereby home and foreign bonds are mutually accessible. This leads to the following home and foreign bond clearing equations

$$rPopH\, d_{H_t} + (1 - rPopH)\, d_{H_t}^\star = 0, \tag{A.46}$$

$$rPopH\, d_{F_t} + (1 - rPopH)\, d_{F_t}^\star = 0, \tag{A.47}$$

where d_{H_t} and $d_{H_t}^\star$ are the home holdings of domestic and foreign bonds respectively. The domestic clearing goods market simplifies to

$$gdp_t = p_{H_t}\, g_t + c_t + i_t + tb_t + p_{H_t}\, y_{H_t}\, \frac{\zeta_P}{2}\left(\pi_{H_t} - \overline{\pi}\right)^2, \tag{A.48}$$

where the trade balance tb_t remains the difference between exports and imports, i.e. the value of goods and investment bought from foreign minus the value of goods and investment sold to foreign, depicted as follows

$$tb_t = \left[p_{F_t}\, (i_{F_t} + c_{F_t})\right] - \left[\left(\frac{1 - rPopH}{rPopH}\right) p_{H_t}\, (i_{H_t}^\star + c_{H_t}^\star)\right]. \tag{A.49}$$

In addition, capital flows exist between economies such that inflows k_{inf_t} and outflows k_{out_t} are characterized by the difference between home (foreign) bonds from period t and $t-1$

$$k_{inf_t} = d_{H_t} - d_{H_{t-1}}, \tag{A.50}$$

$$k_{out_t} = (d_{F_t} - d_{F_{t-1}})\, s_t. \tag{A.51}$$

The domestic capital balance $kBal_t$ and the GDP adjusted financial balance $AdjFinBal_t$ read as

$$kBal_t = k_{inf_t} - k_{out_t}, \tag{A.52}$$

$$AdjFinBal_t = \frac{1}{gdp_t}\,(d_{F_t}\,rexr_t + d_{H_t}). \tag{A.53}$$

In a similar vein to the baseline model, this stylized description completes the extension description, and we call the reader to refer to the section in the Appendix (A.3) for the completion of all the domestic equilibrium equations used in the model.

A.3. Equilibrium Equations of Extension

A.3.1. Households

Equations (A.1), (A.2) and (A.4) through (A.8) remain valid, although the latter disappears from the foreign economy. Former Equation (A.3) becomes

$$\lambda_t = \beta\, E_t \frac{\left(\lambda_{t+1}\, \frac{r^\star_t}{\pi^\star_{t+1}}\, \frac{rexr_{t+1}}{rexr_t}\right)}{\left[1 - \zeta_D\, (d_{f_t} - \overline{d_f})\right]}. \tag{A.54}$$

A.3.2. Firms

Equilibrium equations (A.9) to (A.14) hold.

A.3.3. Banking Sector

Equilibrium equations (A.15) through (A.20) remain valid.

A.3.4. Market Clearing

In addition to Equation (A.23), we have

$$gdp_t = p_{H_t}\, g_t + c_t + i_t + tb_t + p_{H_t}\, y_{H_t}\, \frac{\zeta_P}{2}\left(\pi_{H_t} - \overline{\pi}\right)^2, \tag{A.55}$$

$$y_{H\,t} = g_t + (1-\gamma)\, p_{H\,t}^{-\eta}\, (c_t + i_t) + \frac{1 - relPopH}{relPopH}\, \gamma^\star\, p^\star_{H\,t}{}^{-\eta}\, (c^\star{}_t + i^\star{}_t) + y_{H\,t}\, \frac{\zeta_P}{2}\, (\pi_{H\,t} - \pi_{ss})^2 \tag{A.56}$$

$$y^\star_{F_t} = (1-\gamma^\star)\, p^\star_{F_t}{}^{-\eta}\, (c^\star_{F_t} + i^\star_{F_t}) + g^\star_t + \left(\frac{rPopH}{1 - rPopH}\right) \gamma\, p_{F_t}^{-\eta}\, (c_{H_t} + i_{H_t}) + \left[\frac{\zeta_P}{2}\left(\pi^\star_{F_t} - \overline{\pi^\star}\right)^2\right] y^\star_{F_t}, \tag{A.57}$$

$$rPopH\, d_{H_t} + (1 - rPopH)\, d^\star_{H_t} = 0, \tag{A.58}$$

$$\begin{aligned} tb_t = {} & d_{H\,t} - \frac{r_{t-1}}{\pi_{H\,t}}\, d_{H\,t-1} - rexr_t\, d_{F\,t} - \frac{rexr_t\, r^\star_{t-1}}{\pi^\star_{H_t}}\, d_{F\,t-1} \\ & - \frac{\zeta_D}{2}\, \frac{1 - relPopH}{relPopH}\, (d^\star_{H\,t} - \overline{d^\star_H})^2 + \frac{\zeta_D}{2}\, rexr_t\, (d_{F\,t} - \overline{d_F})^2 \end{aligned} \tag{A.59}$$

$$\begin{aligned} tb^\star_t = {} & d_{F}{}^\star_t - \frac{r_{t-1}}{\pi_{H\,t}\, rexr_t}\, d_{H}{}^\star_{t-1} - rexr_t\, d_{F\,t} - \frac{r^\star_{t-1}}{\pi^\star_{H_t}}\, d_{F}{}^\star_{t-1} \\ & - \frac{\zeta_D}{2}\, \frac{relPopH}{1 - relPopH}\, (d_{F\,t} - \overline{d_F})^2 + \frac{\zeta_D}{2}\, \frac{1}{rexr_t}\, (d_{H}{}^\star_t - \overline{d_H}^\star)^2 \end{aligned} \tag{A.60}$$

A.3.5. Pricing

Equation (A.25) holds.

$$1 = \gamma \, {p_{F}}_t^{1-\eta} + (1-\gamma) \, {p_{H}}_t^{1-\eta} \tag{A.61}$$

$$p_{H\,t} = rexr_t \, p^{\star}_{H\,t} \tag{A.62}$$

A.3.6. Policy

Equations (A.26) and (A.27) hold.

A.3.7. Shocks

Equations (A.28), (A.29), and (A.31) stay valid.

A.3.8. Others

Equations (A.33) to (A.37) hold.

$$k_{inf_t} = d_{H_t} - d_{H_{t-1}} \tag{A.63}$$

$$k_{out_t} = (d_{F_t} - d_{F_{t-1}}) \, rexr_t \tag{A.64}$$

$$kBal_t = k_{inf_t} - k_{out_t} \tag{A.65}$$

$$AdjFinBal_t = \frac{1}{gdp_t} \, (d_{F_t} \, rexr_t + d_{H_t}) \tag{A.66}$$

Finally, the reader should read Equations (A.1), (A.2), (A.54), (A.4) to (A.6), (A.8 (A.9) to (A.20), (A.23), (A.56), (A.58), (A.59), (A.25), (A.61), (A.62), (A.26) to (A.29), (A.31), (A.33), (A.35) to (A.37) and (A.63) to (A.66) as equally valid for the foreign economy. The remaining two equations are either common to both (A.55 and A.34) or only hold for the domestic economy (A.7). In total, we have 81 variables and 81 equations. In contrast to the baseline model, the extension has nine exogenous shocks, i.e. $[\epsilon_a, \epsilon_{a^\star}, \epsilon_{fmp}, \epsilon_g, \epsilon_{g^\star}, \epsilon_k, \epsilon_{k^\star}, \epsilon_{mp}, \epsilon_{qe}]$.

In subsection (7.3), we enrich the TEM. For that purpose, we first modify the following two home Equations (A.50) and (A.53), after which we supplement with the foreign equations:

$$k_{inf_t} = d_{H_t} - d_{H_{t-1}} + (\boldsymbol{cbdc}_t - \boldsymbol{cbdc}_{t-1}) \tag{A.67}$$

$$AdjFinBal_t = \frac{1}{gdp_t} \, (d_{F_t} \, rexr_t + d_{H_t} + \boldsymbol{cbdc}_t) \tag{A.68}$$

$$bankAss^{\star}_t = \boldsymbol{cbdc}_t + dep^{\star}_t + n^{\star}_t + m^{\star}_t \tag{A.69}$$

$$k^{\star}_{out_t} = \frac{\left[(d^{\star}_{H_t} - d^{\star}_{H_{t-1}}) + (\boldsymbol{cbdc}_t - \boldsymbol{cbdc}_{t-1})\right]}{s_t} \tag{A.70}$$

$$AdjFinBal^{\star}_t = \frac{1}{gdp^{\star}_t}\left[\left(d^{\star}_{F_t} + \frac{d^{\star}_{H_t} + \boldsymbol{cbdc}_t}{rexr_t}\right)\right] \tag{A.71}$$

$$q^{\star}_t\, k^{\star}_t = bankAss^{\star}_t + d^{qe\,\star}_{F_t} + \boldsymbol{cbdc}_t \tag{A.72}$$

A.4. Solving the Model

The DSGE model presented above is non-linear and has been solved analytically for a determinate and stable solution to emerge. In particular, we create auxiliary variables to our non-linear model which we considered for the IRF.

Throughout the 1980's, a wave of research in Real Business Cycle models found that log-linearizing the model enabled the use of standard computation techniques to solve the models.[51] While this simple approach performs fairly well around the steady state, this method suffers from a loss of accuracy when deviating too far from it.[52] The rationale behind the argument is that first order linearization only carries the first moment of the shocks, which in turn disappears when expectations are invoked. Thus, as a consequence, unconditional expectations of endogenous variables are equal to their non-stochastic steady state values (Griffoli (2010)). In doing so, we may interpret the responses from the IRF as *percentage deviations* from the trend.

The softwares MATLAB and DYNARE are used for solving the model numerically and generate the IRF (Adjemian et al. (2021)).[53]

[51]See King et al. (1988) and Kydland and Prescott (1982), who pioneered the calibration method for empirical analyses.
[52]As described by Zietz (2008), taking log-deviations around the steady state allows to reduce the computation burden of nonlinear equations.
[53]DYNARE is a software platform for handling a wide class of economic models, in particular DSGE and overlapping generations models. It is freely available on its website.

B. Supplementary Tables

Bank Assets		**Liabilities**	
Reserves	$\left.\begin{matrix} \\ \\ \\ \end{matrix}\right\} bankAss_t(z)$	Money	$m_t(z)$
Interbank Lending		CBDC	$cbdc_t(z)$
Other Assets		Deposits	$dep_t(z)$
		Equity	$n_t(z)$

Table B.1: Bank's z balance sheet

Households		**Baseline**	**Source**
β	Stochastic discount factor	0.99	Bindseil (2020) & Galí and Monacelli (2005)
ϕ	Inverse Frisch elasticity of labor supply	1	Galí and Monacelli (2005)
ζ_L	Labor preference parameter	10.15	Author's elaboration
σ	Inverse of the inter. elasticity of subs. of cons.	1.5	Corbo and Strid (2020)
η	Armington elasticity	3.8	Bajzik et al. (2020)
γ	Trade Openness	0.3	Author's elaboration
Υ	Utility weight of CBDC	0.125	Gross and Schiller (2020)
Γ	Elasticity of liquidity	-0.95	Gross and Schiller (2020)
μ^M	Utility weight of cash	1	Ferrari et al. (2020)
ϑ	Elasticity of substitution	-1.7	Author's elaboration
ξ^M	Storage costs	1	Ferrari et al. (2020)

Banks		**Baseline**	
χ	Survival rate of bankers	0.972	Gertler and Karadi (2011)
θ	Fraction of divertable assets	0.38	Gertler and Karadi (2011)
ι	Transfer to new bankers	0.002	Gertler and Karadi (2011)

Firms		**Baseline**	
ϵ	Elasticity of substitution between diff. goods	6	Galí and Monacelli (2005)
δ	Depreciation rate	0.015	Corbo and Strid (2020)
α	Elasticity of production wrt capital	1/3	Author's elaboration

Central bank and government		**Baseline**	
ϕ_π	Monetary Policy response to inflation	1.5	Gross and Schiller (2020) & Galí and Monacelli (2005)
ϕ_y	Monetary Policy response to output	0.125	Gross and Schiller (2020)
ϕ_{qe}	Monetary Policy response to QE	0	Author's elaboration
ϕ_e	Monetary Policy response to exchange rate	0.125	Author's elaboration

Note: Negligible differences exist within the parameters and their respective referenced authors in light of different dynamics between models.

Table B.2: Summary of key parameters and calibration

Parameters		Baseline
ρ_a	Persistency of TFP shock	0.95
ρ_g	Persistency of Government Spending shock	0.95
ρ_{fmp}	Persistency of Foreign Monetary Policy shock	0.95
ρ_{fy}	Persistency of Foreign Demand shock	0.95
ρ_m	Monetary Policy inertia	0.95
ρ_{qe}	QE inertia	0.95
ρ_s	Persistency of Capital shock	0.66
ϵ_a	Shock in TFP	0.01
ϵ_g	Shock in Government Spending	0.01
ϵ_{fmp}	Shock in Foreign Monetary Policy	0.0025
ϵ_{fy}	Shock in Foreign Demand	0.01
ϵ_m	Shock in Monetary Policy	0.0025
ϵ_{qe}	Shock in QE	0.01
ϵ_s	Shock in Capital	0.05

Table B.3: Summary of exogenous shocks calibration

C. IRF

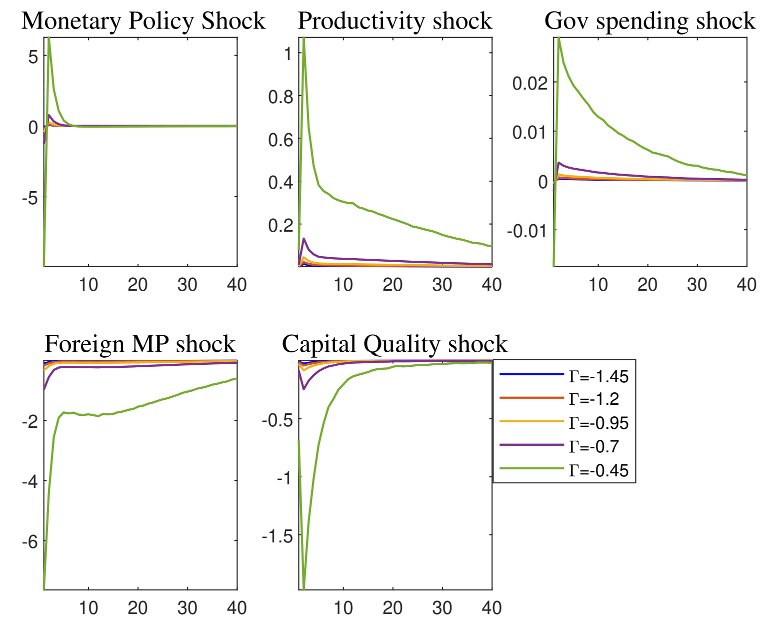


Figure C.1: Shocks on CBDCs depending on parametrization of Γ in SOE baseline, *ceteris paribus*.

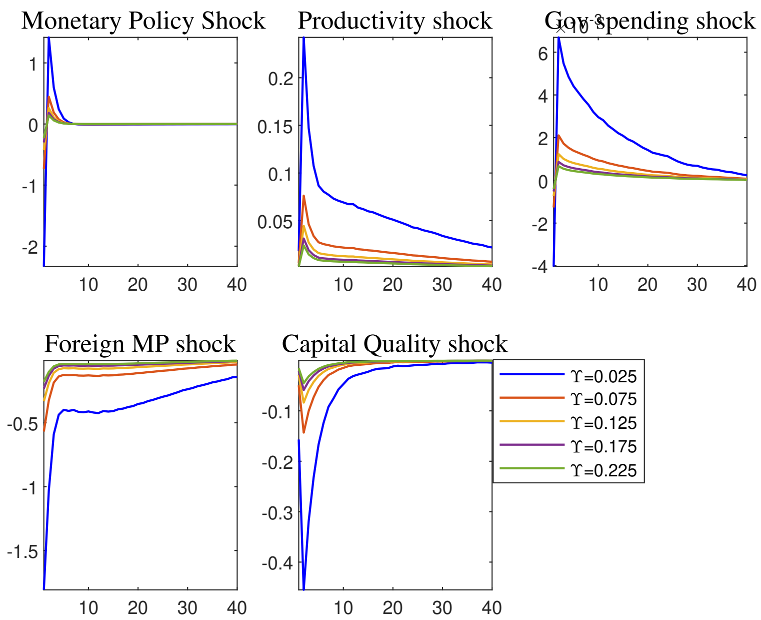


Figure C.2: Shocks on CBDCs depending on parametrization of Υ in SOE baseline, *ceteris paribus*.

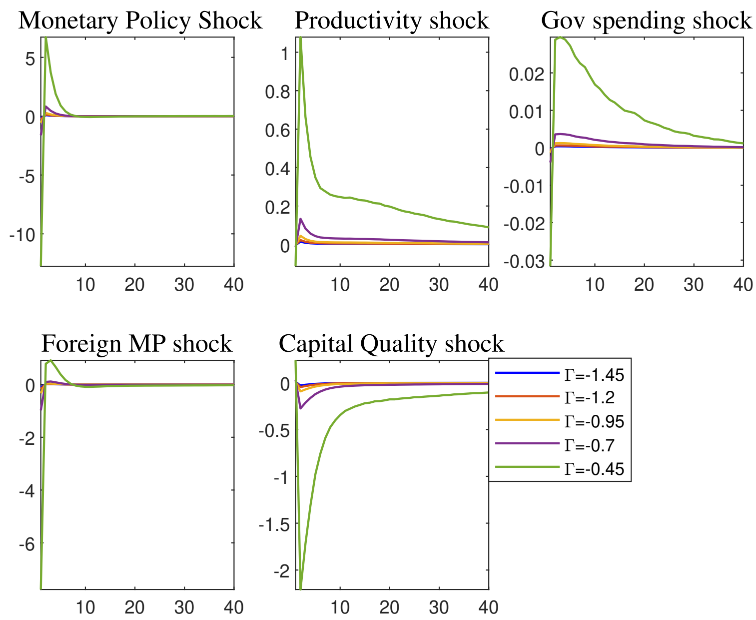


Figure C.3: Shocks on CBDCs depending on parametrization of Γ in initial TEM extension, *ceteris paribus*.

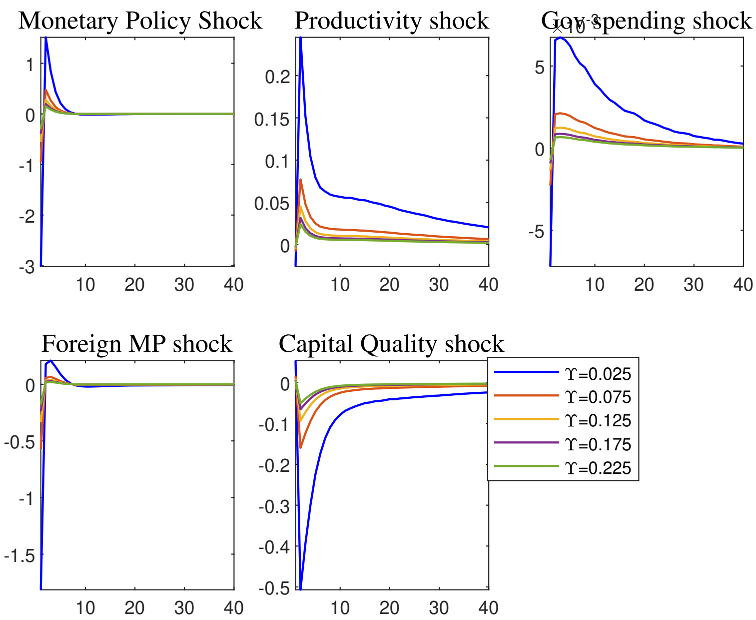


Figure C.4: Shocks on CBDCs depending on parametrization of Υ in initial TEM extension, *ceteris paribus*.

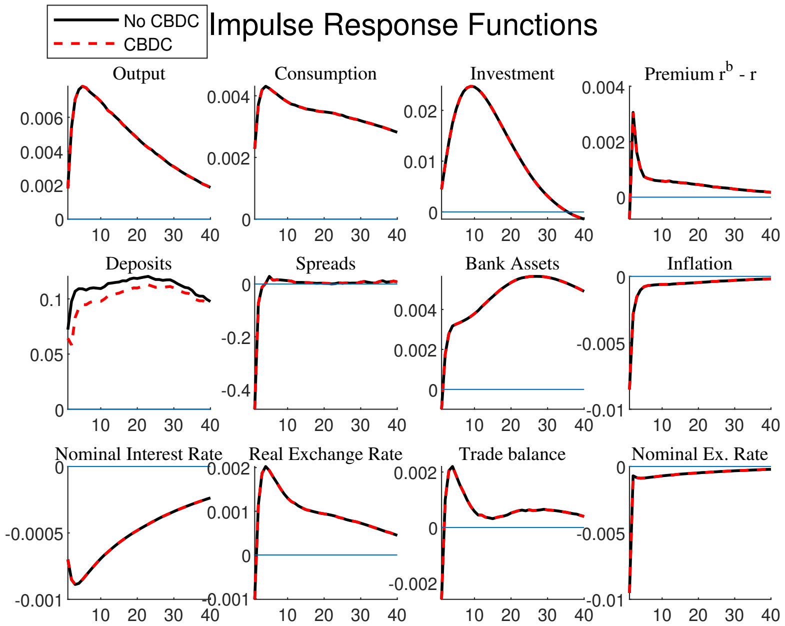


Figure C.5: IRF of selected variables to a one standard deviation expansionary TFP innovation.

Note: Responses are reported as percentage variations from the steady state.

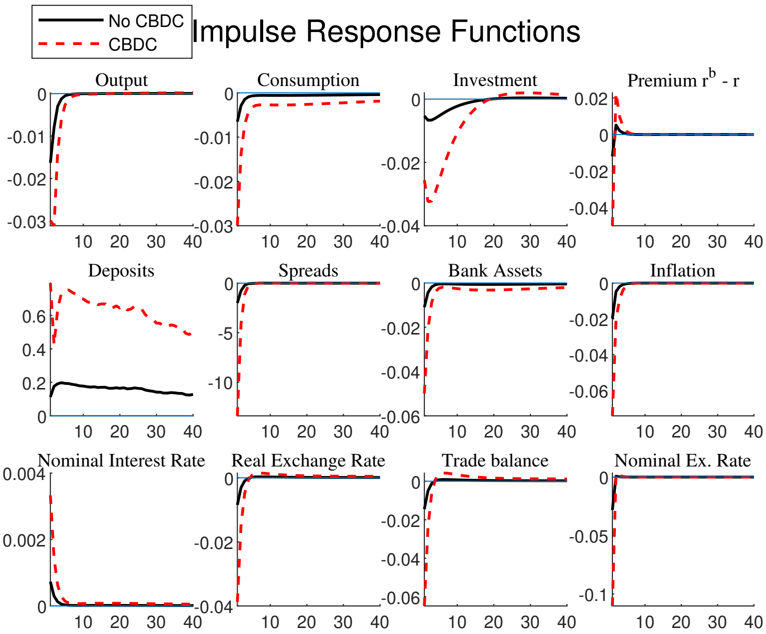


Figure C.6: IRF of selected variables to a contractionary one standard deviation monetary shock.

Note: Responses are reported as percentage variations from the steady state.

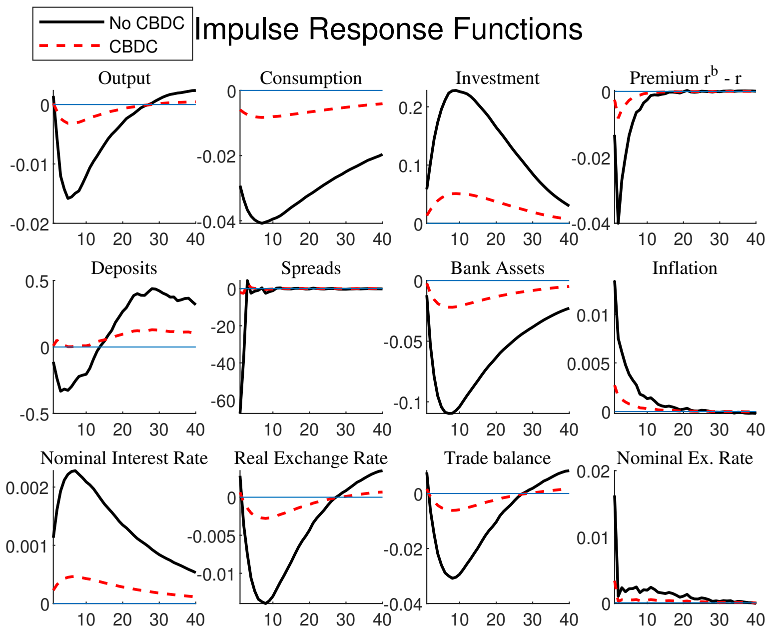


Figure C.7: IRF of selected variables to a 5 percent standard deviation capital quality shock.

Note: Responses are reported as percentage variations from the steady state.

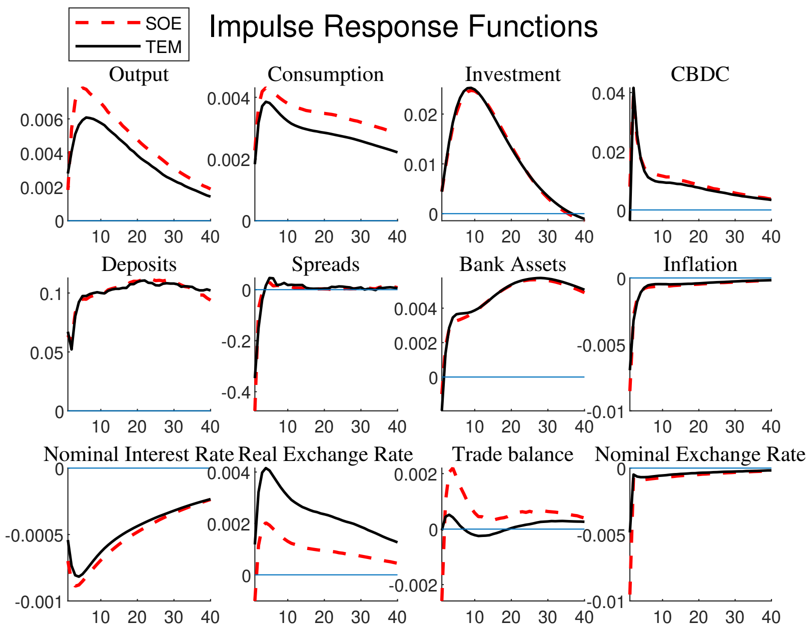


Figure C.8: IRF of selected variables to a one standard deviation expansionary TFP innovation.

Note: Responses are reported as percentage variations from the steady state.

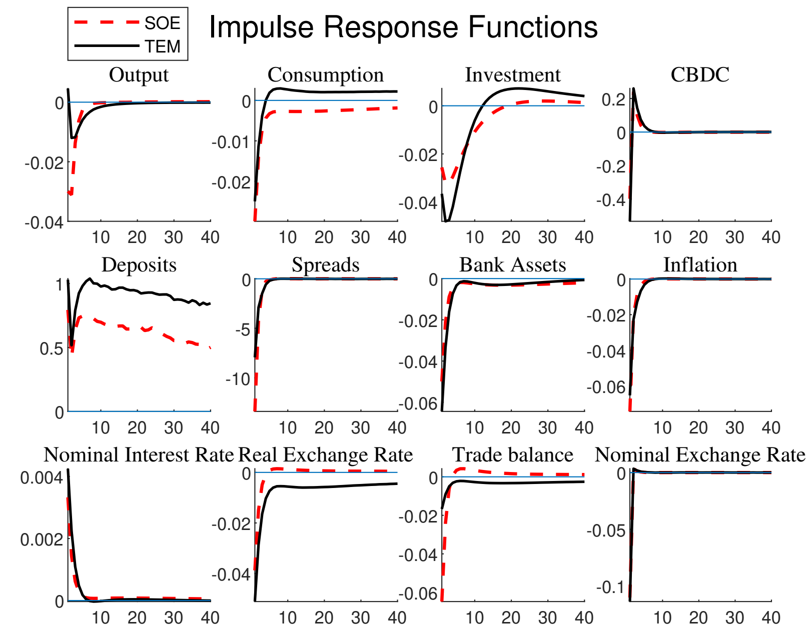


Figure C.9: IRF of selected variables to a contractionary one standard deviation monetary shock.

Note: Responses are reported as percentage variations from the steady state.

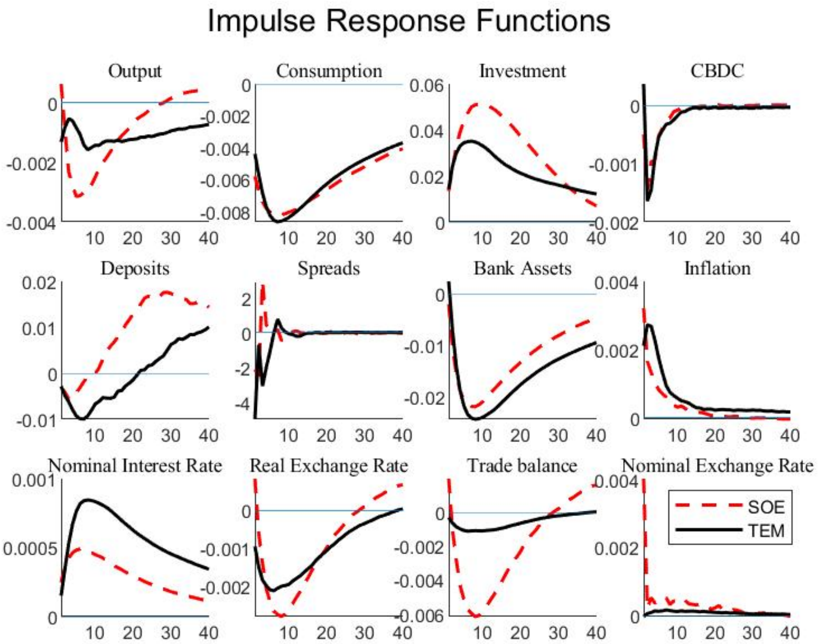


Figure C.10: IRF of selected variables to a 5 percent standard deviation capital quality shock.

Note: Responses are reported as percentage variations from the steady state.

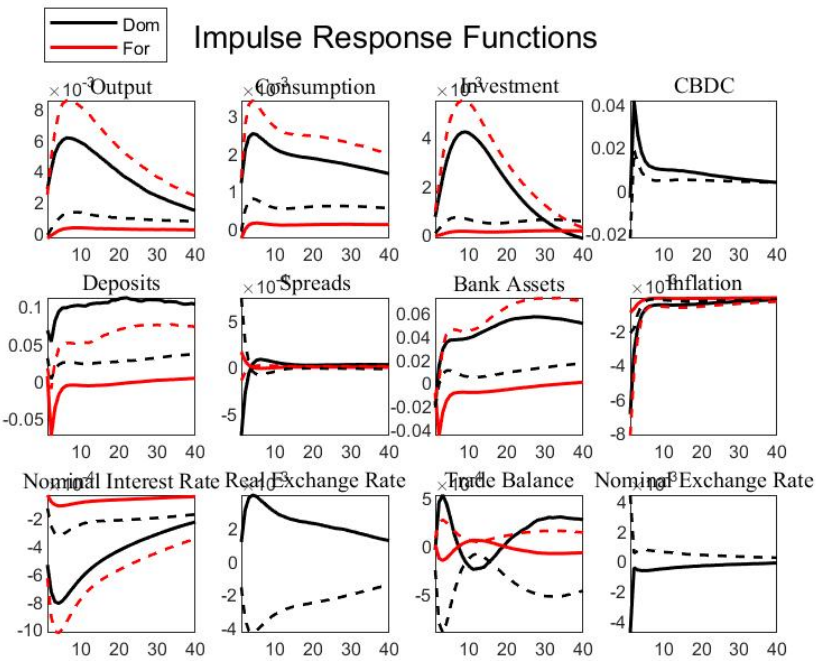


Figure C.11: IRF of selected variables to a domestic (line) and foreign (dash) one standard deviation expansionary TFP innovation.

Note: Responses are reported as percentage variations from the steady state.

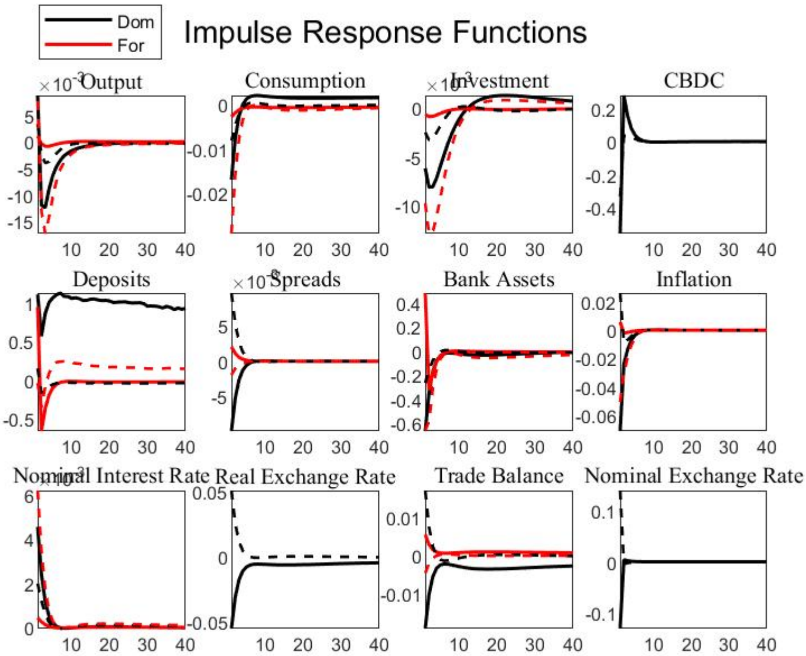


Figure C.12: IRF of selected variables to a domestic (line) and foreign (dash) contractionary one standard deviation monetary shock.

Note: Responses are reported as percentage variations from the steady state.

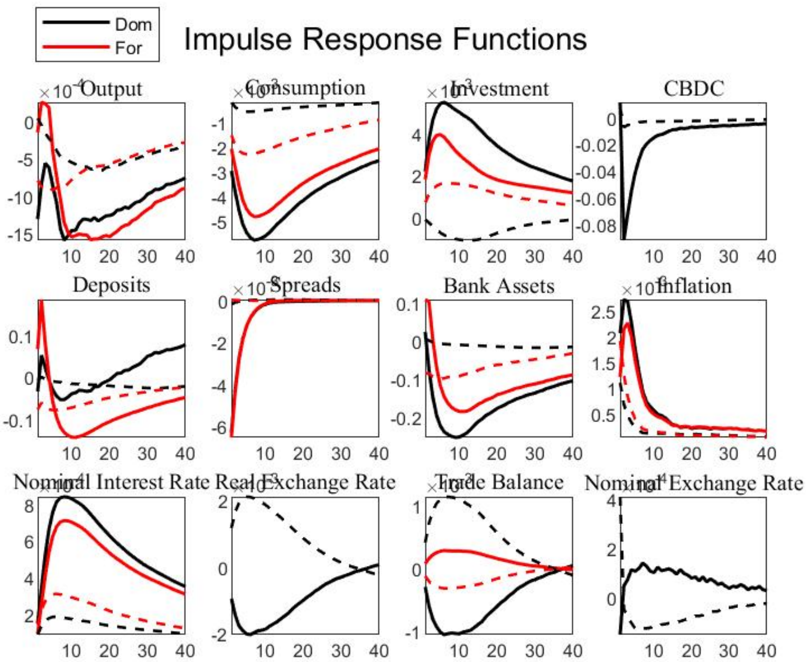
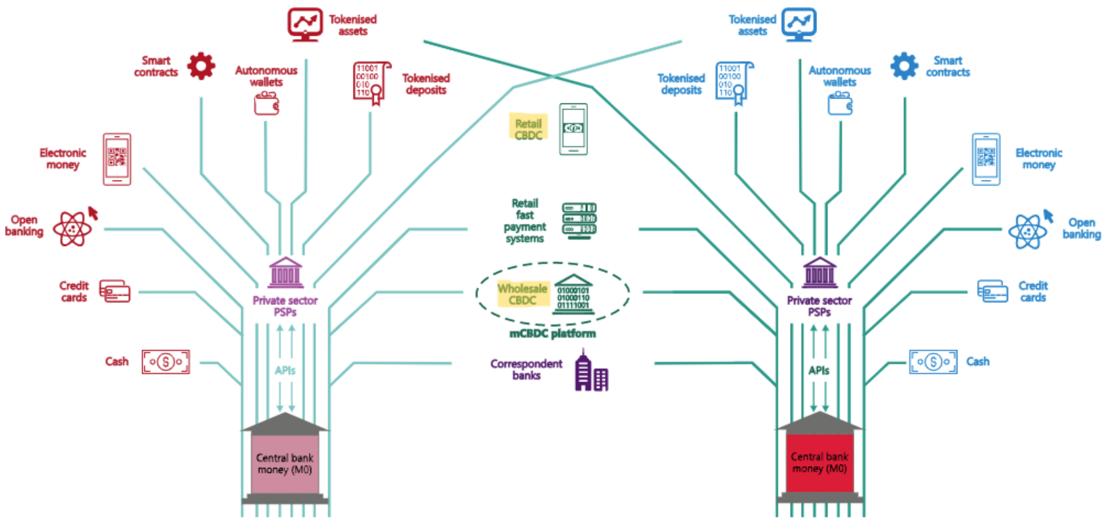


Figure C.13: IRF of selected variables to a domestic (line) and foreign (dash) 5 percent standard deviation expansionary capital quality shock.

Note: Responses are reported as percentage variations from the steady state.

D. Others

A strong canopy supports the global monetary (eco)system Graph 8

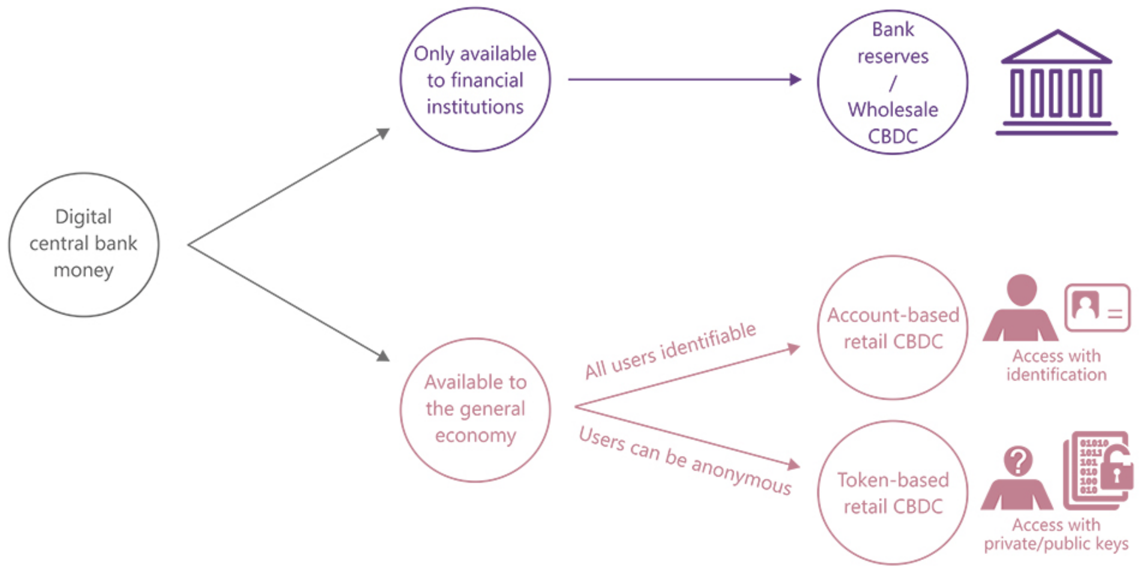


API = application programming interface; CBDC = central bank digital currency; PSP = payment service provider.

Source: BIS.

Figure D.1: Vision of future global monetary system.

Forms of digital central bank money — Graph III.5



In today's financial system, digital fiat money is available only to regulated financial institutions, in the form of reserves accounts held by commercial banks at the central bank. Wholesale CBDCs would similarly be restricted to financial institutions. Retail CBDCs in contrast are available to the general economy. Account-based retail CBDCs would be tied to an identification scheme and all users would need to identify themselves. Token-based retail CBDCs would be accessed via password-like digital signatures and could be accessed anonymously.

Source: BIS elaboration.

Figure D.2: Forms of digital central bank money.

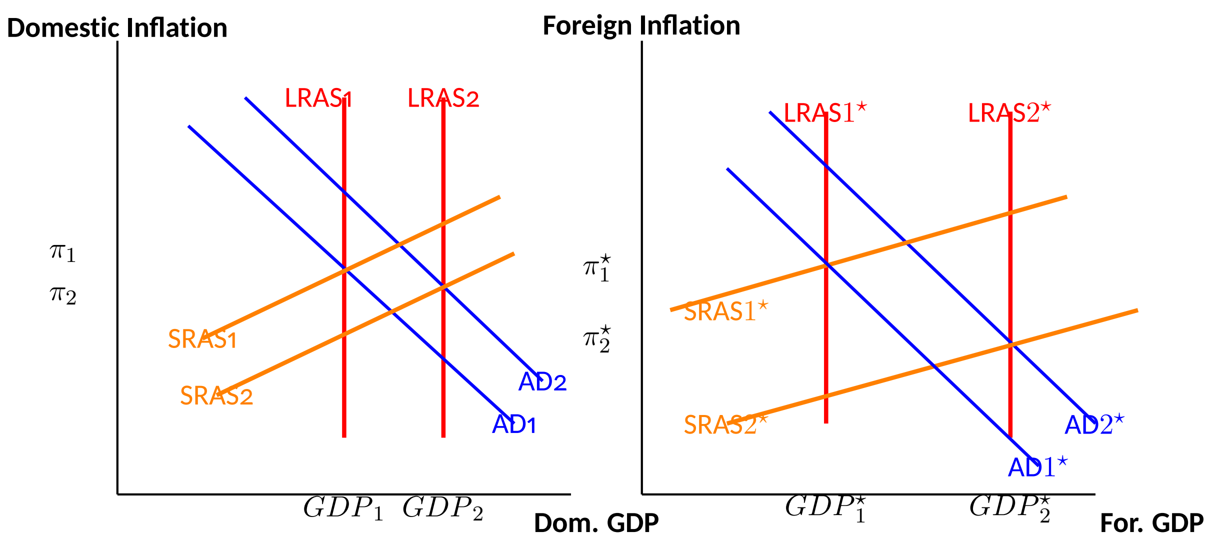


Figure D.3: AS/AD Representation of a foreign technological innovation on domestic (left) and foreign (right) economies

Note: The workhorse AS-AD model contains three curves. On the supply side, there is a long-run aggregate supply curve (LRAS) and a short-run aggregate supply curve (SRAS), thereby bridging Classical and Keynesian thoughts. On the demand side, we have the usual downward aggregate demand curve.

E. DYNARE Code for Baseline Model

Given that our models are non-linear, we solve their steady state equations on separate MATLAB files which contain the structural parameters and steady states. The second file contains the code. Below, we provide the content of the second file for the SOE baseline model, as described in Section 5.

```
%%%%%%%%%%%%%%%%%%%%%%%Endogenous Variables %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
var
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Households
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
c                          % Consumption
cbdc                       % CBDC
h                          % Hours
lambda                     % Marginal utility of consumption
m                          % Cash
w                          % Real wage
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Firms
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
a                        % TFP
gdp                      % Gross domestic product
i                        % Investment
k                        % Capital
kQ                       % Capital quality
mc                       % Marginal cost
q                        % Tobin Q
rk                       % Rental rate of capital
yH                       % Domestic production
ySTAR                    % Foreign demand
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Banking sector
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
bA                      % Banks’s assets
bdf                     % Bank’s discount factor
d                       % Public bonds
dep                     % Deposits
gA                      % Government’s assets
lev                     % Leverage
n                       % Bank’s net worth
newn                    % New bank’s net worth
oldn                    % Old bank’s net worth
rb                      % Bank interest rate
spr                     % Spread
Z                       % Growth rate of bank capital
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Prices
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
pi                      % Inflation
```

```
piH                     % PPI inflation
pH                      % Relative PPI
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Auxiliary variables
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
g                       % Public spending
mp                      % Imports
nom_de                  % Nominal exchange rate
premium                 % Premium
r                       % Nominal interest rate
rSTAR                   % Foreign nominal interest rate
rcbdc                   % CBDC rate
rexr                    % Real exchange rate
rr                      % Real interest rate
tb                      % Trade balance
tot                     % Terms of trade
xp                      % Exports
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Log variables
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
gdplog deplog  sprlog tblog clog ilog nlog levlog bAlog
;
%%%%%%%%%%%%%%%%%%%%%%%Exogenous Variables%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
varexo
e_a                     % Productivity shock
e_fmp                   % Foreign monetary policy shock
e_fy                    % Foreign output shock
e_g                     % Public spending shock
e_k                     % Capital shock
e_mp                    % Monetary policy shock
e_qe                    % Qe shock
;

parameters
alpha                   % elasticity of production wrt capital
aSS                     % Steady state of a
beta                    % discount factor
bigGamma                % elasticity of liquidity
chi                     % survivial rate of bankers
delta                   % depreciation rate
dSS                     % Steady state of d
epsilon                 % elasticity of substitution btw differentiated goods
eta                     % elasticity of intratemporal substitution
gASS                    % Steady state of gA
gamma                   % trade openness
gammaSTAR               % foreign parameter
gSS                     % Steady state of g
iota                    % tranfer to new bankers
levSS                   % Steady state of lev
```

```
mum                     % Utility Weight of Cash
phi                     % inverse of Frisch elasticity
phie                    % mp response to exchange rate
phipi                   % mp response to inflation
phiqe                   % qe response to spread
phiy                    % mp response to output
piSS                    % Steady state of pi
rhoa                    % tfp persistence
rhofmp                  % foreign mp shock persistence
rhofy                   % foreign demand shock persistence persistence
rhog                    % public spending persistence
rhok                    % capital shock persistence
rhom                    % monetary policy inertia
rhoqe                   % qe shock persistence
rSS                     % Steady state of r
sigma                   % Inverse of the intertemporal elasticity of substitution of consumption
sprSS                   % Steady state of spr
theta                   % fraction of divertable assets
Upsilon                 % utility weight of liquidity
vartheta                % Elasticity of Cash
xi                      % Storage costs
zetaD                   % adjusment parameter
zetaI                   % investment adjustment cost (as in CEE)
zetaL                   % labor preference parameter
zetaP                   % adjusment parameter
;

load par_Baseline.m;    % Here we load the external steady state parametrisation and structural values.
for jj=1:length(M_.param_names)
set_param_value(M_.param_names{jj},eval(M_.param_names{jj}));
end;

model;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Households
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
//[name='FOC wrt consumption']
lambda = (c) ^-sigma;
//[name='FOC wrt public bonds']
1=beta*lambda(+1)/lambda*r/pi(+1);
//[name='FOC wrt foreign bonds']
1=beta*lambda(+1)/lambda*rSTAR*rexr(+1)/rexr+zetaD*(d-dSS);
//[name='FOC wrt capital']
1=beta*lambda(+1)/lambda*(rk(+1)+(1-delta)*q(+1))/q;
//[name='FOC wrt labor']
zetaL*h^(phi) =lambda* w;
//[name='law of motion of capital']
k=(1-delta)*k(-1)*kQ+(1-zetaI/2*(i/i(-1)-1)^2)*i;
//[name='FOC wrt investment']
```

```
1=q*(1-zetaI/2*(i/i(-1)-1)^2-zetaI*(i/i(-1)-1)*i/i(-1))+zetaI*beta*lambda(+1)/lambda*q(+1)*(i(+1)/i-1)*(i(+1)/i)^2;
//[name='FOC wrt CBDC']
cbdc^-bigGamma = beta*lambda(+1)/(lambda*Upsilon)*rcbdc/piH(+1);
//[name='FOC wrt cash'].
mum*(m)^-vartheta = lambda-xi*beta*lambda(+1)/piH(+1);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Firms
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
//[name='Cobb Douglas Production function']
yH=a*(kQ*k(-1))^alpha*h^(1-alpha);
//[name='FOC wrt labor']
(1-alpha)*mc*yH=w*h;
//[name='FOC wrt capital']
alpha*mc*yH=rk*k(-1);
//[name='Definition rental rate of capital']
rk=rb*q(-1)-(1-delta)*q*kQ;
//[name='Non linear Philips Curve']
(piH-piSS)*piH=beta*(lambda(+1)/lambda*pH(+1)*yH(+1)/(pH*yH)*piH(+1)*(piH(+1)-piSS))+epsilon/zetaP*(mc/pH-(epsilon-1)/epsilon);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Domestic Banking sector
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
//[name='Aggregage leverage']]
lev=beta*lambda(+1)/lambda*bdf(+1)*r/piH(+1)/(theta-beta*lambda(+1)/lambda*bdf(+1)*(rb(+1)-r/piH(+1)));
//[name='Definition bank leverage']
lev=bA/n;
//[name='Definition bank assets']
bA=dep+n+cbdc+m;
//[name='Evolution Aggregate bank net worth']
n = oldn + newn;
//[name='Evolution bank OLD net worth']
oldn = chi*((rb-r(-1)/piH)*lev(-1)+r(-1)/piH)*n(-1);
//[name='Evolution bank NEW net worth']
newn = iota*bA(-1);
//[name='Growth rate of bank capital']
Z = (rb-r(-1))*lev(-1)+r(-1);
//[name='Expression for bank discount factor']
bdf=1-chi+chi*beta*lambda(+1)/lambda*bdf(+1)*((rb(+1)-r/piH(+1))*lev+r/piH(+1));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Market clearing
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
//[name='Clearing for domestic good']
yH=(1-gamma)*pH^(-eta)*(c+i)+g+gammaSTAR*ySTAR*(tot)^eta+(zetaP/2*(piH-piSS)^2)*yH;
//[name='clearing good market']
gdp=c+i+pH*g-rexr*d+rexr*rSTAR(-1)*d(-1)+(zetaP/2*(piH-piSS)^2)*gdp+rexr*zetaD/2*(d-dSS)^2;
//[name='clearing bond market']
q*k=bA+gA;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Prices
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
//[name='Consuumption bundle']
1=(1-gamma)*pH^(1-eta)+gamma*rexr^(1-eta);
//[name='Pricing condition']
piH=pH/pH(-1)*pi;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Policy
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
//[name='Taylor Rule']
r/(rSS)=((pi/piSS)^(phipi)*(gdp)^(phiy)*(nom_de/piSS)^phie)^(1-rhom)*(r(-1)/rSS)^(rhom)*exp(e_mp);
//[name='QE rule']
gA/(gASS)=((spr/sprSS)^(phiqe))^(1-rhoqe)*(gA(-1)/gASS)^(rhoqe)*exp(e_qe);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Shocks
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
//[name='TFP follows autoregressive process']
log(a)=(1-rhoa)*log(aSS)+rhoa*log(a(-1))+e_a;
//[name='Gov spending follows autoregressive process']
log(g)=(1-rhog)*log(gSS)+rhog*log(g(-1))+e_g;
//[name='Foreign output follows autoregressive process']
log(ySTAR)=rhofy*log(ySTAR(-1))+e_fy;
//[name='Foreign interest rate follows autoregressive process']
rSTAR=(1-rhofmp)*1/beta+rhofmp*rSTAR(-1)+e_fmp;
//[name='Capital quality follows autoregressive process']
log(kQ)=rhok*log(kQ(-1))-e_k;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Auxiliary variables
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
//[name=real interest rate'']
rr=r/pi(+1);
//[name='definition spread']
spr=rb(+1)-r/piH(+1);
//[name='Real exchange rate']
rexr/rexr(-1)=nom_de/pi;
//[name='domestic output']
gdp=pH*yH;
//[name='trade balance']
tb=xp-mp;
//[name='exports']
xp=pH*gammaSTAR*ySTAR*(tot)^eta;
//[name='imports']
mp=gamma*rexr^(1-eta)*(c+i);
//[name='terms of trade']
tot=rexr/pH;
//[name='Definition CBDC rate']
rcbdc = (1+(rb-r));
//[name='Premium']
premium = rb-r;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Others
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clog=log(c); gdplog = log(gdp); ilog = log(i); sprlog = log(spr); tblog = log(tb);
deplog = log(dep); levlog=log(lev); nlog=log(n); bAlog = log(bA);
end;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Steady State
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
steady_state_model;
pi=1;
piH=1;
d=dSS;
yH=1;
pH=1;
gdp=pH*yH;
rexr=1;
h=1/3;
kQ=1;
spr=0.0025;
lev=4;
rr=1/beta;
r=pi/beta;
q=1;
rb=rr+spr;
rk=1/beta-(1-delta);
mc=(epsilon-1)/epsilon;
k=alpha*mc*yH/rk;
w=(1-alpha)*mc*yH/h;
i=delta*k;
g=gSS;
c=yH-i-g-d*(1/beta-1);
lambda=(c)^(-sigma);
zetaL=lambda*w/(h^phi);
a=aSS;
gA=gASS;
bA=k-gA;
Z= spr*lev + 1/beta;
n=bA/lev;
oldn = n*chi*Z;
newn = n - oldn;
rcbdc = (1+(rb-r));
cbdc = (beta/Upsilon*rcbdc/pi)^(-1/bigGamma);
m = 1-(cbdc)/bA;
dep=bA-n-cbdc-m;
bdf=(1-chi)/(1-chi*beta*(spr*lev+rr));
rSTAR=1/beta;
ySTAR=1;
nom_de=1;
tot=rexr/pH;
```

```
xp=pH*gammaSTAR*ySTAR*(tot)^eta;
mp=gamma*rexr^(1-eta)*(c+i);
tb=xp-mp+rexr*zetaD/2*(d-dSS)^2;
premium = rb-r;
clog=log(c);
gdplog = log(gdp);
ilog = log(i);
sprlog = log(spr);
tblog = log(tb);
deplog = log(dep);
levlog=log(lev);
nlog=log(n);
bAlog = log(bA);
end;

resid;
steady;
check;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Shocks
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
shocks;
var e_a;    stderr 0.01;
var e_g;    stderr 0.01;
var e_mp;   stderr 0.0025;
var e_fy;   stderr 0.01;
var e_fmp;  stderr 0.0025;
var e_k;    stderr 0.01;
var e_qe;   stderr 0.01;
end;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% IRFs
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

options_.pruning        = 1;
options_.order          = 1;
options_.irf            = 40;
options_.hp_filter      = 1600;
options_.periods        = 2000;
stoch_simul;
```

F. Declaration of Authenticity

I, Maxime Polis, hereby declare that I wrote this work independently and that no sources other than those explicitly stated across this present internship report are used and that all quotes and citations taken from other works are properly referenced and clearly marked. This thesis was never presented in the past in the same or similar form to any examination board. At last, I hereby confirm that I am aware that my thesis is subject to electronic screening for plagiarism. For that purpose, I give my consent to distribute anonymously my copy to servers located outside the University of Liège.

Liège, 22^{nd} June 2022

Place, Date

Signature

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G. Non-technical Summary

Central bank digital currencies (CBDCs) are admittedly a hot topic worldwide, and rightfully so as they potentially embody the innovative payment rails of tomorrow's monetary system, thereby helping in making money and payments fit for decades to come. Globally, over 90 percent of central banks are cautiously exploring such financial innovation alongside all stakeholders and a dozen guardians of stability have already spearheaded the (r)evolution. Such endeavors are often motivated by public good objectives, from safeguarding public trust in money, ensuring its safe access and financial inclusion to strengthening financial stability and monetary policy altogether. While its wide-ranging impacts are certainly far from being understood, a consensus is growing that the financial stability risks stemming from bank disintermediation are manageable. However, research proves to be far thinner regarding the implications of CBDCs once available to foreign citizens.

This work aims to investigate such intricacies in open economies based on New Keynesian DSGE models.[54] We contribute to the exponentially growing literature in several ways. At first, we provide the latest stance of research concerning the financial and monetary implications of the digital monies. Secondly, we develop tractable models including CBDCs in its most simplistic form. Our two-economy model proves to be most appropriate to study the case of Sweden, with its world oldest central bank expected to lead the change in the medium term.

In line with existing literature, we found the existence of real and financial international spillovers, most apparent in light of CBDCs. Unsurprisingly, we also unravelled that its demand is left unchanged when offered at a lower remuneration rate than bonds. At last, we conclude that our simplistic inclusion of CBDCs is likely to have limited impact on the conduct and transmission of monetary policy, in accordance with initial central banks' efforts.

Our results depend crucially on the models' underlying assumptions, and in particular in regard to the CBDC parameters upon which there is currently little benchmark, and which heavily influence the responses. Numerous avenues for future work are also outlined.

Keywords: Central bank digital currencies, open economy, DSGE model, e-krona, monetary policy.

[54] This research thesis comprises 13.336 words.