CRYPTOCURRENCY AS AN ADVERSE SHOCK TO A MACROECONOMY: AN ABM PERSPECTIVE

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DECLARATION

This thesis entitled, “CRYPTOCURRENCY AS AN ADVERSE SHOCK TO A MACROECONOMY: AN ABM PERSPECTIVE”, was conducted under supervision of Associate Professor Dr. Resham Thapa-Parajuli of Central Department of Economics, Tribhuvan University. I declare that the information reported in this thesis is the result of my own work, except where due reference has been made. The thesis has not been accepted for any degree nor has been concurrently submitted to for candidature in other degree granting programs.

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LETTER OF RECOMMENDATION

This thesis entitled, “CRYPTOCURRENCY AS AN ADVERSE SHOCK TO A MACROECONOMY: AN ABM PERSPECTIVE”, is submitted by Mr. Manab Prakash Poudel under my supervision for partial fulfillment of the requirements for the degree of MASTER OF ARTS *in* ECONOMICS. I forward it with a recommendation for approval.

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Associate Prof. Resham Thapa, PhD
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APPROVAL LETTER

We certify that this thesis entitled, "CRYPTOCURRENCY AS AN ADVERSE SHOCK TO A MACROECONOMY: AN ABM PERSPECTIVE" submitted by Mr. Manab Prakash Poudel to the Central Department of Economics, Faculty of Humanities and Social Sciences, Tribhuvan University, in the partial fulfillment of the requirement for the MASTER OF ARTS *in* ECONOMICS has been found satisfactory in scope and quality. Therefore, we accept this thesis as a part of the said degree.

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The inception of a thought for using a simulator to study macro-economy began on gentle slopes behind the zoology department's building that oversees some of the last big open spaces left in the Kathmandu Valley. I, then, was reading Jordi Galí with Ajay Gautam. Those discussions left me with deep suspicions about mathematical models in macroeconomics, especially those using dynamic optimizations. We decided to go both ways; Ajay used DSGE, and I did agent-based models. We both became increasingly disillusioned with models, whom we were big fanboys before, and their calibration techniques. Thus, I owe Ajay a significant intellectual debt.

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ABSTRACT

Cryptocurrencies or digital private monies, have rocked the traditional central bank's monopoly on money printing.Thought they have been eulogized as future of finance, the next big thing, and democratization of banking, sometime seven as a panacea for all of the societal problems, adoption by the masses has been sheepish in the last decade. In this study, we examine the impact of cryptocurrency design on its profitability and present a mathematical argument about its nature. We also develop a theoretical framework for an agent-based macroeconomic model that incorporates cryptocurrency. The key features of the model include: (a) buffer-stock style consumption, (b) adaptive heuristic decision making, (c) sticky wages, (d) two classes of firms, (e) realistic inventory and loan applications (f) lifelike cryptocurrency growth function, (g) state-dependent trading strategies, and (h) a banking sector limited by Taylor-like monetary rule. Our findings suggest that cryptocurrency has a ponzi-like structure due to its design, which leads to ongoing volatility and the need for liquidity. While this characteristic may decrease over time, it does not disappear completely. The only way to ensure sustained value is to have a clear and specific use case. Our agent-based macroeconomic model of cryptocurrency captures important characteristics of cryptocurrency and household financial behavior, which can be used in further research to understand the effects of cryptocurrency speculation on macroeconomic stability.

Keywords: Agent-based macroeconomics, Cryptocurrency, Modeling.
JEL Codes: C50, C51, E50

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LIST OF ABBREVIATIONS

ABM	Agent Based Macroeconomics
CBDC	Central Bank Digital Currency
DSGE	Dynamic Stochastic General Equilibrium
FTX	Futures Exchange Trading Ltd.
LLoC	Law of Library of Congress
NRB	Nepal Rashtra Bank
UoCCAF	University of Cambridge Centre for Alternative Finance

CHAPTER I
INTRODUCTION

1.1 Background of the study

Policy regarding money in staid days of average inflation, employment rates, and economic growth garners less interest than its cousin, fiscal policy. It is the latter where myriad segments of economic life are fixated on who got subsidized, taxed, and where the transfers flowed. Every time a precarious balance of payment status, supply-induced recession, or inflationary bout strikes the economy, modern economic actors look to the central bank, the modern money printer. This partly comes from the firefighting ability of monetary tools but also from the institutional arrangement; modern central banks have been given brahminical status. The arcane monetary economics rituals that the central bank runs are supposedly efficient and above election-related political economy. Why in a democratic society, central bankers don't have to face the same level of scrutiny as their fiscal counterparts is a question for another day. But, their ability to print or vacuum money out at will is real, and this is often the key bone that critics of fiat currency innovation like to pick.

Both modern academic works (Stein, 2012; Taylor, 2009; Tucker, 2009) that study the monetary mechanisms and policymakers that were at the helm when economies were tanking (Bernanke, 2015) have defenestrated any doubts about whether the central bank's money-related tools work. It is true that mainstream economists could not predict the 2008 financial crisis and Queen Elizabeth of the United Kingdom was entirely justified when she wondered, "If things were so large, how come everyone missed them" while visiting the London School of Economics at the height of the crisis (Besley & Hennessy, 2009). But, equally justified were the countermeasures that were seen across most countries that were struck by the crisis; thanks to these tourniquets, it stanched at a recession without regressing to a depression. The most important of those countermeasures, Quantitative easing (QE), is a round-about way of printing money and channeling it to the economy through financial institutions. Modern central banks have routinely used variations of QE in COVID-19 induced recession all over the world to such an extent that QE and its variants are now entrenched as a critical component of monetary policymakers' toolkit. The historical monopoly on money printing and its recent use case begs the question, why on earth would central banks knowingly hollow out their money printing business by allowing private money, i.e., cryptocurrency? If cryptocurrency functions primarily as the medium of exchange, as its proponents claim, why should private money be allowed to compete against public money given that this public enterprise has proven its social use-case time and again.

When one buys a cryptocurrency, one is getting an entry in a public ledger that stores one's public key and the amount of cryptocurrency one is holding. Since the ledger is a type of data storage format, albeit irreversible and public, it can be cloned by any decent software engineer to produce a competing product. Then, in the ecology of clones, biosimilars, and derivative ledgers, what makes one specific entry in one specific ledger that special? If a ledger is supposed to be the ledger that rules them all, then there has to be an institutional force with coercive power. An analogy can be found in the history of the modern monetary system. Despite the USA having more GDP than the British empire by the 1910s, it was after the end of the second world war in 1945 that the US dollar gained the status of the international reserve currency (Frankel, 1992). Basically, prominence in currency came after the show of prominence in military might. But, cryptocurrencies are private enterprises that will always have to be subservient to national sovereignty and politics. This means there is no telling when a particular US president might sign an executive order making a certain cryptocurrency, possibly of foreign provenience, illegitimate.

If, say, modern economies came together to declare certain classes of cryptocurrencies with origin in their countries as a legitimate form of currency. Then still, cryptocurrency requires the continual interest of people perpetually to have value. Taleb (2021) argues that while all most all technologies are replaced by something newer, items such as gold and silver have been resistant to extinction. For a non-dividend-yielding, technology-based asset like cryptocurrency, we have to assume perfect infallibility and non-obsolescence, not just for now but perpetually. The history is widespread with the technological obsolesce and change of public taste. So if there is even the slightest mortality rate, it puts a particular cryptocurrency's fundamental value at zero(Taleb, 2021).

The energy required by the crypto network is another issue. According to Cambridge Bitcoin Electricity Consumption Index, the annual energy consumption of the Bitcoin network in 2022 reached 144.41 Terra watt-hours. This usage is 0.65% of total electricity energy and 0.22% of total energy consumed globally (UoCCAF, 2022). The number is larger than the annual consumption of Norway or Ukraine. The energy consumption must be put into perspective by the transaction volume processed per minute. Bitcoin processes approximately seven transactions per second (tsp). Ethereum does 20; their mainstream alternative VISA does 24000 (Crypto.com, 2022). The electricity consumption is a side-effect of intentional design choice since the proof-of-work protocol requires repeated hashing, a computationally inefficient process, by all competing miners. The design requirement of a trustless system enforces higher energy usage under currently implemented protocols.

The double whammy is that large energy consumption and CO_2 emission was mostly for speculation. A large portion of cryptocurrency is demanded for trading purposes rather than means of payments (Blandin et al., 2020; Hileman & Rauchs, 2017; Rauchs et al., 2018). The crypto asset is a poor hedge and unsuitable for risk diversification (Bouri et al., 2017) as exemplified by the price fluctuation over the last decade and fails to exhibit correlation with the behavior of other currencies(Yermack, 2013). On top of these, Griffin and Shams (2020) report fraudulent trading practice even in a stable-coin. In the year of 2013, it remained at approximately US$ 1100, which grew to US$ 19700 in 2017. After reaching US$ 66000 in 2021, it came down to US$30000 by mid-2022. At the year-end of 2022 price reached US$ 17000. It is unimaginable to think that an asset that decreases by 74% in a year will be used, without any coercion, as a currency. Historically, we have seen similar or higher changes in sovereign currencies (Hanke, 2022), and people did continue to use them. But, most of those users were citizens who had no option but to receive wages and purchase services in their national currencies; often, they couldn't exchange such currencies without going through hoops. We have to doubt if anyone who has an opportunity to not lose the value of one's savings by three-quarters in a year would not take it. The commonly observed behavior during hyperinflation is barter. In that scenario, producers, retailers, and consumers are all trying to stave off any loss they can potentially stave from their rapidly diminishing wealth. Now, why would a consumer enjoying a stable currency in a modern economy would want to change it to a currency showing hyperinflation/hyperdeflation and is not accepted by most of the merchants in his/her vicinity if it were not for speculation purposes? This fragility makes cryptocurrency very difficult to describe as a means of payment.

The final bone of contention is the perceived superior security of cryptocurrency. It is true that cryptographic currencies bring with them transparent records of all transactions being conducted in their networks in irreversible and chronologically ordered manner(Potgieter & Howell, 2021). But, if an economic actor's public key used to register in a cryptocurrency network is linked to its real identity, all of its transactions in that particular cryptocurrency using that public key can be publicly identified. Another corollary of such mechanism design is that if the private key is lost, then all cryptocurrency tokens linked with that key are lost from the network. Alternatively, if any unauthorized actor gets a hand on the private key of another, then that malignant actor can enforce its heart's wishes upon the value secured by that private key. Thus, despite the cryptocurrency being touted as very secure and anonymous, it is impregnable only if both public and private keys are safely away from prying eyes. In a recent case, the Canadian government tracked all crypto donations made to the protesters and confiscated them (Fraser, 2022). Thus a government with a sufficiently sophisticated tool-set can easily thwart libertarian desire for freedom from the government's reach on financial matters.

1.2 Statement of the problem

Given the pros and cons of cryptocurrency, it is natural to wonder what kind of price incentives its design imposes. In particular, understanding how the rate of growth of cryptocurrency in circulation affects the token's value in dollars is crucial for understanding the motivations of crypto investors. However, much of the existing literature has treated cryptocurrency within an equilibrium framework, which may not be appropriate given the fragile nature of cryptocurrency. As a result, there is a gap in the literature for a study that introduces cryptocurrency into a macro model in a dynamic framework without using assumptions that require equilibrium conditions.

1.3 Research question

To study the cryptocurrency's impact on macro economic outcome, we frame the research question for this study as:

(i) What is the effect of cryptocurrency's design decision on returns from cryptocurrency ?

(ii) How do we introduce cryptocurrency in an agent based macroeconomic model?

Within this general area of curiosity, we define the objectives of this study.

1.4 Objectives of the study

The main objective of this study is to examine how can one introduce cryptocurrency in an macroeconomic model. In accomplishing this objective the study's specific objectives are:

(i) To construct a mathematical argument on impact of cryptocurrency's design decision on its profitability; and

(ii) To construct an agent based micro-founded closed-economy macro-model with cryptocurrency.

1.5 Significance of the study

This study aims to contribute to the understanding of the impact of cryptocurrency on the economy by developing a mathematical representation of cryptocurrency and introducing it into an agent-based macroeconomic model. The findings of this research are expected to provide insight into how the design of cryptocurrency can influence its price incentives, as well as how the rate of growth in cryptocurrency circulation may affect its dollar value. Additionally, this study is expected to inform potential changes to regulatory policies related to cryptocurrency trading, particularly for central banks considering allowing such trading on a larger scale.

1.6 Limitation of the study

The study is limited in its scope, as it only focuses on the closed economy and does not consider external factors such as trade. Additionally, the model of cryptocurrency transactions is simplified in order to prioritize tractability and ease of implementation, potentially missing out on certain investment strategies observed in the real economy. Additionally, the model does not consider Nepal's definitive characteristic of being a labor exporter and goods importer, as it is designed as a closed economy. These limitations should be kept in mind when using the model developed in this study.

1.7 Outline of the study

The study is organized as follows. In the next chapter, we provide a literature review. In Chapter 3, we describe the research design. Theoretical results are reported in Chapter 4. In Chapter 5, we discuss the results obtained and conclude the study.

CHAPTER II
LITERATURE REVIEW

2.1 Cryptocurrency

This section discusses the history of cryptocurrency, underlying technology, and current legal status in different countries. This review helps us understand cryptocurrency's technical nitty-gritty, eventually facilitating us to construct its mathematical model. The review also allows us to find research and the methodological gap in our research context.

2.1.1 Origin

The origin story of cryptocurrency is intertwined with the 2008 great recession. At the peak of the recession, Satoshi Nakamoto proposed the distributed ledger system in a white paper (Nakamoto, 2008). Though there had been other prior works in the field of distributed currency, e.g., b-money and bit gold (Sunyaev, 2020), the white paper achieved a breakthrough by solving the double spending problem using cryptographic hashing in a trust-permissive system. By January 2009, open source bitcoin client software was publicly hosted.

The world is increasingly using digital payment system for all sort of payments (Thakor, 2020), and each such payment, when being processed, are taxed by financial institutions. Additionally, the 2008 crisis raised the question about the trustworthiness of centralized trusted financial intermediaries (Stevenson & Wolfers, 2011). A peer-to-peer internet-based cash can potentially solve both concerns: it removes transaction costs levied by the financial institutions, and one does not have to rely upon their trustworthiness for payment processing. The promise of the cryptocurrency meant that by 2020, seven thousand cryptocurrencies were being actively traded with a total market cap of US$ 300 billion(Wu et al., 2021).

2.1.2 Technology

Cryptocurrency uses blockchain, which is an incorruptible distributed ledger of economic transactions with incorruptibility resting on cryptographic hash function(Cocco et al., 2019; Fang et al., 2020). The cryptocurrency coin is essentially a chain of digital signatures. In each new transaction, a hash is created using the new owner's public key and past transaction, which is then signed by the seller's private key. At the end of the new transaction, the new owner's public key and the last owner's signature are added. This design creates a structure that can only be modified in a single direction. If a hostile attacker wants to undo a transaction, it has to calculate hashes of that past transaction and all subsequent transactions in chronological order. But, if a simple majority of participants, in terms of computational power, in the network act in good faith, then they will always generate newer blocks faster than the fraudster. Thus the longest chain of blocks available in the network will be the most recent version of the system; basically, a robust trust-permissive ledger.

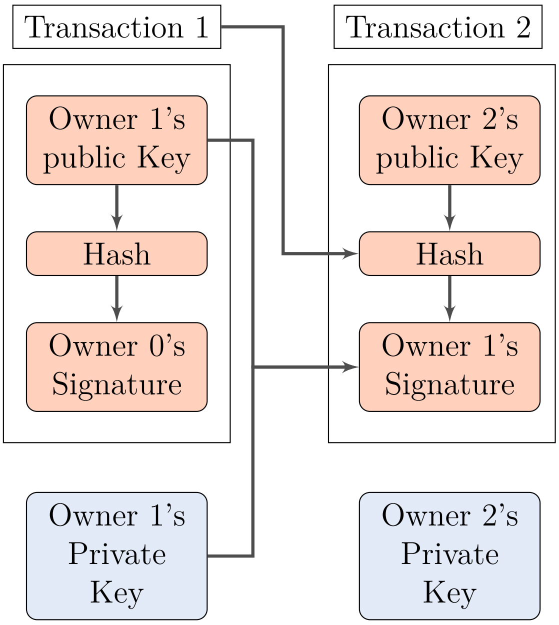


Figure 2.1: Bitcoin transaction mechanism(Nakamoto, 2008).

A sender sends currency to the receiver's public key using its private key. Anyone on the network can verify that the sender is a legitimate account holder, as prior crypto coin transactions have the sender's public key. It means distributed verification without central authority can take place. Generally, numerous transactions are bundled together by network participants simultaneously in parallel, and they compete in solving the bundling puzzle posted by the system. The fastest solver of the verification puzzle gets to add the newest block in the public ledger and receives crypto coins for it, i.e., coinbase reward. This winner takes all mechanism causes wastage of most computational power being used in block generation by the network. But due to it, any malicious actor aiming to double spend is forced with a costly computational problem (Halaburda et al., 2020).

Blockchains can be both permissioned and permissionless based on a set of entities allowed to act as validators. It can also be private or public. Access is restricted to authorized parties in the private network, whereas in the public

Table 2.1: Different types of consensus protocols

Consensus protocols	Domains
Proof-of-work	Premissionless cryptocurrencies
Proof-of-stake	Permissionless cryptocurrencies
Delegated PoS	Permissionless cryptocurrencies, Permissioned Systems
Round Robin	Permissioned Systems
Proof of Authority/Identity	Permissioned Systems, Hybrid (sidechain) Systems
Proof of Elapse Time (PoET)	Permissioned Networks

Source: Yaga et al. (2018)

network, anyone can read, read, and publish a new block. Cryptocurrency uses permissionless public blockchain and trust-less trust architecture, where anyone can be a participant or a validator(Makarov & Schoar, 2022). How exactly transactions are bundled and which of the competing bundle is accepted as an official new state of the system depends on the consensus protocol implemented in that specific cryptocurrency. The two of the most common protocols in a permissionless public blockchain are *Proof-of-Work* and *Proof-of-Stake*. Both protocols are popular in the cryptocurrency mining industry and have their own sets of merits and dismerits.

In Proof-of-Work(PoW) protocol, as proposed by Nakamoto (2008), network participants group the transactions in a block and generate a hash using a previously mined block. The miner first selects the transaction requests to build a Merkle tree, then extract the hash from the root of the Merkle tree, adds nonce, and hashes the block header to obtain the new hash. Until this new hash satisfies the predetermined conditions, it keeps on increasing nonce and rehashing. Once the miner gets the hash with desired properties, the block is added to the blockchain, and the miner gets reward(Böhme et al., 2015). Since the cryptographic hashing function is deterministic but too complex to guess inputs for output, it makes the whole process probabilistic with a controllable success rate. This property allows the system to keep the block generation rate approximately constant even when newer and faster computer hardware is introduced in the network. However, as only one miner wins the hash guessing game and gains all coin-base rewards, all other processing power spent in the network by its competitors is wasted. Therefore, Proof-of-Work(PoF) is considered relatively resource inefficient compared to Proof-of-Stake (Ma et al., 2018; Saleh, 2020).

The PoS was first proposed by (King & Nadal, 2012) and further extended by (Saleh, 2020). In this protocol, the validator gets the reward on the basis of the number of coins it is staking. So, miners (validators) have incentives to pool their stakes together and co-insure each other. So reward probability depends on the number of coins owned by the mining syndicate. The criticism of PoS that it can cause the Stake-of-Nothing (SoN) problem has been formally addressed by Saleh (2020), who suggests that under certain mechanism design space, SoN is not a problem for PoS. Another frequently discussed problem of PoS is the richer-get-richer effect since the probability of being selected to be a validator is based on the total holding. But, Rosu and Saleh (2021) after studying wealth concentration within a PoS blockchain, shows on contrary position, i.e., PoS does not induce wealth concentration.

2.1.3 Legality of Cryptocurrency

Despite making headlines in the news, cryptocurrency has been slow to be accepted as a legal tender worldwide. El Salvador became the first country to accept cryptocurrency, i.e., Bitcoin, as legal tender by enacting the “Bitcoin Law”. Many countries across the globe are regulating cryptocurrency by adopting the tax law, anti-money laundering law, and Counter-Financing of Terrorism laws(Hammond, 2022; LLoC, 2021). The legal status varies widely among countries, which we briefly review for important cases.

El Salvador enacted “Bitcoin Law” on September 7th, 2021, and became the first country to legalize cryptocurrency. The aforementioned law stipulates that people can use Bitcoin to pay taxes and outstanding debts, and it is mandatory for the business to accept it as a medium of exchange for all transactions. The government launched an app named “Chivo Wallet” which allowed users to digitally trade both bitcoin and dollars. The introduction was done with financial transfer to citizens on first use, which was a significant sum for an average El Salvador citizen. Despite this introduction, 95% of the respondents in a survey did not prefer a mobile app for tax payment(Alvarez et al., 2022). Usage of bitcoin was low and concentrated among the banked, educated, young, and male population(Alvarez et al., 2022).

India’s central bank, RBI, issued a warning to the public in 2013. It further gave notice in 2017 stipulating that any kind of virtual currency can not be used in legal tender of any kind. The later notice was dissolved by the supreme court of India, which paved the way for the government of India to make the legal framework for the regulation of virtual currency. In 2022, the Union budget, the central government’s budget, introduced a tax rate of 30% on cryptocurrency gains, thereby giving cryptocurrencies legal status in India. The budget also had a proposal for Central Bank Digital Currency(CBDC) by 2023 that utilizes blockchain technology(Shukla et al., 2022).

People's Republic of China has a long history of regulating cryptocurrency. In 2013, People's Bank of China, the Ministry of Industry and Information Technology, the China Banking Regulatory Commission, China Securities Regulatory Commission, and China Insurance Regulatory Commission jointly enacted the "Notice on Preventing Risks of the Bitcoin". In subsequent years, China tightened the noose around the crypto industry. The primary areas of concern for Chinese mandarins were crypto's orientation towards illicit activities and the massive capital flight it facilitated. On September 21st, 2021, China deemed all cryptocurrency transactions and its associate business services to be illicit financial activities(Xi, 2022). At the same time, China is a leader in CBDC research, and it is widely expected to be the first major economy to roll out it(Wang, 2022).

In the USA, the Securities Exchange Commission(SEC), Federal Reserve Board, Internal Revenue Service (IRS), Financial Crimes Enforcement Network (FinCEN), Commodity Futures Trading Commission (CFTC), Federal Trade Commission, Department of Justice are the major regulatory office that regulates the cryptocurrency in their respective role(Hammond, 2022). IRS stipulates that a miner of the virtual currency as a trade or business is subjected to a self-employment tax(Hughes, 2017). The major focus of the US regulatory bodies is to combat money laundering, crime financing, and tax evasion using cryptocurrency. The cryptocurrency industry is one of the biggest spenders for lobbying in US capitol hill and political financing; thus, it has enormous influence in the highest rungs of the US political system (Newmyer, 2021).

The UK government 2018 formulated a crypto-asset task force for the investigation of risks and benefits posed by crypto-assets and distributed ledger. The financial policy committee's report notes that crypto-assets are highly unstable and inefficient in acting as a medium of exchange. Based on these reports, the UK government's bodies like the Financial Stability Board, His Majesty's Treasury, and Financial Conduct Authority have issued numerous consumer warnings, directives, and regulatory perimeters(HMT, 2021). The cryptocurrency has legal recognition and is taxed (LLoC, 2021). The plans for the CBDC report have also been published entitled "The Central Bank Digital Currency Report -Opportunities, Challenges and Design" in 2020(Coulter, 2022).

In the first report on virtual assets in 2012, European Central Bank(ECB) warned about the money laundering and terrorist financing risks of virtual assets. The European Commission presented 4^{th} money laundering directive (MLD4) in 2016 and 5^{th} MLD (MLD5) in 2018 focused on addressing money laundering and terrorist financing(Poskriakov et al., 2020). The general attitude of the EU has been regulation over the rejection of cryptocurrency. Meanwhile, the EU has committed itself to explore the possibility of adoption of CBDC (Bindseil, 2020; ECB, 2020, 2022).

Japan is the first country in the world which enact a law defining crypto-assets. Its regulations are primarily focused on protecting customers of cryptocurrency exchange providers and combating money laundering and financing of terrorism. Japan amended the Payment service act (PSA) and Act on privation of transfer of criminal services (APTCP) in 2016. It also revised the Financial Instruments and Exchange Act (FIEA) and PSA in 2020 to bolster the regulatory framework of crypto assets. Crypto traders are liable to progressive capital gain tax, which ranges from 4% to 45%(Nagase et al., 2021). The country also plans to develop CBDC, having already completed the first phase (Shinichi, 2022).

Nepal has completely banned cryptocurrency, citing the possibility of cryptocurrency facilitated illicit financing, money laundering, capital flight, and tax evasion(NRB, 2022). Despite this moratorium on all crypto-related activities, Nepal's central bank (NRB) has announced the feasibility study CBDC(NRB, 2021).

2.1.4 Summary of legal status

Modern economies having strong regulatory history have not shied away from declaring cryptocurrency as a new source of growth in the blockchain-enabled future economy. However, what that blockchain will enable has not been clear. In a recent UK prime ministerial competition, both competitors, Rishi Sunak and Liz Truss, were openhearted in their support of cryptocurrency despite the UK government's past positions having been more cautious. Before FTX collapsed in late 2022, most political pundits in the advanced economies described cryptocurrency as an innovation and contrasted it with the Chinese ban on it. There is no way to separate which parts of these arguments are china bashing, democratic virtue signaling, or innovative western spirit.

A powerful tool for economic stabilization is a monetary policy, i.e., regulation over the money supply, to control the general price level, stabilize the balance of payments and interest rate and determine the investment level. The dilution of the monetary tools if cryptocurrency happens to gain wider traction is a serious concern. But, cryptocurrency, despite having a decade under its belt, is still in the infancy of adoption. The untethered and mercurial nature of cryptocurrency has dispirited both the government and the public to accept it as a medium of exchange and government payments. The lack of broader adoption has given breathing space for regulators, and they have been able to focus on immediate concerns, i.e., consumer protection, illicit financing, money laundering, capital flight, and tax evasion. Whenever it has been accepted as a type of financial asset, cryptocurrency does not offer legal consumer protection at the level offered by the traditional capital markets and generally faces higher tax rates.

2.2 Modeling choice

The dynamic stochastic general equilibrium (DSGE) model is the bread and butter of contemporary macro models. The steps in DSGE can be summarized as the formulation of equilibrium constraints of state variables, followed by writing an objective function to maximize, then finding first-order maximizing conditions, and finally solving those conditions to get steady-state state variables. The overarching goal is to formulate the problem in terms of equilibrium conditions, which then is disturbed by exogenous shocks on state variables. The path of shock propagation in the equilibrium framework illuminates our suitably chosen research question.

After the great recession, it faced a wide range of criticisms. Stiglitz (2018), in his ambitiously titled “Where modern macroeconomics went wrong” essay, singles out the DSGE modeling framework at the heart of the failure of the macroeconomic profession in the great recession. The argument runs along the line of wrong microfoundations, inadequate financial sector, and overreliance on homo economicus. The criticism also relies on the model’s elaboration choice; the use of constant elasticity utility functions and homothetic preferences that result from the same portfolio of risky assets and unitary income elasticities for all goods may not be the best tool to study financial markets. Similarly, he is perplexed by the narrative of technology shock and mocks the meaning of technological shock in the modern industrial economy by asking if such shock meant an endemic of some disease that results in collective amnesia on how to produce.

The DSGE approach has led to significant progress in many areas, but it also has created biases and blind spots in understanding macroeconomy (Korinek, 2017). New progress could be found if the use of other techniques breaches the DSGE’s methodological restrictions. In Korinek (2017)’s opinion, implementation of DSGE has a particular interpretation of dynamic, stochastic, and equilibrium. The dynamic component is expected to be an infinite horizon model, the stochastic is expected to be derived from productivity shocks, and equilibrium is expected to mean the economy is a closed system in which all variables of interest are determined endogenously. This interpretation provides elegance and progress in some fields but can create a methodological trap in others.

Romer (2016)’s “post-real economics” criticism can be understood as a manifestation of the methodological trap. The calibrated DSGE models never stray far from real business cycle dogma - thus, if monetary policy matters at all, it matters very little. Smets and Wouters (2007)’s result for the role of monetary policy in US data, which included Volckner’s shock - Monetary policy shocks account for a small fraction of inflation and output developments - can be because of the implemented method. Haldane and Turrell (2018) notes that pre-crisis forecasts of the 2008 recession by available models were remarkably similar and bunched in a range of 1 percentage point, which authors consider a natural outcome given all models were based on the same RBC framework with the Keynesian appendages. In Caballero (2010)'s criticism, the internal logical consistency and precision of DSGE have been confused by its adherents with precision about the real world. Confident claims that emerge from DSGE, as a result, create the illusion of knowledge where it does not exist.

The significant themes of DSGE criticism have been confidence in the market, rationality, overreliance on representative agents, unrealistic assumptions, and lack of financial details(Caverzasi & Russo, 2018). The focus on the equilibrium means DSGE models don't sufficiently address out-of-equilibrium dynamics and transition mechanisms between different equilibriums. The informational requirement for adjustment between different equilibriums is considerable even when iterative price mechanisms converge to a competitive equilibrium(Saari & Simon, 1978). Further, assuming that economic agents know the "model economy" framework and have access to all relevant information is against Knightian fundamental uncertainty and does not absorb ideas from the behavioral economics revolution. Finally, even when the choices of aggregate are considered as those of maximizing individuals, the reaction of the representative-agent to policy experiment may not be the same as the aggregate reaction of the individuals the representative-agent represents(Kirman, 1992), i.e., the system may show the emergent properties that may be missed by simple aggregation.

While these are strong criticisms, these objections are hot research topics within the DSGE research community(Christiano et al., 2018). Due to the lack of better techniques, DSGE remains a favored tool of choice in central banks and other policy-making institutions(Lindé, 2018). Therefore, the onus lies with the critics of DSGE to supply a robust micro-founded macro framework that can replicate the strength of DSGE and bring in new insights from the new platform. Further, the strength DSGE offers (Christiano et al., 2018), and the potential research paradigm available within the framework mean changing the whole paradigm may be a knee-jerk reaction.

2.3 Agent-based macroeconomic model

Adding extensions to DSGE makes them computationally tricky and often shows identification issues with increased variables. Canova and Sala (2009) study a large class of DSGE structures in widespread use and conclude many have weak identification and observational equivalence. The recent work of (McDonald & Shalizi, 2022), who go back to canonical Smets and Wouters (2007), casts severe doubts on the meaningfulness of parameter estimates for DSGE and if such specifications represent anything structural about the economy. One alternative to DSGE modeling is agent-based computational modeling, which has the organic property of studying emergent system characteristics. Further, the cryptocurrency being as chaotic as it is, studying it as an equilibrium phenomenon would be a disservice to the program of understanding its macroeconomic effects.

An agent-based model (ABM) is a computational study of economics as complex evolving systems. In the ABM setting, we do not set the overarching objective functions for the economy's agent to optimize under the constraints. ABMs do not have first-order conditions connecting different sectors of the economy like DSGE; instead, we define the relationship directly. The agents themselves may be optimizing under certain circumstances, but their information set bounds them, and thus optimizing behavior does not translate to optimizing representative-agent behavior in aggregate as in DSGE. Theoretically, it is possible to represent the DSGE framework by the ABM model. If we provide homogeneity, optimize behavior, and complete global information set to economic agents, ABMs can replicate the results of the DSGE framework. The strength of ABM comes from the fact that by removing the equilibrium and having heterogeneity, we can have a far richer characterization of the economy.

One important benefit of using ABM is that they are very pliable for studying a wide range of economic behavior. They can be tailored to study specific segments of the economy in greater detail while abstracting other parts. The micro-behavior of the firm drives the macro outcomes; macro results have strong micro groundings. Given the depth of the model, one can study the feature of interest.

ABMs are relatively newer in macroeconomic modeling but have lineage starting from Herbert Simon's bounded rationality arguments. The study of organizations in the real markets has pointed out a lot of heterogeneity and non-equilibrium pricing (Graddy, 1995; Härdle & Kirman, 1995). These rich interactions are typically not captured in detail by traditional models. Though ABM models can hardly match feature sets of real markets, they try to encapsulate more. Agents who are not entirely rational can give an economy that is optimizing on aggregate. Thus ABMs have the potential to represent the emergence of matching supply and demand in the macro framework without underlying homo economicus agents doing sophisticated calculations(Kirman, 2010). The institutionalism strand of macroeconomics focuses on narrative as it believes no mathematical model can describe the richness of real-life economics. On the opposite corner, the Neo-classical framework believes in specialized quantitative mathematical formulations; sometimes, it can be the precise formulation of a largely irrelevant world. The key to a good

Table 2.2: Key characteristics of economic ABM models

Characteristics	
A bottom-up perspective	ABMs throw away central auctioneer which balances supply and demand. Rather, aggregate properties are obtained as macro outcome of a unconstrained micro dynamics going on at level of agents.
Heterogeneity	Agents are heterogeneous in various dimensions.
Evolving complex system approach	Agents live in an evolving complex world which evolves through time. Aggregate properties emerge out of repeated interactions among simple entities.
Non-Linearity	Interactions between agents are non-linear, thus non-linear feedback loops are in existence between macro and micro level of economy.
Direct interactions	Agents interact directly among themselves. There interactions are subset of a set of all possible interactions.
Bounded rationality	Agents are boundedly rational entities with adaptive expectations.
Nature of learning	Agents engage in open-ended search of dynamically changing environments.
True dynamics	ABMs have true, non-reversible dynamics and system evolves in a path-dependent manner.
Endogenous and persistent novelty	Agent face true Knightian uncertainty and are only able to form partial expectations.
Selection-based market mechanisms	Goods and services produced by competing firms are selected by consumers. The selection criterion may evolve with time.

Source: Fagiolo and Roventini (2017)

framework might be to find a way which can embody the richness of the Institutional framework with the robustness of the Neo-classical framework(Caverzasi & Russo, 2018).

2.3.1 Key ABM components

According to Tesfatsion (2017), an agent-based model is a discrete-time space modeling of a system populated by agents whose subsequent interactions drive all system events over time. Caiani et al. (2016) give four differences that set ABM apart from the traditional models. They are: (1) the agent's behavioral rules are not derived from optimization but empirical studies of the real economy; (2) the representation of markets is more vibrant compared to traditional models; (3) aggregation is computed ex-post; and (4) direct interaction between the agents is possible.

In the traditional model, economists set the utility function, which is optimized under the budget constraint. This optimization gives first-order conditions that describe the behavior of economic agents in the equilibrium state. The utility function is not observed by economists directly but is used to represent an objective function that allows the subsequent analysis of finding the optimum allocation. ABM models differ from the traditional model by directly stating these behavioral rules which govern the economic agents; thus, the need to postulate optimizing agents is optional. These behavioral rules, which are important to describe the economic agent, are influenced by the information set of the agent. Let Ω_{it} be the agent's information set.

$$\Omega_{it} = \{x_{it}, e_{it}, n_{it}\} \tag{2.1}$$

Information set consists of three parts which are: (1) x_{it} individual characteristics like preference, technology, and asset holding; (2) e_{it} external signals which denote knowledge of the market in which they operate, and news-media information; (3) n_{it} neighborhood of the agent. We, thereby, can define a behavioral rule as the agent's choice given the information set at a given time t.

In a typical sequence of modeling using ABM in economics, agent first form the expectations for t period based on information set $\Omega_{i,t}$ (See figure 2.2). Based on formed expectations, agent make production choices and demand for loan. Depending on scale of production, agents may or may not participate on credit market. Firms may use internal resources and borrowed funds for production. We also account for government and central bank's action as they directly affect the agent's behavior. At the end of the period, entry and exit conditions are updated to remove the bankrupt firms.

Expectation formation

Agent's behavior is formed by expectation for the future path of the economy, which itself is based on information set available to the agent. There are different types of expectation mechanism that are used in ABMs Anufriev and Hommes (2012), e.g., adaptive, trend-following, anchoring and adjustment. In adaptive expectation, the simplest one, if p_t^e is the expectations on prices for period t future expectation is formed by weighing current expectation with difference of

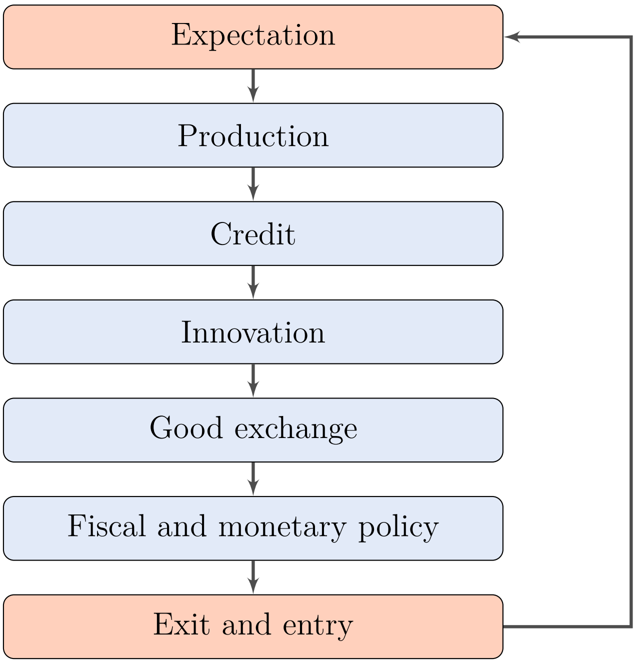


Figure 2.2: Simulation schema of ABM. Source Caiani et al. (2016).

past period price with current period price expectation.

$$p^e_{t+1} = p^e_t + w(p_{t-1} - p^e_t) \tag{2.2}$$

Expectations rule can be implemented one off , or alternatively, agents can choose among different heuristic rules based on their performance.

Production, Credit, and Innovation

Production by a firm depend on firm's expectation about economy. One can model the production by profit maximization or through adaptive rules. Gatti, Gallegati et al. (2010) model firm production level depending on expected profit minus bankruptcy costs. The maximization equation is:

$$\max_{Y_{it}} V(Y_{it}, A_{it}) = E(\pi(Y_{it}, A_{it})) - C(Y_{it})\Omega(Y_{it}, A_{it}) \tag{2.3}$$

Expected profit $E(\pi(Y_{it}, A_{it}))$ increases with production scale Y_{it} and firm net worth A_{it}. Bankruptcy costs $C(Y_{it})$ and probability of bankruptcy $\Omega(Y_{it}, A_{it})$ increase with production scale.

Gatti, Gallegati et al. (2010) model interest charged on borrowing firm as function of financial leverage of borrowing firm and net-worth of the bank.

$$r_{z,i,t} = \alpha A_{zt}^{-\alpha} + \alpha l_{it} \tag{2.4}$$

A_{zt} is the net-worth of bank z and l_{it} is the leverage of firm i, given the $\alpha > 0$.

Firm specific component αl_{it} increase interest rate as leverage of firm increase, whereas, bank specific component $\alpha A_{zt}^{-\alpha}$ decrease interest rate as the bank size increase. In every period borrowing firms observe the interest rate of a fraction of population of lenders. Borrowers can switch lenders based on probability p_s as:

$$p_s = \begin{cases} 1 - e^{\lambda(r_{new} - r_{old})/r_{new}}, & \text{if } r_{new} < r_{old} \\ 0, & \text{if } r_{new} \geq r_{old} \end{cases} \tag{2.5}$$

r_{new} is interest rate offered by another bank, and α is intensity of choice, whose lower value represents preference for preserving previous credit relation.

In Dosi and Nelson (2010), technological change comes in the form of productivity improvement of capital goods. Technological change derive from two processes, (1) innovation and (2) imitation. Probability of innovating depends on investment in research and development RD_{it}, which itself depends on previous sales $S_{i,t-1}$:

$$\begin{aligned} RD_{it} &= \nu S_{i,t-1} \\ IN_{it} &= \xi RD_{it} \\ IM_{it} &= (1-\xi) RD_{it} \end{aligned} \tag{2.6}$$

Expenditure in R&D is either in innovation or in imitation. $0 < \nu < 1$ and ξ are shares. Probability of imitating and innovating are expressed as:

$$\begin{aligned} \theta_{it}^{in} &= 1 - e^{-\zeta_1 IN_{it}} \\ \theta_{it}^{im} &= 1 - e^{-\zeta_2 IM_{it}} \end{aligned} \tag{2.7}$$

Probabilities depend on expenditure along with $0 < \zeta_1 \leq 1$ and $0 < \zeta_2 \leq 1$. For further details on this approach consult Dosi and Nelson (2010).

Consumption

In Riccetti et al. (2015) consumption is defined according to simple behavioral rule. Desired level of consumption depends upon wage received $w_{h,t}$ and wealth$A_{h,t}$.

$$c_{h,t}^d = c_1 w_{h,t} + c_2 A_{h,t} \tag{2.8}$$

Each consumer then randomly visits a set of firms and buys the cheaper goods. Firms then, compete through price which is set based on the dynamics of the inventories,

$$p_{i,t} = \begin{cases} p_{i,t-1}(1+\alpha U(0,1)), & \text{if } \hat{y}_{i,t-1} = 0 \text{ and } y_{i,t-1} > 0 \\ p_{i,t-1}(1-\alpha U(0,1)), & \text{if } \hat{y}_{i,t-1} > 0 \text{ or } y_{i,t-1} = 0 \end{cases} \tag{2.9}$$

where, $y_{i,t}$ is amount of goods produced by firm in period t and $\hat{y}_{i,t}$ is produced amount plus the inventories.

Government and Central Bank

Various implementation of ABMs have used different formulation of the government and central bank in their model. Bank's interest rate determination can be described as sum of central bank's policy rate, bank specific part and borrowing firm's leverage dependent part.

$$R_{b,f,t} = rCB_t + \gamma A_{b,t-1}^{-\gamma} + \gamma \frac{\text{leverage}_{f,t}}{1 + \frac{A_{f,t-1}}{\max A_{f,t-1}}} \tag{2.10}$$

Some implementation like Riccetti et al. (2015) consider the case that government also provides employment and model the employment role of government specifically. Government collect fixed rate tax on assets of households, firms and banks.

$$A_{h,t} = (1-\tau') \cdot [A_{h,t-1} + (1-\tau) \cdot w_{h,t} + ...] \tag{2.11}$$

Where τ' is the tax rate on wealth applied on wealth exceeding a threshold and τ is tax rate on income.

2.4 Structure of ABM based model

Modeling in ABM framework can be thought as generating a time series through implementation of micro-foundation rules . First, we lay out the initial conditions for the various parameters of the model. θ are micro-parameters which affect the individual agents like initial distribution of assets and skills. Θ are macro parameters which affect the global environment. We then through computational means generate the times series of variables $x_{i,t}$ and X_t. To get the statistics from this time series, we use necessary aggregation operation, generally summation. For example, by summing the outputs of the firms, we can generate GDP of the fictional economy. A single run of model will be biased by starting conditions and sequence of random number generations. By repeating the process by M times and computing Monte Carlo distribution of the statistics (See figure 2.3 on the following page) , we can increase our understanding on how the model generates its feature and how stable those features are.

A typical ABM code (See figure 2.4 on page 21) has both sensitivity test and

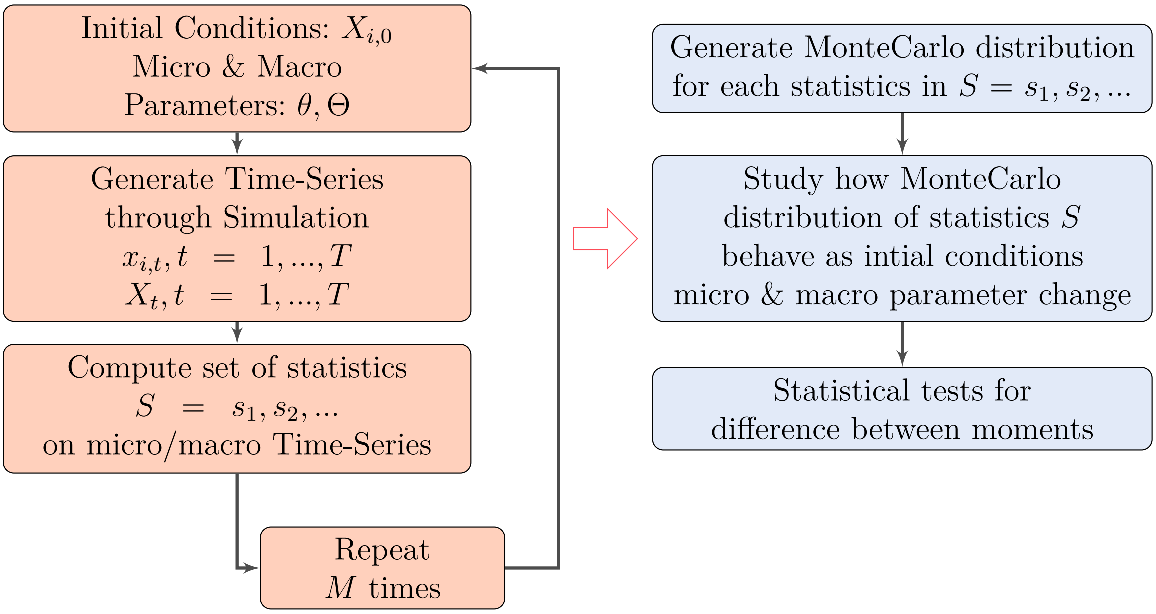


Figure 2.3: Structure of modeling with ABM (Haldane & Turrell, 2018).

Monte Carlo of different run. The critical difference between them is in the use of random number generator. Computer programs generate pseudo-random numbers and are not truly random. By providing the same single seed, we can replicate the computer produced random numbers. In Monte Carlo part of the program, we are concerned with how the system reacts to the impact of stochastic components. We want to know the robustness of the model to stochastic properties. Whereas, in the sensitivity test, we want to check how the behavior of the system changes under different parameter configurations compared to the baseline scenario. Thus, we want to have the same stochastic component in the different runs of sensitivity test but separate stochastic elements in the different runs of the Monte Carlo cycle. We achieve this by setting the seed of random number generator between the start for sensitivity test and Monte Carlo. This seed positioning gives different Monte Carlo runs a different segment from a random number generated by the seed. It enables to construct different stochastic component in each run. Having seed inside the sensitivity loop allows us to have the same stochastic property for different parameter settings, allowing us to separate the impact of the parameter from the stochastic term.

2.5 ABM in applied literature

ABM took off with the development of faster computer chips in the early 2010s. Gatti, Gaffeo et al. (2010) was one of the first articles to implement the heterogeneous production and banking sector. Firms were interacting directly with financially fragile heterogeneous banks to finance their production. The au-

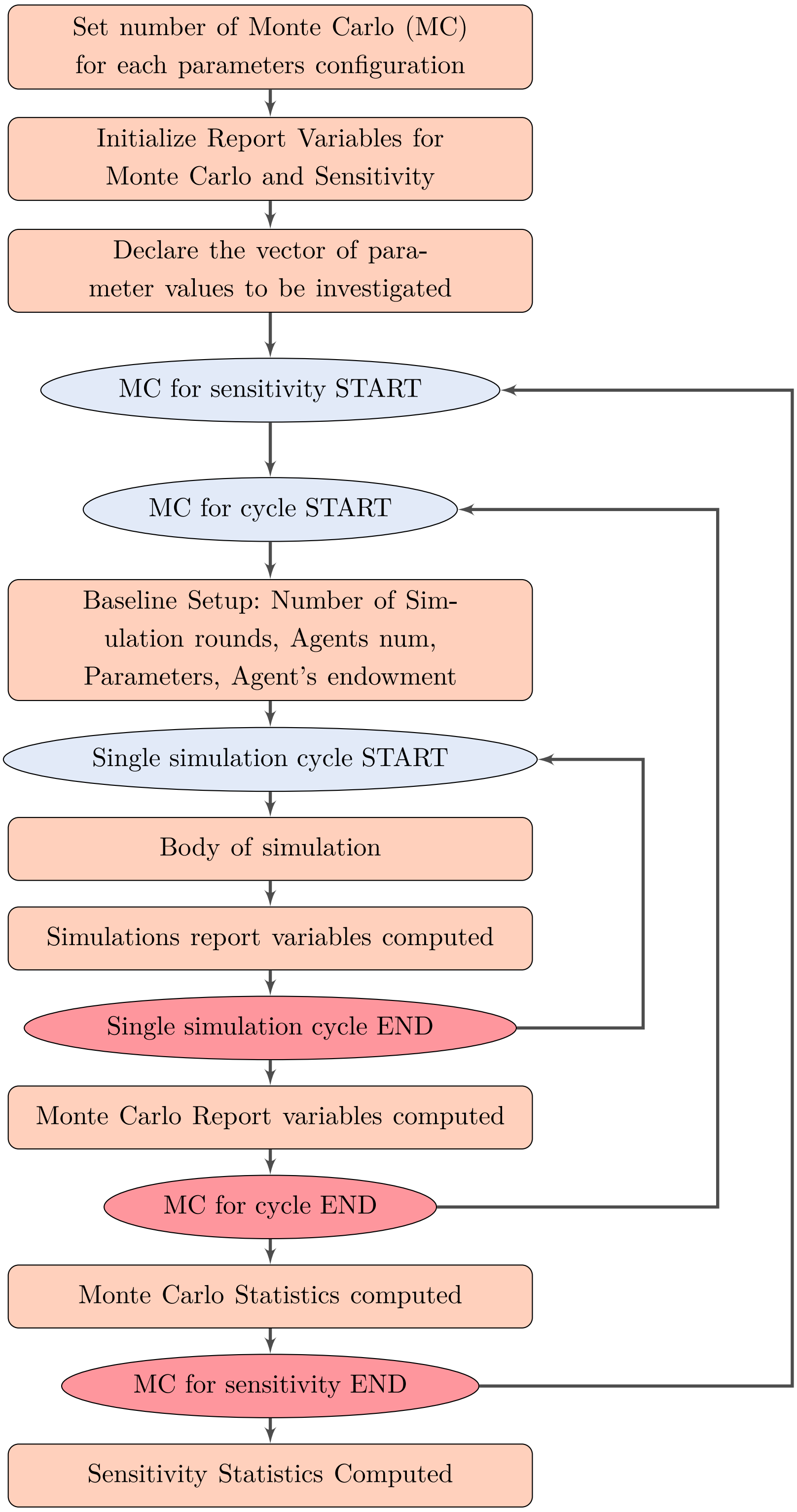


Figure 2.4: Code structure of generic ABM

thors demonstrated the presence of a network-based financial accelerator in such a model. The mid-decade saw the development of several macro models by various institutions and research groups (Caiani et al., 2016; Dawid et al., 2012; Lengnick & Wohltmann, 2016; Riccetti et al., 2015; Tesfatsion, 2017). Huge efforts were spent on trying to replicate the stylized facts on both macro and micro levels. An example would be Platas-lópez et al. (2019), which is NetLogo based implementation of the Bottom-up Adaptive Macroeconomics (BAM) model by Gatti et al. (2011). It describes the BAM implementation in Overview, Design concepts, and Details (ODD) protocol and demonstrates replication of both macro and micro stylized facts.

Recent papers utilizing ABM are actively utilizing the framework to study critical economic issues. Salle et al. (2013) investigated inflation targeting and the role of the central bank in implementing inflation targeting via monetary policy, assuming economic agents with heuristic behavior. The result of the study point to the prime importance of the credibility of the central bank's inflation target regarding macroeconomic stabilization, as well as the beneficial role played by that target as an anchoring device for private inflation expectations. In Popoyan et al. (2017), ABM is used to study financial and macroeconomic stability, especially policy mix that can achieve the banking sector's resilience to foster macroeconomic stability. They found the triple-mandate Taylor rule, which focused on the output gap, inflation, and credit growth with Basel III to improve the stability of the banking sector and smooth output fluctuation. Whereas, Bardoscia et al. (2017) use ABM to study topological features of network structures which influences how distress spreads within the network. They showed that market integration and diversification, which are generally believed to stabilize the financial system, can contribute to creating cyclical structures which amplify financial distress and make large crises likely. Assenza et al. (2017), studying the loan market in ABM framework, shows that a small fraction of pessimistic traders can have a large aggregate effect leading to a crisis characterized by high-interest rates for loans and low output; highlighting how pessimistic expectations can amplify crisis and slow down recovery.

Poledna et al. (2022) develop an ABM of a small open economy to forecast the macroeconomic impact effect of different scenarios for the lock-down measure taken in Austria to combat the COVID-19 pandemic using micro and macro data from national accounts, sector accounts, input-output tables, government statistics, and census and business demography data. The authors made detailed projections on the sectoral impacts of the COVID-19 pandemic and pointed out the potential application of the model, including stress testing and predicting the effects of the monetary and fiscal policy. Stress testing is also a feature of Liu et al. (2020)'s model that studies the banking choice and inter-bank lending system. The model reproduces dynamics similar to those of the 2007-09 financial crisis and shows how bank losses and failures arise from network contagion and lending market illiquidity. After calibration to post-crisis data, the model shows that the US banking system reduced its likelihood of bank failures through network contagion and illiquidity. In Lin and Zhang (2021), Chinese inter-bank contingent risk is studied using ABM. The authors simulated the contagion risks under credit shocks using financial data from 2014 to 2019 from 299 commercial banks. The failure of four banks caused 12 other banks to fail; foreign banks and rural commercial banks were less resilient to the contagion risks.

Another chain of literature on ABM has been to use it for studying financial markets. Darley and Outkin (2007)'s celebrated work examined the effects of potential rule changes in the NASDAQ stock exchange. The proposed change was related to decimalization, with the minimum price increment reducing from $1/16^{th}$ of dollar to $1/100^{th}$. The results of Darley and Outkin (2007) pointed out that under the presence of parasitic Dealer strategies, a reduction in tick size caused the simulated market to suffer a reduction in its ability to reflect the actual value of the traded asset accurately. These effects were observed in live market data following decimalization of NASDAQ trading (Paulin et al., 2018). Newer ABM papers have used the tool to examine blockchain technology and cryptocurrency. In Lohmer et al. (2020), resilience strategies and ripple effects in blockchain-coordinated supply chains are studied. The price of bitcoin, given the wide swings, has been studied using ABM. Cheng and Lin (2022) explores cryptocurrency appreciation and estimated parameters of the cryptocurrency market using an interactive Agent-Based Model. The authors' central identification is that fundamentalists' risk-taking behavior pushes the price of Bitcoin. In their opinion, increasing Bitcoin prices may not be a speculative bubble. Whereas, Fratric et al. (2022) find fraudulent behavior in the crypto market as an essential explanation for Bitcoin price development. They investigate the behavior of the Bitcoin market using the Agent-Based Model and identify that the presence of the fraudulent agent was essential to obtain Bitcoin price development in the given period.

2.6 Summary

In our literature review, we attempted to find agent-based literature that specifically addresses cryptocurrency in a macroeconomic model. However, we found that there is a gap in the theoretical study of cryptocurrency in a macroeconomy. While there have been some studies on cryptocurrency in a macroeconomic framework, most of these utilize the equilibrium framework, which may not be well-suited for a fragile asset like cryptocurrency. This indicates a gap in the existing literature in terms of methodology as well.

CHAPTER III

RESEARCH METHODOLOGY

3.1 Philosophical issues

Economics has a diverse philosophical foundation in terms of methodology and theory. The research paradigm of this work is influenced by both the radical humanist paradigm and the radical structuralism paradigm. The radical humanist paradigm suggests that reality is socially constructed and maintained, while the radical structuralism paradigm suggests that reality is objective and concrete(Trochim & Donnelly, 2006). The agent-based model used in this study is motivated by the idea that macroeconomic outcomes are the result of emergent properties when many micro-level economic agents are assembled. These agents act based on past experiences, so future outcomes are influenced by past macro and micro environments. This perspective aligns with the radical humanist paradigm, as the economy is seen as being socially constructed and maintained by the actions of micro-level actors. Additionally, the assumption that we can postulate the rules that mimic the economic actions of micro-level actors aligns with the radical structuralism paradigm.

The ontological position of this study is objectivism, meaning that social entities are considered to exist independently of social actions. As part of economics research, this study is objective and value-free, and aims to produce real explanatory and predictive knowledge about reality. The epistemological position of this study is positivism, which emphasizes the use of empirical data and models to develop theories that can be tested and confirmed or refuted through further investigation. In order to align the research methods with this epistemological position, this study will use the latest available theories, results, and data sets in the field of economics.

The axiological position of this research is to conduct the study in a value-free manner, i.e., the researcher will not be influenced by or influence the subject or results of the research. The philosophical tradition underlying this analysis is the Post-Keynesian framework.

3.2 Conceptual framework

Cryptocurrency can be thought of as an asset that has a fixed generation function, which is explained in the white paper when the cryptocurrency conducts an initial coin offering (ICO). Unlike traditional monetary institutions, the governing team of a cryptocurrency (which varies for each cryptocurrency in circulation) does not alter the supply of the cryptocurrency in response to changes in demand, but instead adheres to the original design. This characteristic allows us to mathematically model the generator function to understand its implications.

Since much of cryptocurrency is used for trading and only a tiny fraction is used for exchanging value as a currency, we can assume that the returns from cryptocurrency investments will be the main determinant of an asset and investors' participation in the market. Based on this assumption, we design a market participation mechanism for cryptocurrency investors that takes into account their prior investment status and individual characteristics. We use existing literature on agent-based finance to model the market participation mechanism of investors.

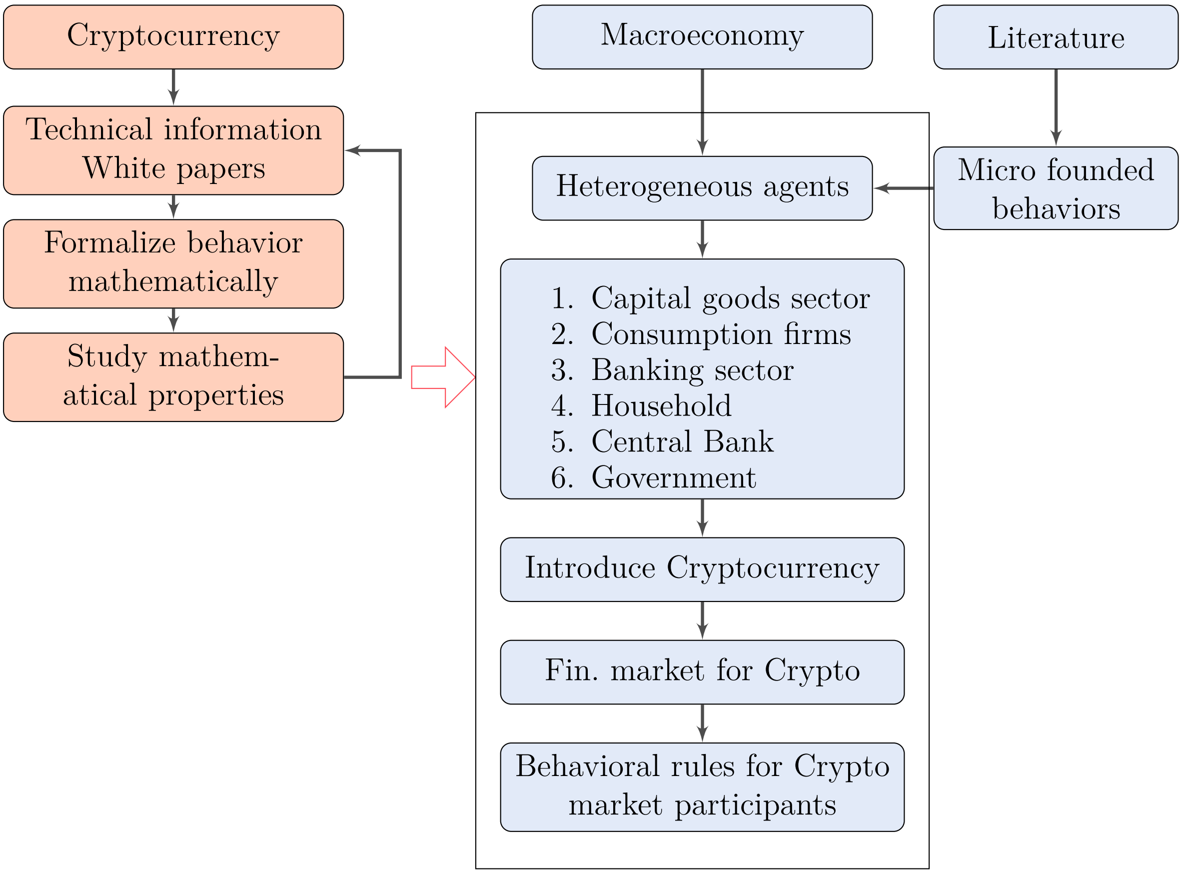


Figure 3.1: Conceptual framework

In the agent-based macro-model, the cryptocurrency is introduced using a formal structure based on the study of white papers and existing literature on agent-based finance models. The model also includes other components that are modeled using existing literature and the author's priorities. Given the focus on cryptocurrency, its generation and trading are examined in detail, while the banking sector is represented by a single agent. The model includes heterogeneous households that differ in wealth, income level, investment strategy, and targeted saving, which allows the model to be stock-flow consistent. Only when a household decides to sell an asset can another household purchase it, and the monetary value of the goods is exchanged when a purchase occurs. Money in the economy can only be earned through work, dividends from firm profits, or government redistribution, so households can only spend what they earn and cannot endlessly speculate on the cryptocurrency price.

3.3 Research design

We develop an ABM theoretical framework in a closed macro model, in which consumption firms (C-firms) use the Leontief production function with two inputs, while firms in the capital goods sector (K-firm) use a single input Leontief production function. The model includes a fixed number of households, firms, and banks. Based on these starting conditions, we have designed the behavioral rules for firms, households, the government, and the central bank. The cryptocurrency is treated in line with literature on agent-based finance. The model is stock-flow consistent, meaning that there is no creation of new monetary value without an explicit transfer or production process. Transfers must be from one agent to another. The banking sector is designed to apply loan rationing, meaning that firms do not automatically receive loans just because they request them. Instead, the banking sector calculates the expected returns based on variables related to the firms' financial soundness and decides whether or not to provide the loan.

Table 3.1: Starting condition

Variable	Value
Number of households	n_h
Number of C-firms	n_c
Number of K-firm	1
Number of Banks	1
Mean household saving	d_h
Price of 1 Labor	P_N
Price of Capital	P_i
Mean output of C firm	Y_c
Mean output of K firm	Y_k
Unemployment Level	u_N
Debt to equity ratio	der

Say, there are n_h households in an economy, each providing 1 unit of labor to n_c C firms and 1 K firm. Say, price of Labor is P_N at equilibrium, interest rate is i and households have d_h financial assets. Then, total output by C firms is equal to the consumption of households, i.e.,

$$n_c Y_c = n_h \left[u C_{min} + (1-u) c_h P_N + c_f d_h \right] \tag{3.1}$$

$$\text{or, } \kappa_N^c \left(n_h (1-u) - \frac{Y_K}{\kappa_N^k} \right) = n_h \left[u C_{min} + (1-u) c_h P_N + c_f d_h \right] \tag{3.2}$$

where, u, κ_N^c, and κ_N^k are unemployment rate, labor productivity of C-firm, and labor productivity of K-firm. During starting equilibrium, K-firm produces K-good in such an amount that it is just sufficient to replenish depreciation of K-good invested in C-firms. If δ_K is depreciation rate of investment in C-firms, then total depreciation across all C-firms is $\delta_K n_c \frac{Y_c}{\kappa_K^c}$. As a result, we can write equilibrium condition as

$$\kappa_N^c \left(n_h (1-u) - \frac{\delta_K n_c \frac{Y_c}{\kappa_K^c}}{\kappa_N^k} \right) = n_h \left[u C_{min} + (1-u) c_h P_N + c_f d_h \right]. \tag{3.3}$$

Let us assume $P_N = 1$, $\frac{n_h}{n_c} = n^*$, $\frac{\kappa_N^c}{\kappa_K^c} = \kappa^{c*}$, $C_{min} = \bar{C}_{min}$, $u = \bar{u}$, $c_h = \bar{c}_h$, and $c_f = \bar{c}_f$. Then, we can write the term inside the square bracket on the right side as $a + \bar{c}_f d_h$. Rearranging the equilibrium conditions, we get

$$\kappa_N^c \left((1-\bar{u}) - \frac{\delta_K \left[a + \bar{c}_f d_h \right]}{\kappa_K^c \kappa_N^k} \right) = n^* \left[a + \bar{c}_f d_h \right] \tag{3.4}$$

$$\text{or, } \kappa_N^c = \left(\frac{\delta_K \kappa^{c*}}{\kappa_N^k} + n^* \right) \frac{\left[a + \bar{c}_f d_h \right]}{(1-\bar{u})}, \tag{3.5}$$

i.e., labor productivity of the C-firm is expressed as a function of labor productivity of K-firm κ_N^k, number of households n_h, and household financial assets d_h, ceteris paribus. Another equilibrium can be derived for these starting condition using the identity that total debt in the economy is a fraction of the total savings of firms and households, plus banking sector's equity. If the equity of the K-firm is assumed to be equal to wage bill of one period $\frac{P_N Y_K}{\kappa_N^k}$, whereas, C-firm's equity is supposed to cover wage bill and a fraction of K-good invested, i.e., $\frac{Y_c P_N}{\kappa_N^c} + \frac{Y_c P_K}{(1+der)\kappa_K^c}$, where der is debt to equity ratio. This assumption, along with $P_N = 1$, allows us to calculate the total debt in the economy as

$$der \left[\frac{Y_K}{\kappa_N^k} + n_c \left(\frac{Y_c}{\kappa_N^c} + \frac{Y_c P_K}{(1+der)\kappa_K^c} \right) \right]. \tag{3.6}$$

The total deposits in the economy will be

$$\begin{gathered}(1 + der_k)E_{Kf} - P_{Kg} \cdot K_{inv} + n_c(C_{depo}+ \\ (1 + der_k)E_{Cf} - P_{Cg} \cdot C_{inv} - P_{Kg} \cdot I_c) + n_h d_h + B_{\text{equity}}.\end{gathered} \tag{3.7}$$

Under these circumstances, the model's starting condition will be designed based on the following table:

Table 3.2: Starting model condition

Variable	Value
K firm	
Existing K good inventory K_{inv}	$(\delta^{min}_{inv,K} + \delta^{min}_{inv,K})/2 \cdot 1 \cdot Y_k$
Employment in K firm	Y_k/κ^k_N
K firm equityE_{Kf}	$P_N \cdot Y_k/\kappa_N$
K firm debt K_{debt}	$der_k \cdot E_{Kf}$
K good price P_{Kg}	$((K_{debt}/144 + P_i \cdot K_{debt}) + P_N \cdot Y_k/\kappa_N) \cdot (1/Y_k) \cdot 1.025$
K firm's bank deposit K_{depo}	$(1 + der_k)E_{Kf} - P_{Kg} \cdot K_{inv}$
C firm	
Existing C good inventory C_{inv}	$(\delta^{min}_{inv,C} + \delta^{min}_{inv,C})/2 \cdot 1 \cdot Y_c$
K invested in C firm I_c	Y_c/κ^c_K
N demand in C firm	Y_c/κ^c_N
C firm equity E_{Cf}	$Y_c/\kappa^c_N \cdot P_N + (Y_c/\kappa^c_K \cdot P_{Kg})/(1 + der_c)$
C firm debt C_{debt}	$der_c \cdot E_{Cf}$
C good price P_{Cg}	$((C_{debt}/144 + P_i \cdot C_{debt}) + P_N \cdot Y_c/\kappa^c_N) \cdot (1/Y_c) \cdot 1.20$
C firm's bank depositC_{depo}	$(1+der_k)E_{Cf} - P_{Cg} \cdot C_{inv} - P_{Kg} \cdot I_c$
Total K invested by C firms	$n_c \cdot I_c$
Total C inventory by C firms	$n_c \cdot C_{inv}$
Available N for C firm N_{av}	$n_h \cdot (1 - u_N) - Y_k/\kappa_N$
Total output by C firms TY_c	$\kappa^c_N \cdot N_{av}$
Total K depreciation by C firms D_I	$TY_c \cdot \delta_K$
Total debt in economy T_{debt}	$n_c \cdot C_{debt} + K_{debt}$
Total deposits in economy	$K_{depo} + n_c \cdot C_{depo} + n_h \cdot d_h + E_b$
Household	
Total consumption demand TC_h	$n_h \cdot u_N \cdot C_{min,t} + n_h \cdot (1 - u_N) \cdot (c_h \cdot P_N + c_f \cdot d_h)$

Source: Author's calculations

CHAPTER IV

THEORETICAL MODEL: CRYPTO INSIDE ABM

The next two sections describe the results of our two objectives. To address the first objective, we present a mathematical representation of cryptocurrency and discuss its design implications. In the following section, we use this information to introduce cryptocurrency into an agent-based macroeconomic model, fulfilling our second objective of constructing an agent-based, micro-founded, closed-economy macro-model with cryptocurrency.

4.1 System design and profitability

In reality, all generators of cryptocurrencies operate in discrete time steps, but these time steps are small enough that we can represent the generator as a smooth function. As a result, we describe the supply of cryptocurrency using a continuous function. We then present an argument on the impact of the generator function on the dollar pool in a cryptocurrency market, and show that under certain reasonable assumptions, cryptocurrency behaves like a Ponzi scheme, relying entirely on positive price expectations for any positive value growth.

4.1.1 A ponzi structure

Consider a cryptocurrency with new currency supply $\mathbb{X}_t$ at t period. Let the supply be increasing but at decreasing rate, i.e., $\frac{d\mathbb{X}_t}{dt} > 0$ and $\frac{d^2\mathbb{X}_t}{dt^2} < 0$. For simplicity, if $a > 0$ and $b > 0$, $\mathbb{X}_t$ is defined as

$$\mathbb{X}_t = at - bt^2. \tag{4.1}$$

Let us assume that entrants n_t and exiteers e_t at the time t in the cryptocurrency market are function of expected and realized profit in-terms of non-Crypto currency, i.e., dollars. We can simplify it by assuming that expected and realized profits are function of expected price P_t^e. Then, net gain of new entrants at a time t is $g_t \equiv n_t - e_t$ is a function of P_t^e. We can now find the net inflow of dollar to the cryptocurrency system at t time as $P_t \cdot g_t$, where P_t is price of cryptocurrency in dollars. The total pool of the dollar available to the market participants to liquid their crypto holding is

$$L_t = \int_0^t P_t \cdot g_t dt, \tag{4.2}$$

such that $\forall i < t, L_i > 0$ for the system to be liquid in the system's history. But the claim on the L_t per unit of cyrptocurrency l_t at each period is

$$l_t = \frac{L_t}{\int_0^t \mathbb{X}_t dt} = \frac{\int_0^t P_t \cdot f(P_t^e) dt}{\mathbb{T}_t}. \tag{4.3}$$

If $l_t < P_t$ situation is known by the market participants, that would create a run on the crypto system, forcing a net loss of value worth $(P_t - l_t) \cdot \left(\frac{a}{2}t^2 - \frac{b}{3}t^3\right)$. Then, we can write simple comparative statistic.

$$\frac{dl_t}{dt} = \frac{L_t^{'} \cdot \mathbb{T}_t - L_t \cdot \mathbb{T}_t^{'}}{\mathbb{T}_t^2} \tag{4.4}$$

$$= \frac{L_t^{'}}{\mathbb{T}_t} - \frac{\mathbb{X}_t}{\mathbb{T}_t^2} L_t \tag{4.5}$$

For increasing pool of dollars per unit cryptocurrency, it follows that $\frac{dl_t}{dt} > 0$, or,

$$\frac{1}{L_t} L_t^{'} > \frac{1}{\mathbb{T}_t} \mathbb{T}_t^{'} \tag{4.6}$$

$$> \frac{6at - 6bt^2}{3at^2 - 2bt^3}, \tag{4.7}$$

i.e., growth of dollar liquidity must be greater than the growth of total cryptocurrency in the circulation. The first derivative of right hand term of the equation 4.7 decreases with time, i.e., growth of total dollar liquidity can slow down with time but has to be positive. If we assume that current market price embodies the future price expectations, the dollar liquidity can be expressed entirely in terms of price expectations as,

$$L_t = \int_0^t P_t \cdot g_t dt \tag{4.8}$$

$$= \int_0^t h(P_t^e) \cdot j(P_t^e) dt, \tag{4.9}$$

where $h(.)$ and $j(.)$ are increasing functions in P_t^e and that spew out P_t and g_t. This can be further simplified as a function $H(.)$ increasing in P_t^e , as,

$$L_t = \int_0^t H(P_t^e) dt. \tag{4.10}$$

If there was a sustained use case of cryptocurrency, then the $H(.)$ in equation 4.10 on the previous page would have to be modified to $H(P_t^e, U_t)$, with $H(.)$ being positively increasing in the both price expectation P_t^e and use case U_t. With the sustained or growing use case, the lower limit on the growth of total dollar liquidity, equation 4.7 on the preceding page, can be easily overcome. As dollar required to liquid the crypto coin can come only from another participant, without sustained use case, P_t^e must be sufficiently positive in early t periods for the continuous growth of l_t. But, it also mean that at the early stage of cryptocurrency without rosy P_t^e, right hand term of equation 4.7 on the previous page will dominate, i.e., initial crypto participants must bring in new entrants at sufficiently strong pace for keeping l_t constant or growing. This makes the cryptocurrency a negative sum game with a ponzi like structure if it does not have a sustained use case.

4.2 An ABM macro-model with cryptocurrency

In this section, we describe the macro model developed for our research question. The key features of the model include: (a) buffer-stock style consumption, (b) adaptive heuristic decision making, (c) sticky wages, (d) two types of firms, (e) realistic inventory and loan applications, (f) realistic cryptocurrency growth functions, (g) state-dependent trading strategies in the cryptocurrency market, and (h) a banking sector that is limited by monetary policy. The various components of the model are described in more detail in the following sections.

4.2.1 Information set and heuristics

An economic agent's information set, Ω_{it}, is a collection of its state variables x_{it}, general economy related signals e_{it}, and sampled signals n_{it} from its neighborhood. General signals are provided by the public institutions, whereas, sampled signals are generated by a limited sampling λ of the fellow participants N such that $\lambda < N$. Thus, a behavioral rule is the agent's choice given its information set at a given time t.

Agents use heuristics to form expectations. Such a decision making rule requires examining fewer cues, at lower retrieving costs through simpler weighting mechanisms (Shah & Oppenheimer, 2008). Heuristics do not necessarily mean trade-off of accuracy with effort (Czerlinski et al., 1999; Dawes, 1979; Gigerenzer & Gaissmaier, 2011; Martignon et al., 2008; Wübben & Wangenheim, 2008) and are common as not all decisions are essential to warrant resources for find the best course of action, cognitive limitations on part of the decision-maker, and time and effort associated with the information search and processing.

Expectations in the model are endogenous and evolving, and are computed using heuristic switching model of Anufriev and Hommes (2012). If y_t^e is the beginning of the period expectation for generic variable for its value at the end of period t, then an economic agent computes expectations through four different rules, namely, adaptive y_t^{ae}, weak trend following y_t^{wtf}, strong trend following y_t^{stf}, and anchoring and adjustment y_t^{aa}, as

$$\begin{aligned} y_t^{ae} &= y_{t-1}^e + w_{ada}(y_{t-1} - y_{t-1}^e), && (4.11)\\ y_t^{wtf} &= y_{t-1} + \gamma_{wtr}(y_{t-1} - y_{t-2}), && (4.12)\\ y_t^{stf} &= y_{t-1} + \gamma_{str}(y_{t-1} - y_{t-2}), && (4.13)\\ y_t^{aa} &= 0.5(y^f + y_{t-1}) + (y_{t-1} - y_{t-2}), && (4.14) \end{aligned}$$

where, y^f is a fundamental value assumed to be the average of the past values $(1/t)\sum_{j=0}^{t-1} y_j$. The agent, then, weights each rules based on their past period performance using a fitness function $U_{h,t-1} = -(y_{t-1} - y_{h,t-1}^e)^2 + \eta U_{h,t-2}$ where η measures the weight given for the past performance of the heuristics. Probability $n_{h,t}$ of choosing a heuristic h is $\delta n_{h,t-1} + (1-\delta)\frac{\exp(\beta U_{h,t-1})}{Z_{t-1}}$, where $0 \le \delta \le 1$ is heuristic rule updating inertia, $\beta \ge 0$ is sensitivity to the differential performance of strategies, and Z_{t-1} is a normalizing factor such that it is equal to $\sum_{h=0}^{H} \exp(\beta U_{h,t-1})$). Finally, the expectation for the variable, denoted as $Æ(y_t)$, is given by sum of probability weighted expectations formed by different heuristics, i.e., $\sum_h n_{h,t} y_{h,t}^e$.

4.2.2 Consumption

Households supply labor to firms, consume goods produced by consumer goods (C-goods) producing firms (C-firms), and hold savings in the bank. An employed household supplies one unit level of labor and consumes C-goods as fractions of human and financial wealth as

$$C_{h,t}^{exp} = \begin{cases} C_{min,t} & \text{if } \mathbb{D}_{h,t} + \mathbb{D}_{h,t}^{crypto} \le C_{min,t}, \\ \min(c_h W_{h,t}^h + c_f W_{h,t}^f,\ \mathbb{D}_{h,t} + \mathbb{D}_{h,t}^{crypto}) & \text{otherwise and } 0 < c_f < c_h < 1, \end{cases} \quad (4.15)$$

where, c_h and c_f are marginal consumption out of human and financial wealth. The household consumes a subsistence level of consumption $C_{min,t}$ when its deposits are below $C_{min,t}$. This shortfall is covered by the government. The human wealth $W_{h,t}^h$ is a weighted sum of expected income and the past period income, i.e., $\zeta_Y Y_{h,t}^e + (1-\zeta_Y) Y_{h,t-1}$, whereas, financial wealth $W_{h,t}^f$ is sum of deposits in normal and crypto currencies. The consumption target in equation 4.15 can be reformulated in the buffer-stock style as

$$C^{exp}_{h,t} = W^h_{h,t} + c_f \left(W^f_{h,t} - \frac{1 - c_h}{c_f} W^h_{h,t} \right) \tag{4.16}$$

$$= Y + \kappa_{bs}(W - \phi_{bs} Y), \tag{4.17}$$

i.e., household use financial wealth to buffer the shortfall in the income flow; wealth is the buffer for the hard times. There is a wealth to income ratio ϕ_{bs}, that household aims to achieve and κ_{bs} controls the sensitivity of change in consumption with respect to deviation from the targeted wealth to income ratio.

4.2.3 Reservation wage

Wages are determined when the firm's wage offer exceeds or, at minimal, matches the reservation wage, $w^R_{h,t}$, of the household. In inflationary circumstances, the expected price ratio $\bar{P}_{r,h} > 1$ causes reservation wage to increase proportionally to the expected price movements; households desire to maintain their purchasing power. However, when prices are decreasing, labor wages show stickiness. Reservation wage of the unemployed declines steadily with the rate $\eta^R_{w,u}$ till it hits a floor set by the minimum wage w^{min} regulation.

$$\bar{P}_{r,h} = \begin{cases} \frac{\text{Æ}(\bar{P})_h}{\bar{P}_{past,h}} & \text{if } \text{Æ}(\bar{P})_h < \bar{P}_{past,h} \\ 1 & \text{if otherwise} \end{cases} \tag{4.18}$$

$$w^R_{h,t} = \begin{cases} \bar{P}_{r,h}(1 + \eta^R_w) w_{h,t} & \text{if employed} \\ w^R_{h,t-1}(1 - \eta^R_{w,u}) & \text{if unemployed} \\ w^{min} & \text{if } w^{min} \geq w^R_{h,t-1} \end{cases} \tag{4.19}$$

4.2.4 Capital goods producing firm

A single firm, representative of the capital goods (K-good) industry, in the economy converts labor inputs into capital goods at a fixed ratio κ^K_N. For simplifying reasons, it is assumed that the price of the K-good, $P_{K,t}$, changes linearly plus small randomness with the average cost of production,

$$P_{K,t} = (1 + \eta_K) p^0_{K,t} \tag{4.20}$$

$$p^0_{K,t} = \frac{w_{K,t} N_{K,t} + \sum_b \mathcal{L}^K_{b,t} \mathbb{i}^K_{b,t}}{Y_{K,t}}, \tag{4.21}$$

where, $\mathcal{L}^K_{b,t}$, $w_{K,t}$, and $N_{K,t}$ are loan, labor wage, and employee size of K-firm. Inventory $\triangle_{K,t}$ is the function of the past period production $Y_{K,t-1}$ and sales

$S_{K,t-1}$. The firm aims to bound it between $\triangle^m_{K,t}$ and $\triangle^M_{K,t}$.

$$\triangle_{K,t} = (Y_{K,t-1} - S_{K,t-1}) + \triangle_{K,t-1} \tag{4.22}$$

$$\triangle^m_{K,t} = \delta^{min}_{inv,K}\, Æ(S_{K,t}) \tag{4.23}$$

$$\triangle^M_{K,t} = \delta^{max}_{inv,K}\, Æ(S_{K,t}) \tag{4.24}$$

The production technology is a single factor fixed proportion production function, i.e., $Y_{K,t} = \kappa^K_N N_{K,t}$. Given this technology, the desired output level, $Y^*_{K,t}$, is given by

$$Y^*_{K,t} = \begin{cases} Y_{K,t-1} & \text{if } \triangle^m_{K,t} \leq \triangle_{K,t} \leq \triangle^M_{K,t} \\ Æ(S_{K,t}) + \triangle^m_{K,t} - \triangle_{K,t} & \text{if } \triangle_{K,t} < \triangle^m_{K,t} \\ Æ(S_{K,t}) + \triangle^M_{K,t} - \triangle_{K,t} & \text{if } \triangle^M_{K,t} < \triangle_{K,t} \end{cases} . \tag{4.25}$$

The key idea being that the planned output targets to cover expected sales $Æ(S_{K,t})$ keeping inventory within an acceptable band $[\triangle^m_{K,t}, \triangle^M_{K,t}]$. The K-firm's wage offers are average of the wage offered by the consumer goods producing firm in the last period. New labor hiring $H^N_{K,t}$ is calculated as

$$H^N_{K,t} = \frac{Y^*_{K,t}}{\kappa^K_N} - N_{K,t}. \tag{4.26}$$

4.2.5 Consumer goods producing firm

The f^{th} consumer good producing firm (C-firm) produces output $Y_{f,t}$ using $N_{f,t}$ labor and $K_{f,t}$ capital governed by a Leontief production technology, i.e.,

$$Y_{f,t} = \min(\kappa_N N_{f,t}, \kappa_K K_{f,t}), \tag{4.27}$$

where, κ_K and κ_N are capital and labor productivity. Output level and prices are set with information on sampled competitor's prices, cost of production, and future sales expectation $Æ(S_{f,t})$. When inventory level is out of the desired threshold and prices are favorable vis-a-vis competitors, the firm updates its desired production level $Y^*_{f,t}$.

$$\triangle_{f,t} = (Y_{f,t-1} - S_{f,t-1}) + \triangle_{f,t-1} \tag{4.28}$$

$$\triangle^m_{f,t} = \delta^{min}_{inv}\,Æ(S_{f,t}) \tag{4.29}$$

$$\triangle^M_{f,t} = \delta^{max}_{inv}\,Æ(S_{f,t}) \tag{4.30}$$

$$Y^*_{f,t} = \begin{cases} Y^*_{f,t-1} & \text{if } \triangle^m_{f,t} \leq \triangle_{f,t} \leq \triangle^M_{f,t} \\ Æ(S_{f,t}) + \triangle^m_{f,t} - \triangle_{f,t} & \text{if } \triangle_{f,t} < \triangle^m_{f,t} \text{ and } P_{f,t} > \bar{P}_{f,t} \\ Æ(S_{f,t}) + \triangle^M_{f,t} - \triangle_{f,t} & \text{if } \triangle_{f,t} > \triangle^M_{f,t} \text{ and } P_{f,t} < \bar{P}_{f,t} \end{cases} \tag{4.31}$$

If price is unfavorable and inventory is not within the threshold, the firm updates its markup after calculating the approximate per-unit output cost, $p^0_{f,t}$, using information on labor costs and bank loans. When there is shortfall (excess) in inventory and price is low (higher) , new prices are higher (lower). Markup growth rate, η^p, is randomly picked from the folded normal distribution.

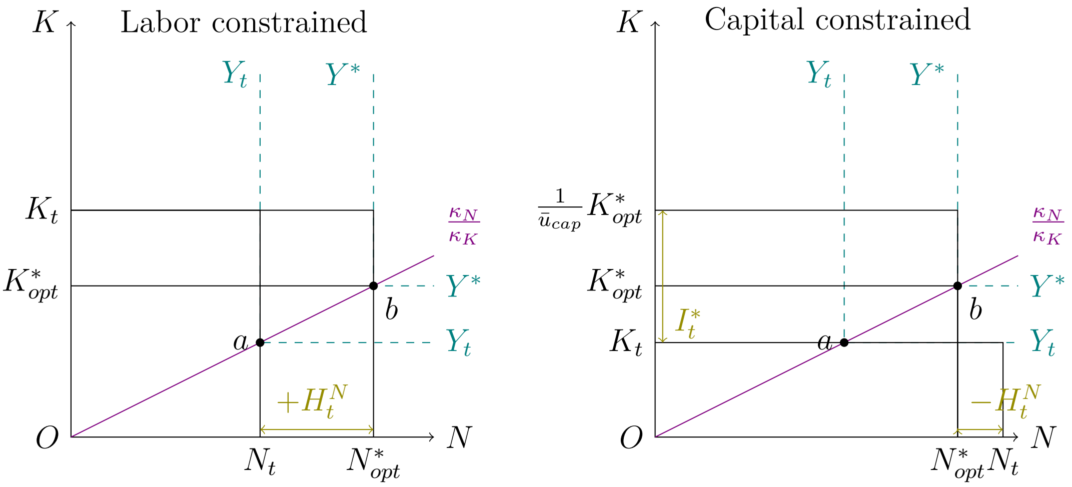
$$p^0_{f,t} = \frac{w_{f,t}N_{f,t} + \sum_b \mathcal{L}^f_{b,t}\mathbb{i}^f_{b,t}}{Y_{f,t}} \tag{4.32}$$

$$mu_{f,t} = \begin{cases} mu_{f,t-1} & \text{if } \triangle^m_{f,t} \leq \triangle_{f,t} \leq \triangle^M_{f,t} \\ mu_{f,t-1}(1+\eta^p) & \text{if } \triangle_{f,t} < \triangle^m_{f,t} \text{ and } P_{f,t} < \bar{P}_{f,t} \\ mu_{f,t-1}(1-\eta^p) & \text{if } \triangle_{f,t} > \triangle^M_{f,t} \text{ and } P_{f,t} > \bar{P}_{f,t} \end{cases} \tag{4.33}$$

$$P^*_{f,t} = \begin{cases} P_{f,t-1} & \text{if } \triangle^m_{f,t} \leq \triangle_{f,t} \leq \triangle^M_{f,t} \\ p^0_{f,t}(1+mu_{f,t}) & \text{if otherwise} \end{cases} \tag{4.34}$$

Given the desired output, $Y^*_{f,t}$, firm then decides if it has to invest capital input or hire additional labor. It wants to have an excess capital capacity, controlled by capacity utilization rate $\bar{u}_{cap}$, so slight variations in the future period desired outputs can be accommodated by existing capital stock. The optimal production plan, given the Leontief production function, is the kink in the iso-output curve. If the firm is labor constrained, ($N_t < N^*_{opt}$), to produce at a desired level of output Y^*, it hires H^N_t to reach state b in figure 4.1 on the next page, where it uses less capital K^*_{opt} than available K_t to produce Y^*. Alternatively, if the firm had a labor surplus and was capital constrained, it would remove $-H^N_t$ workers and invest I^*_t to bring capital stock to $\frac{1}{\bar{u}_{cap}}K^*_{opt}$. Note that in this case, the firm would invest more than required, i.e., K^*_{opt} as it is comfortable with having a slight overcapacity. Mathematically, following equations represent this mode of decision about desired

Figure 4.1: Derivation of desired investment and labor demand



investment and labor.

$$K^*_{opt} = \frac{Y^*_{f,t}}{\kappa_K} \tag{4.35}$$

$$N^*_{opt} = \frac{Y^*_{f,t}}{\kappa_N} \tag{4.36}$$

$$I^*_{f,t} = \begin{cases} 0 & \text{if } K^*_{opt} \leq K_{f,t} \\ \frac{1}{\bar{u}_{cap}}K^*_{opt} - K_{f,t} & \text{if } K_{f,t} \leq K^*_{opt} \end{cases} \tag{4.37}$$

$$H^N_{f,t} = \begin{cases} -(N_{f,t} - N^*_{opt}) & \text{if } \frac{1}{\bar{u}_{lab}}N^*_{opt} \leq N_{f,t} \\ N^*_{opt} - N_{f,t} & \text{if } N_{f,t} < N^*_{opt} \end{cases} \tag{4.38}$$

The profit of the firm is revenue less expense. The revenue sources are sales, interest from deposits, and nominal variation in inventories. Expenses are wages, interest payments, capital depreciation, and new crypto currency purchase. Capital is assumed to depreciate at a constant rate δ_K and is valued at prevailing market price, whereas, inventory is valued using unit cost of production.

$$\begin{gathered} \text{Revenue} = S_{f,t}P_{f,t} + \mathrm{i}_{b,t}\mathbb{D}^b_{f,t} + (\triangle_{f,t}p^0_{f,t} - \triangle_{f,t-1}p^0_{f,t-1}) \\ + \text{net change in crypto position} \end{gathered} \tag{4.39}$$

$$\text{Expenses} = w_{f,t}N_{f,t} + \sum_b \mathcal{L}^f_{b,t}\mathbb{i}^f_{b,t} + p_{K,t}K_{f,t}\delta_K \tag{4.40}$$

$$\pi_{f,t} = \text{Revenue} - \text{Expenses} \tag{4.41}$$

Firms distribute tax and dividends when they have positive profits as

$$T_{f,t} = \max(0, \tau^f_{g,t}\pi_{f,t}), \tag{4.42}$$

where, $\tau^f_{g,t}$ is government's tax rate on c-firm at period t. The liquidity status of the firm is given by operating cash flow (OCF), which is defined as

$$OCF_{f,t} = S_{f,t}P_{f,t} + \mathrm{i}_{b,t}\mathbb{D}^b_{f,t} - w_{f,t}N_{f,t} - \sum_b \mathcal{L}^f_{b,t}\mathbb{i}^f_{b,t} - \sum_b \frac{\mathcal{L}^{*,f}_{b,t}}{t^{\mathcal{L}}} \tag{4.43}$$

where $\mathcal{L}^{*,f}_{b,t}$ is the original loan principle amortized in a linear fashion over the loan's lifetime $t^{\mathcal{L}}$. OCF acts as a barometer of financial soundness of the firm. Using Caiani et al. (2016)'s financial soundness categorization, i.e., hedge, speculative, and ponzi, firms are classified on their ability to service interest payments and principle amortization.

$$\text{Hedge position:} \qquad OCF_{f,t} \geq 0 \tag{4.44}$$

$$\text{Speculative position:} \qquad OCF_{f,t} < 0, \qquad |OCF_{f,t}| < \sum_b \frac{\mathcal{L}^{*,f}_{b,t}}{t^{\mathcal{L}}} \tag{4.45}$$

$$\text{Ponzi position:} \qquad OCF_{f,t} < 0, \qquad |OCF_{f,t}| > \sum_b \frac{\mathcal{L}^{*,f}_{b,t}}{t^{\mathcal{L}}} \tag{4.46}$$

The firm has financial commitments to creditors (loan repayment), shareholders(dividend), government (taxes), and production process (investment). The priority of these commitments is in order of taxes, loan repayment, investment, and, finally, dividend. Internal resources are prioritized to fullfill its commitments before retorting to the external sources (Myers & Majluf, 1984). When the firm is unable to cover all of its obligations, it applies for the bank loan. Despite using its internal resources, the firm does not wholly exhaust savings. It has a desire to hold a certain amount of deposits expressed as a share $\varkappa_{prec,w}$ of wage bill for precautionary reasons. Faced with the credit rationing, the firm first sets dividend zero and re-scales the production plan downward. When completely lacking funds for the production plan, firm sets the production level to zero. The dividend is fraction of the moving average of the previous periods' after-tax profits, i.e.,

$$Div_{f,t} = \rho_{f,t}\frac{1}{n}\sum_{s=t-n}^{t}(\pi_{f,s} - T_{f,s}). \tag{4.47}$$

The firm lacks information on the end of the period dividend, wage bill, and cash flow, and as a result it uses last period values for these variables to compute loan demand as

$$\mathcal{L}^d_{f,t} = p_{K,t}I^*_{f,t} + Div_{f,t-1} + \varkappa_{prec,w}w_{f,t-1}N_{f,t} - OCF_{f,t-1}. \tag{4.48}$$

Wage offered by the firm depends on its ability to fulfill labor vacancy and wedge in existing wage and sampled reservation wage of the households. If the firm persistently can not fullfill the beginning of the period vacancies and if that gap $t_{vac,f}$ is above a threshold $n_{vac,thres}$ then it increases its wage offer $w^O_{f,t}$. The growth rate of offered wage $\eta_{w,O}$ is randomly sampled from the folded normal distribution.

$$t_{vac,f} = \begin{cases} \frac{\text{Unfilled vacancies}}{\text{Open vacancies}} & \\ 0 & \text{if no open vacancies} \end{cases} \tag{4.49}$$

$$w^O_{f,t} = \begin{cases} w_{f,t} & \text{if } t_{vac,f} < t^{max}_{vac} \text{ for past } n_{vac,thres} \text{ periods} \\ w_{f,t}(1+\eta_{w,O}) & \text{if } t_{vac,f} \geq t^{max}_{vac} \text{ for past } n_{vac,thres} \text{ periods} \\ w_{f,t}(1-\eta_{w,O,u}) & \text{if } t_{vac,f} = 0 \text{ \& } \bar{w}^R_t < w_{f,t} \text{ for } n_{vac,thres,u} \text{ periods} \end{cases} \tag{4.50}$$

4.2.6 Cryptocurrency

There is a single cryptocurrency in the economy with supply $\mathbb{X}_t$ in a given period. If b new blocks are generated each week with each new block generation providing coinbase reward of R that is halved after every w weeks, then the maximum supply of the cryptocurrency is

$$\mathbb{X}_{max} = \mathbb{X}_0 + bRw(1 + \frac{1}{2} + \frac{1}{4} + ...) \tag{4.51}$$

$$= \mathbb{X}_0 + 2bRw, \tag{4.52}$$

where $\mathbb{X}_0$ is the crypto coupons that are distributed at the inception of the cryptocurrency. It implies that at the end of any given week, the cryptocurrency in supply is given by

$$\mathbb{X}_t = \mathbb{X}_0 + bR \sum_{n=1}^{t} \left(\frac{1}{2}\right)^{\lfloor \frac{n-1}{w} \rfloor}, \tag{4.53}$$

where $\lfloor \cdot \rfloor$ is a floor function.

The ownership of the cryptocurrency token can be earned by purchase in cryptocurrency exchange, assigning of newly minted cryptocurrency for mining participation, ie., coinbase, and through trade. The newly minted cryptocurrency tokens are assigned with the probability equal to the ratio of owned token by total token in the cryptocurrency network at that time, i.e.,

$$p^{\mathbb{X}}_{h,t} = \frac{\mathbb{X}_{h,t}}{\mathbb{X}_t}. \tag{4.54}$$

This mechanism is similar to the Proof-of-Stake validation applied in the newer cryptocurrencies but is simplified by not calculating how and what amount of tokens are staked by the currency holders.

4.2.7 Investment in Cryptocurrency

Following the standard literature (Chiarella et al., 2012; Farmer & Joshi, 2002; Lengnick & Wohltmann, 2016; Tramontana et al., 2013; Westerhoff, 2008) on synthetic agent based financial markets, household is either chartist (trend follower) or fundamentalist (value investor). Using information set that consists of past prices, interest rates on bank deposits, and inflation target of the central bank, the household decides to allocate its wealth between bank deposits and cryptocurrency $\mathbb{X}$ by submitting an order $x^{\mathbb{X}}_{h,t}$ to the cryptocurrency market-maker.

Chartist

Chartist expects that cryptocurrency price has momentum, and will move in the direction of recent changes. This household class takes a long position (investment) if prices have been recently increasing and a short position (dis-investment) if prices have been decreasing. We assume that different households have different randomly selected anchoring price $P_{\mathbb{X},t-d_h}$, which they use to determine the future investment decision $x^{\mathbb{X}}_{h,t}$. Anchoring price is the average price with a random time lag of d_h. The investment (disinvestment) demand with out state-dependent threshold strategy is computed according to

$$x^{\mathbb{X}}_{h,t} = z_{\mathbb{X}} \operatorname{sign}(P_{\mathbb{X},t-1} - P_{\mathbb{X},t-d_h}), \tag{4.55}$$

where $z_{\mathbb{X}}$ is a positive constant setting the magnitude of the position.

Fundamentalists

The fundamentalists expect cryptocurrency to revert back to its fundamental value $u^{\mathbb{X}}_{h,t}$, and therefore buy (sell) asset when the current price is below (above) $u^{\mathbb{X}}_{h,t}$.

$$x^{\mathbb{X}}_{h,t} = z_{\mathbb{X}}\operatorname{sign}(u^{\mathbb{X}}_{h,t} - P_{\mathbb{X},t-1}) \tag{4.56}$$

Estimating the fundamental value of cryptocurrency with traditional valuation tools is tricky as it provides no income stream nor we know the holding period. Because of these difficulties, we assume that the currency appreciates at a constant rate as observed in the immediate past and household use a n-weeks window in calculating the present value. After adding an inertia generating weighted lag term, the fundamental value of cryptocurrency is approximated as

$$u_{h,t}^{\mathbb{X}} = (w_{u_{\mathbb{X}}})\frac{\bar{P}_{\mathbb{X}}(1+\bar{r}_{\mathbb{X}})^n}{(1+\boldsymbol{r}_{h,t}^{\mathbb{X}})^n} + (1-w_{u_{\mathbb{X}}})u_{h,t-1}^{\mathbb{X}}, \tag{4.57}$$

where $\boldsymbol{r}_{h,t}^{\mathbb{X}}$ is a required rate of return. The required rate of return is sum of risk-free rate and risk premium, and later is composed of individual bias $r_{h,\mathbb{X}}^{*}$ and compensation for risk over the risk free rate i_t^*. Individual bias models the heterogeneity in the household risk preference and is sampled from a uniform distribution, whereas, risk-free rate is proxied by interest rate available for depositing funds in a bank.

$$\boldsymbol{r}_{h,t}^{\mathbb{X}} = i_t^* + r_{h,\mathbb{X}}^* + \beta_{\mathbb{X},t}(r_{\mathbb{X},t-1} - i_t^*) \tag{4.58}$$

$$r_{h,\mathbb{X}}^* \sim \mathcal{U}(0, 0.5) \tag{4.59}$$

$$\beta_{\mathbb{X},t} = \frac{\text{Co-variance}_t(r_{\mathbb{X}}, i^*)}{\text{Variance}_t(i^*)} \tag{4.60}$$

$$r_{\mathbb{X},t-1} = \frac{p_{\mathbb{X},t-1} - p_{\mathbb{X},t-2}}{p_{\mathbb{X},t-2}} \tag{4.61}$$

State-dependent threshold strategies

If a household participated in the crypto-trading at any price differential, it would imply both high transaction cost and unrealistic trading frequency. A cost minimizing household participates in the market, only if perceived mis-pricing $m_{h,t}^{\mathbb{X}}$ is beyond a certain threshold. Every households have an associated threshold pairs, entry threshold $T_{\mathbb{X},h}$ and exit threshold $\tau_{\mathbb{X},h}$ drawn from uniform distributions $\mathcal{U}(T_{\mathbb{X}}^{\min}, T_{\mathbb{X}}^{\max})$, and $\mathcal{U}(\tau_{\mathbb{X}}^{\min}, \tau_{\mathbb{X}}^{\max})$. The mis-pricings are defined either as a fraction of fundamental or the current price and signal how big are deviations compared to the anchors.

$$\text{Chartist: } m_{h,t}^{\mathbb{X},c} = \frac{P_{\mathbb{X},t-d_h} - P_{\mathbb{X},t-1}}{P_{\mathbb{X},t-1}} \tag{4.62}$$

$$\text{Fundamentalist: } m_{h,t}^{\mathbb{X},f} = \frac{P_{\mathbb{X},t-1} - u_{h,t}^{\mathbb{X}}}{u_{h,t}^{\mathbb{X}}} \tag{4.63}$$

At $m_{h,t}^{\mathbb{X}} \geq T_{\mathbb{X},h}$, households enter a short position of $-z_{\mathbb{X}}$, which is exited if $m_{h,t}^{\mathbb{X}} < \tau_{\mathbb{X},h}$ in the next period. Similarly, at $m_{h,t}^{\mathbb{X}} \leq -T_{\mathbb{X},h}$, households enter long position which they exit in the next period if $m_{h,t}^{\mathbb{X}} > -\tau_{\mathbb{X},h}$. If $m_{h,t}^{\mathbb{X}} \geq T_{\mathbb{X},h}$ condition is continuously satisfied, the household keeps on selling the crypto-currency. When the mis-pricing drops below the exit threshold $\tau_{\mathbb{X},b}$, the household exits only the position created in the last period, i.e., the household buys a single bundle of the crypto-currency but not all of the previously sold crypto-currency. In this situation, the household dis-invested from the crypto-currency and has increased its bank deposits. Equivalent arguments apply in the case of continuous investment i.e., $m^{\mathbb{X}}_{h,t} < T_{\mathbb{X},h}$ continuously for a length of time. This mechanism allows for portfolio rearrangement. If crypto-currency is continuously over-valued (under-valued), the household sells (buy) crypto-currency to invest in competing assets. We summarize the conditions of crypto-currency demand in the table 4.1.

Figure 4.2: State dependent strategy of market participation

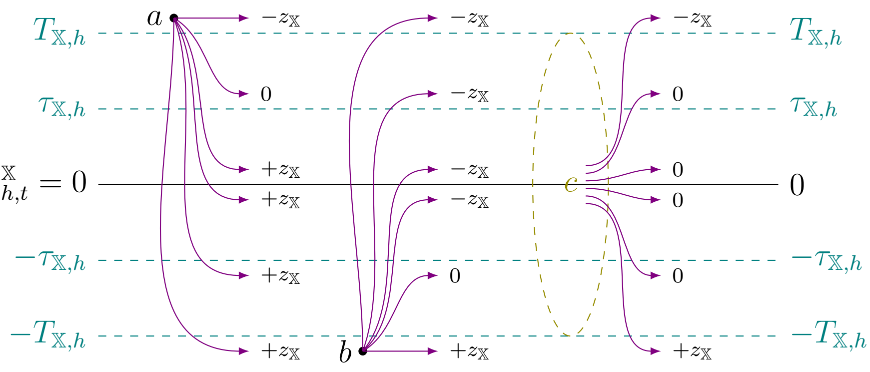


Table 4.1: Market participation summary

Mispricing		Past Market	Availability		Demand
Past	Current	Participation	Asset	Fund	$x^{\mathbb{X}}_{h,t}$
Any	$m^{\mathbb{X}}_{h,t} > T_{\mathbb{X},h}$	Any	True	Any	$-z_{\mathbb{X}}$
Any	$m^{\mathbb{X}}_{h,t} < -T_{\mathbb{X},h}$	Any	Any	True	$+z_{\mathbb{X}}$
$m^{\mathbb{X}}_{h,t-1} > T_{\mathbb{X},h}$	$m^{\mathbb{X}}_{h,t} < \tau_{\mathbb{X},h}$	True	Any	True	$+z_{\mathbb{X}}$
$m^{\mathbb{X}}_{h,t-1} < -T_{\mathbb{X},h}$	$m^{\mathbb{X}}_{h,t} > -\tau_{\mathbb{X},h}$	True	True	Any	$-z_{\mathbb{X}}$

The market-maker, then, aggregates the household demands to determine the new price $P_{\mathbb{X},t}$ based on a closed-form equation. The aggregation of the demand and supply occurs as

$$d^{\mathbb{X}}_{h,t} = \begin{cases} x^{\mathbb{X}}_{h,t}, & x^{\mathbb{X}}_{h,t} \geq 0 \\ 0, & x^{\mathbb{X}}_{h,t} < 0 \end{cases}, \qquad s^{\mathbb{X}}_{h,t} = \begin{cases} 0, & x^{\mathbb{X}}_{h,t} \geq 0 \\ |x^{\mathbb{X}}_{h,t}|, & x^{\mathbb{X}}_{h,t} < 0 \end{cases} \tag{4.64}$$

$$D_{\mathbb{X},t} = \sum_h d^{\mathbb{X}}_{h,t}, \qquad S_{\mathbb{X},t} = \sum_h s^{\mathbb{X}}_{h,t}. \tag{4.65}$$

The market maker bases the price formation on the net order, liquidity of the concerned market, and price growth rate boundaries. The market liquidity is average of past aggregate supply.

$$L_{\mathbb{X},t} = \sum_{i=1}^{n} \frac{S_{\mathbb{X},t-i}}{n} \tag{4.66}$$

This formulation of liquidity helps to use fractional excess demand instead of absolute excess demand in calculating price growth. The price growth function is a bounded generator of growth rate based on how big is the excess demand vis-a-vis market liquidity.

$$g_{\mathbb{X},t} = g_{\mathbb{X}}^{\min} + \frac{g_{\mathbb{X}}^{\max} - g_{\mathbb{X}}^{\min}}{1 + e^{-\left(\lambda_{g_{\mathbb{X}}} \cdot \frac{D_{\mathbb{X},t} - S_{\mathbb{X},t}}{L_{\mathbb{X},t}} - g_{\mathbb{X}}^{0}\right)}} + \xi_{g,\mathbb{X}} \tag{4.67}$$

$$g_{\mathbb{X}}^{0} = \ln \frac{g_{\mathbb{X}}^{\max} - 1}{1 - g_{\mathbb{X}}^{\min}} \tag{4.68}$$

$$\xi_{g,\mathbb{X}} \sim \mathcal{N}(0, \sigma^2_{\xi_{g,\mathbb{X}}}) \tag{4.69}$$

$$P_{\mathbb{X},t} = g_{\mathbb{X},t} \cdot P_{\mathbb{X},t-1} \tag{4.70}$$

The $g_{\mathbb{X}}^{0}$ is sigmoid curve's midpoint, i.e, when demand and supply are equal. The parameter $\lambda_{g_{\mathbb{X}}}$ controls the responsiveness of the price growth to the excess liquidity, whereas, randomness is generated by adding a normally distributed error term $\xi_{g,\mathbb{X}}$ with zero mean and $\sigma^2_{\xi_{g,\mathbb{X}}}$ variance. Afterwards, the household decides the feasibility of market participation at a new price with resources at its disposal . If the budget condition based on the new price is satisfied, the transaction happens with randomly matched buyers and sellers on a first-come, first-serve basis.

Adaptation of mechanism

The market strategy, i.e., to be chartist or fundamentalist is continuously adapted based on the recent performances of the said strategies. This updating allows different household mixes during different phases of bitcoin price movements. During a period of strong upswing or downswing, chartist strategy performs better and more households are likely to be chartist and amplify the market movement, i.e., they generate positive short-term auto-correlations. On the other hand, fundamentalists, by their construction, generate negative short-term auto-correlations. The fitness of a position for market strategy s is product of position taken at $t-1$ with price movement from $t-1$ to t. Household compute the fitness of strategy by adding positions' fitness across the length of time n. We derive the fitness of strategy $U_{h,t-1}^{\mathbb{X},s}$ and probability of switching to s strategy $n_{h,t}^{\mathbb{X},s}$ as:

$$U_{h,t-1}^{\mathbb{X},s} = \sum_{k=1}^{n} x_{h,t-k-1}^{\mathbb{X},s} (P_{\mathbb{X},t-k} - P_{\mathbb{X},t-K-1}) \tag{4.71}$$

$$n_{h,t}^{\mathbb{X},s} = \delta_s n_{h,t-1}^{\mathbb{X},s} + (1 - \delta_s) \frac{\exp \beta_s U_{h,t-1}^{\mathbb{X},s}}{\sum_s \exp \beta_s U_{h,t-1}^{\mathbb{X},s}} \tag{4.72}$$

Where, δ_s is strategy updating inertia, and β_s is intensity of choice measuring how sensitive households are to differences in strategy performance.

4.2.8 Banking sector

The present model simplifies the banking by assuming a single agent 'banking sector' which represents the aggregate of commercial banking in a real economy. The banking sector collects deposits and supplies loans to firms. It charges the lenders based on its base interest rate and premium on lending to that particular lender. The base interest rate is central bank policy rate plus time-varying operating costs captured by a random variable $\xi_{b,t}$ picked from a $U(0, \xi_{b,max}]$.

$$\mathbb{i}_{b,t} = i_t^*(1 + \xi_{b,t}) \tag{4.73}$$

Larger loanee firms have substantial bargaining power vis-à-vis bank and on top of it, larger firms generally demand bigger loan leading to a lower supervision cost. This attribute mean, the bank charges additional premium above the base rate depending on the relative firm size in the industry. Flexible interest rate that varies with base-rate changes over the life span of loan is

$$\mathbb{i}^f_{b,(t0+n)} = \phi_{flex} \cdot \mathbb{i}_{b,(t0+n)} + (1 - \phi_{flex})\mathbb{i}_{b,t0} + \frac{\gamma^p_{size}}{1 + \frac{K_{f,t0}}{\max K_{f,t0}}}, \tag{4.74}$$

where γ^p_{size} is the maximum size penalty while lending and ϕ_{flex} controls the degree of interest rate flexibility. When ϕ_{flex} is equal to zero (one), loans have flexible (fixed) interest rates.

Loan acceptance

Loan disbursement follows a credit rationing method (Caiani et al., 2016) implementing a case by case evaluation of borrower's credit worthiness. If a firm f applies for loan of $\mathcal{L}^d$ for n periods, then debt service associated with the loan in the next period is

$$ds^{\mathcal{L}^d} = \left(\mathbb{i}^f_{b,t} + \frac{1}{n}\right)\mathcal{L}^d. \tag{4.75}$$

The bank compares the firm's $OCF_f/ds^{\mathcal{L}^d}$ ratio to its acceptable OCF/DS ratio $\varkappa_b$ to compute default probability as

$$pr^D_f = \frac{1}{1 + \exp\left(\frac{OCF_{f,t}}{ds^{\mathcal{L}^d}} - \varkappa_b\right)}. \tag{4.76}$$

Additionally, the bank expects to recover a fraction of the outstanding loans through a fire sale of the defaulter's assets. The recovery share δ_r^x is

$$\delta_r^f = \frac{K_{f,t} \cdot p_{K,t}}{\sum \mathcal{L}_f}. \tag{4.77}$$

With information about loan demand, probability of firm default, firm specific interest rate, and expected recovery share on hand, the bank calculates expected payoff by summing each possibilities with their probability weights. The loans are conditionally accepted if the expected return is greater than zero.

$$\begin{aligned} \text{Payoff} = (1 - pr_f^D)^n \sum_{j=0}^{j=n-1} \mathbb{i}_{b,t}^f (1 - \frac{j}{n}) \mathcal{L}^d - pr_f^D \cdot \mathcal{L}^d - \\ \sum_{j=1}^{j=n-1} (1 - pr_f^D)^j \cdot pr_f^D \cdot \left[\mathcal{L}^d (1 - \frac{j}{n})(1 - \delta_r^f) - \sum_{k=1}^{k=j-1} \mathbb{i}_{b,t}^f (1 - \frac{k}{n}) \mathcal{L}^d \right] \end{aligned} \tag{4.78}$$

The positive payoff, however, is not a sufficient condition, since banking sector can not exceed the central bank's regulatory limits. The banking sector must not extend loans beyond a fraction Λ of the total deposits. Thus, the loan is only accepted if it satisfies

$$\Lambda \cdot \left[\sum_h \mathbb{D}_{h,t}^b + \sum_f \mathbb{D}_{f,t}^b \right] - \sum_f \mathcal{L}_{b,t}^f \geq \mathcal{L}^d. \tag{4.79}$$

Interest rate in bank deposits is modeled as average loan interest rate at a given time minus interest rate spread, i.e.,

$$\mathrm{i}_{b,t} = \bar{\mathbb{i}}_{b,t}^f - \mathrm{i}_0, \tag{4.80}$$

where i_0 is a exogenous variable set by the central bank.

4.2.9 Monetary Policy

Central bank uses a Taylor type rule with interest rate as its key instrument variable targeting a real interest rate i^r and inflation rate π^* to maintain a constant growth rate as

$$i_t^* = i^r + \pi^* + \delta_\pi(\pi_t - \pi^*) + \delta_x(x_t - \bar{x}_t), \tag{4.81}$$

where $\bar{x}_t$ is a long term trend of GDP growth derived from applying Hodrick-Prescott-filter in a quarterly data series.

4.2.10 Government

The government collects taxes (income tax, corporate profit tax and tax on investment) and doles out surpluses in a pro-poor manner after bailing households that fail to consume a minimum threshold in a period. Thus the budget equation is

$$C_{min,t}U_t + \text{Disbursement} = \sum_x T_{x,t}, \tag{4.82}$$

where, U_t is number of minimum-consumption bailouts, and $T_{x,t}$ are taxes on investment, income and corporate profit. Deficits are financed by decreasing disbursement and increasing tax rates proportional to the shortfall. The redistribution occurs following a discrete distribution based on the household total wealth. Each wealth decile group is assigned a weight such that sum of weights is equal to one.

4.2.11 Stock market aggregator

The profit from firms and banking sectors are aggregated by stock market aggregator and channeled back to the household after paying income tax and restarting defaulting firms. The redistribution occurs following a discrete distribution based on the household total wealth. Each wealth decile group is assigned a weight such that sum of weights is equal to one. By design, households, K-firm, and the banking sector do not default in the model. In contrast, C-firms can default either through liquidity crunch or when their net worth is less than zero. After default, all existing capital and inventory are sold at the start of the next period by priority and returns are paid to the banking sector. Any excess value over the loan is paid to the stock market aggregator and defaulting firm goes into hibernation. After a randomly selected number of weeks, the stock market aggregator reactivates the firm by spending its resources to purchase capital and provide liquidity to the firm. Reactivated firm starts with capital stock and liquidity equal to 25^{th} percentile firm in the economy.

4.3 Calibration and programming

The provided model can be calibrated using national dateset and implemented in software. In this section, we provide example for both calibration of the a function used in the model and an example of programming the economic agent in C++ programming. For calibration, we show how to estimate consumption function, as used in the model, using household level data. We also show composite wage estimation using firm level revenue and cost of input data.

4.3.1 Calibrating consumption function

To estimate the coefficients for the parameters used in our model, we can utilize household-level data such as the Nepal Living Standard Survey (NLSS) produced by the Central Bureau of Statistics. This survey includes data on income, expenditure, and assets for a nationally representative sample of 5988 households. The NLSS categorizes household consumption into three categories: food expenditure, housing consumption, and other non-food consumption.

The food expenditure category included the value of food items that were purchased, grown at home, or received in kind, with the exception of tobacco and tobacco products. The other non-food expenditure category was further divided into five subcategories: tobacco and tobacco products, selected non-food items, expenditure on durable goods, expenditure on utilities, and expenditure on education. The selected non-food items category included expenditure on fuels, apparel and personal care items, and frequent and infrequent expenses such as public transportation, entertainment, stationery, household products, legal and insurance expenses, holidays, postal services, and more. Some non-food expenditure categories were excluded from the analysis due to difficulties in price imputation or because they did not accurately reflect household welfare, such as firewood, health expenses, repair and maintenance, home construction and improvements, taxes and fines, and expenses related to social and religious functions.

The consumption of household expenses includes housing, which includes rent for those who do not own a house and expected rent from a house for homeowners. For households that live in free housing, we estimate the expected rate for this dwelling. We estimate household income based on the instructions provided by the Central Bureau of Statistics (CBS). There are three sources of household income: firm income, wage income, and non-farm enterprises income. Firm income includes income from crops (total output minus the cost of inputs), income from renting assets (assets minus maintenance cost), income from the sale of livestock (sales minus cost), and cash and in-kind payments from tenants (receipts minus payments). Non-farm enterprises income includes income from non-agricultural rental properties, transfers (such as remittances), and income from owner-occupied housing. Other sources of household income include interest, dividends, social security contributions, commission fees, and royalties. Household wealth consists of the value of the house and land, livestock and farm equipment, enterprises owned by the household, net credit, and financial assets such as stocks, bonds, employment provident funds, citizen investment funds, internal and external pensions, commission fees, and royalties.

We assume income to approximate the human capital with household income and financial wealth with household wealth. The basic empirical regression equation in line with the theoretical model,

$$C = \beta_1 Y + \beta_2 W \qquad\qquad 0 < \beta_1 < \beta_2 < 1 \ , \tag{4.83}$$

can not be directly estimated as income(Y) and wealth(W) violate independence assumption. To side skirt this estimation issue, we rewrite the equation 4.83 in buffer-stock style as

$$C = Y + \beta_2(W - \phi Y), \tag{4.84}$$

where $\phi = \frac{1-\beta_1}{\beta_2}$ is optimum level of targeted wealth to income ratio. We assume ϕ can be approximated as a median value of wealth to income ratio for a given consumption decile. Now we have $\hat{\phi_i}$ where, i is i^{th} consumption decile group. This gives us a simple formulation of observed dis-saving vis-á-vis targeted dis-saving, i.e.,

$$C - Y = \beta_2(W - \hat{\phi} Y). \tag{4.85}$$

The estimation equation that is applied over the data is

$$C - Y = \beta_2(W - \hat{\phi} Y) + \alpha \cdot F + \gamma \cdot Z + +\epsilon, \tag{4.86}$$

where, F and Z are vectors of household and sampling area characteristics. The estimate $\hat{\beta}_2$ and observed $\hat{\phi}$ can then be used to extract both $\hat{c}_h$ and $\hat{c}_f$ as

$$\hat{c}_h = 1 - \hat{\beta}_2 \hat{\phi}, \tag{4.87}$$

$$\hat{c}_f = \hat{\beta}_2. \tag{4.88}$$

4.3.2 Calibrating composite labor wage

To estimate the productivity coefficients, we can use the data on labor and capital expenditure collected from the National Economic Census of 2018 conducted by the Central Bureau of Statistics (CBS). This enterprise survey covers all firms except for government institutions and foreign-based institutions. It records the number of people employed and their remuneration paid by the firm, as well as the total revenue generated and total capital employed. We can classify the number of workers employed into two categories: technical and non-technical, and use fixed effects for industries, districts, and their interactions. Using this data, we can calculate the composite wage across the sector and divide the total expenditure on labor salaries by the effective number of composite labor to estimate

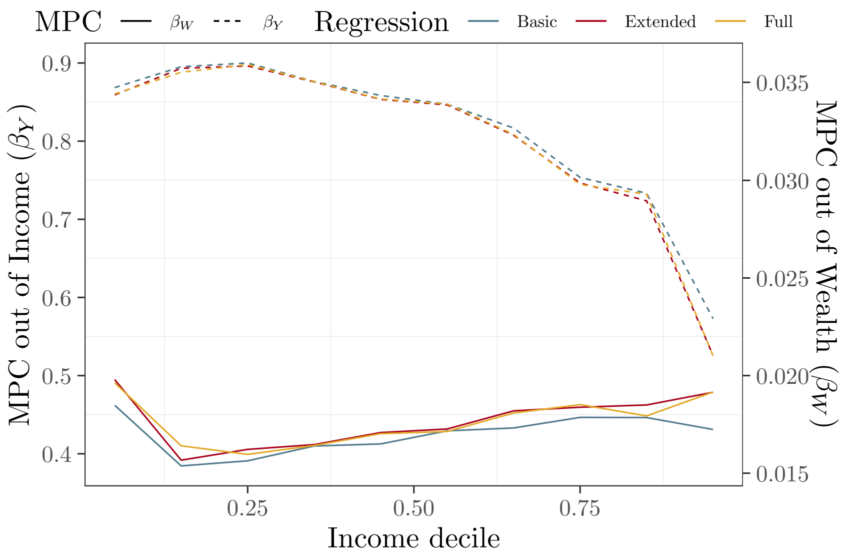


Figure 4.3: Distribution of marginal propensity to consume out of income and wealth across income decile.

Table 4.2: Marginal propensity to consume out of wealth

Dependent Variable:	Yearly consumption expenditure		
Model:	(1)	(2)	(3)
MPC out of Wealth (β_W)			
τ =0.25	0.016***	0.016***	0.016***
	(246.91)	(127.87)	(46.71)
τ =0.55	0.017***	0.017***	0.017***
	(191.52)	(73.27)	(101.82)
τ =0.75	0.018***	0.018***	0.019***
	(96.08)	(125.50)	(90.16)
Fixed-effects			
Household Characteristics		Yes	Yes
District			Yes
Urban			Yes
Season			Yes
Fit statistics			
Observations	5971	5971	5971

Signif. Codes: ***: 0.01, **: 0.05, *: 0.1; t-statistics in round brackets; Household characteristics include number of < 5 yr children, number of $5-15$ yr children, number of working age members, sex of household head, years schooling of household head, caste group; Source: Author's calculations based on NLSS III.

labor productivity. For our purpose, we grouped the industrial sectors into ten categories as shown in table 4.3 on the following page.

The coefficients in regression in the table 4.4 on the next page represents

Table 4.3: Industrial sectors categories

Group	Industry classification (Activities)
1	Agriculture, Forestry and Fishery
2	Mining and Quarrying
3	Manufacturing
4	Electricity, gas, steam and air conditioning; Water supply, sewerage, waste management and remediation
5	Construction
6	Wholesale, retail and repair; Transportation and storage; Accommodation and food
7	Information technology; Professional, scientific and technical
8	Financial and Insurance; Real estate; Administrative and support service
9	Education; Human health and social work
10	Arts, entertainment and recreation; Other service

Table 4.4: Wage estimation

Dependent Variable:	Yearly expenditure on labor salary		
Model:	(1)	(2)	(3)
Variables			
(Intercept)	6,292,505.0		
	(6,611,662.3)		
Technical	486,551.0*	556,269.7**	603,297.6**
	(287,674.3)	(185,800.6)	(185,841.1)
Non technical	290,225.4***	292,136.0***	290,188.2***
	(107,397.4)	(88,665.9)	(84,552.1)
Fixed-effects			
Industrial sector		Yes	Yes
District		Yes	Yes
Industrial sector×District			Yes
Fit statistics			
Observations	176,727	176,727	176,727
R^2	4.28×10^{-5}	0.00020	0.00041
Within R^2		4.45×10^{-5}	4.49×10^{-5}

Signif. Codes: ***: 0.01, **: 0.05, *: 0.1; Standard errors in round brackets; The first model's standard errors are heteroskedastic robust standard errors, whereas, other two model have two way clustered standard errors by Industrial sectors and District; Source: Author's calculations based on Economic census 2018.

the shadow price of different types of labor (technical and non-technical). We can calculate the average wage in a firm by multiplying the shadow wages by the fraction of each type of labor employed. The composite labor wage then can be used to divide the total expenditure on labor salary to get effective number of composite labor. This composite labor index then can be regressed against yearly revenue to get estimate for labor productivity.

4.3.3 Programming economic agents

The model can be implemented in a programming language, with each economic agent represented as a class containing variables representing their characteristics. Mechanisms can also be implemented as classes with their own variables. An example of an expectation class and a banking sector class is provided in the appendix to demonstrate how the model can be coded. Our programming language of choice is C++ for its excellent computational performance and natural support for the object oriented programming.

4.4 Discussions

Our results are inline with the arguments of Yermack (2013), who find bitcoin to be speculative asset rather than currency. Urquhart (2016) finds that inefficiency in bitcoin market to be inefficient overall, but less inefficient in the later period. This result sits well with our finding that cryptocurrency's structure is more ponzi like in the beginning than later. Thus, that ponzi structure may result in less efficient market behavior at the initial stage as found by Urquhart (2016). Methodologically, our model is more extensive compared Cheng and Lin (2022), who focus on building agent based model of the crypto-market. But, there is some similarities between our arguments and results of Cheng and Lin (2022), who report cryptocurrency market to be unstable and agitated. Modeling wise, the model can incorporate insight from Fernandez et al. (2022), who delve deep into how does initial crypto-token distribution affect token concentration. Our arguments are different from Coulter (2022), who view private cryptocurrencies, with legal maturity, can provide choice to consumer in competition with central bank digital currency. We view, informed by results and literature review, cryptocurrency as an energy-expensive speculative asset that can not provide a socially viable finance infrastructure. With this position, we see CBDC as a natural evolution of private crypto-currency which can succeed as digital cash. Model development wise, we believe that the model is a good starting point for future researchers to use it for studying cryptocurrency's macroeconomic effect.

CHAPTER V
CONCLUSION AND RECOMMENDATIONS

This chapter presents major conclusions based on the results form the previous chapters. Based on these findings, this chapter also recommend possible extensions for the presented work.

5.1 Conclusion

The study found that cryptocurrency has a ponzi-like structure due to its design, which leads to constant volatility and the need for liquidity. While this characteristic may decline over time, it does not disappear completely. The only way to ensure sustained value is to have a clear and specific use case. Without this, we find, mathematically, that cryptocurrency to be a negative sum game with a fragile structure and is susceptible to collapse from strong economic shocks, resulting in losses for market participants.

This study used tools from agent-based macroeconomic and finance models to create an agent-based model (ABM) that includes cryptocurrency. Our model captures important characteristics of cryptocurrency and household financial behavior. Future research should continue to explore the use of ABMs with cryptocurrency to gain a better understanding of the effects of cryptocurrency speculation on macroeconomic stability.

5.2 Recommendations

Private cryptocurrency has significant drawbacks that should be taken into consideration before it is widely adopted. Regulators should be cautious in their approach to regulating the cryptocurrency market, and in some cases, it may be necessary to ban it outright. While the benefits of a blockchain ledger are clear, it is not necessary to rely on private cryptocurrency as a digital cash-equivalent. Instead, we should avoid using the desire for digital cash to justify the creation and proliferation of a highly concentrated and speculative asset with characteristics similar to a Ponzi scheme.

5.3 Possible extensions

Monte Carlo experiments can be run on the model after being fully calibrated. We have provided example for both calibration of the a function used in the model and an example of programming the economic agent in C++ programming language.

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Annex A

APPENDIX ON PROGRAM

A.1 Anufriev expectation class

Here, we provide an implementation of Anufriev expectation class as an example[1].

```cpp
#ifndef ANUFRIEVEXPECTATION_HPP_
#define ANUFRIEVEXPECTATION_HPP_
#include <cmath>
#include <iostream>
#include <numeric>
#include <vector>

#include "../include/t_buffer.hpp"

// Anufriev_expectation
template <typename T>
class Anufriev_expectation {
   private:
    struct expectData {
        double fitness;
        double weights;
        double past_pred;
    };
    std::vector<expectData> expectations;
    t_buffer<T> past_x;
    double expected_x;
    double mu, lambda, beta;
    double ADA_c, WTR_c, STR_c, LAA_c;

   public:
    double expect(T x_new);
    double lastExpectation() const { return expected_x; }
    double lastEntry() const { return past_x.get_latest(); }
    double avgOfPast() const {
        return past_x.gAvg(past_x.get_bufferlength()).value();
```

---

[1] Author has implemented all of the theoretical model in C++, which is privately hosted in https://github.com/manab-prakash/. Source code is available under reasonable request. Please sent an email to manab2678 [at] gmail [dot] com with title “Code for ABM model with crypto”.

```
    }
    explicit Anufriev_expectation(double filler_, std::size_t past_mem_len = 5,
                                  double mu_ = 0.7, double lambda_ = 0.9,
                                  double beta_ = 0.4, double ADA_c_ = 0.65,
                                  double WTR_c_ = 0.4, double STR_c_ = 1.3,
                                  double LAA_c_ = 0.5)
        : past_x(past_mem_len, filler_),
          expected_x(0),
          mu(mu_),
          lambda(lambda_),
          beta(beta_),
          ADA_c(ADA_c_),
          WTR_c(WTR_c_),
          STR_c(STR_c_),
          LAA_c(LAA_c_) {
        expectations.resize(4);  // 4 mechanisms of expectation formation
        for (expectData& exp : expectations) {
            exp.fitness = 0;
            exp.weights = 0.25;
            exp.past_pred = filler_;
        }
    }
    void bug_print();
};

// Implementation of new expectation formation
template <typename T>
double Anufriev_expectation<T>::expect(T x_new) {
    // get last entry
    T past = past_x.get_latest();
    // Add new entry in to buffer
    past_x.add_new(x_new);
    // Note this avg uses newly entered value too
    auto avg = past_x.gAvg(past_x.get_bufferlength()).value();
    // New temp variable to store new predictions by 4 mechanisms
    T pred_x[4];
    // Adaptive expectation
    pred_x[0] = ADA_c * x_new + (1 - ADA_c) * expectations[0].past_pred;
    // Weak trend following
    pred_x[1] = x_new + WTR_c * (x_new - past);
    // Strong trend following
    pred_x[2] = x_new + STR_c * (x_new - past);
    // Anchoring and adjustment
    pred_x[3] = LAA_c * (avg + x_new) + (x_new - past);

    T sum_exp = 0;  // Update fitness based on new entry & past prediction
    for (expectData& exp : expectations) {
```

```
        exp.fitness = mu * exp.fitness - std::pow((x_new - exp.past_pred), 2);
        sum_exp += std::exp(beta * exp.fitness);
    }

    // Update these new prediction as past prediction to use below
    for (size_t i = 0; i < 4; i++) {
        expectations[i].past_pred = pred_x[i];
    }

    // Calculate the weights for each methods
    double sum_weights = 0;
    for (expectData& exp : expectations) {
        auto temp_frac = std::exp(beta * exp.fitness) / sum_exp;
        temp_frac = (std::isnan(temp_frac)) ? 0 : temp_frac;
        exp.weights = lambda * exp.weights + (1.0 - lambda) * temp_frac;
        // Round the weights to 0.0001
        exp.weights = std::floor(exp.weights * 10000 + 0.5) / 10000;
        sum_weights += exp.weights;
    }

    // If sum of weight is not almost equal to 1
    if (std::abs(1 - sum_weights) > 0.001) {
        // check which has max weight
        int max_index = 0;
        for (size_t i = 0; i < 4; i++) {
            if (expectations[i].weights > expectations[max_index].weights) {
                max_index = i;
            }
        }
        // Max_weight will accommodate float errors
        expectations[max_index].weights += (1 - sum_weights);
    }

    expected_x = std::accumulate(expectations.begin(), expectations.end(), 0.0,
                                 [](double sum, const expectData& exp) {
                                     return (sum + exp.weights *
 ↪  exp.past_pred);
                                 });
    return expected_x;
}

template <typename T>
void Anufriev_expectation<T>::bug_print() {
    std::cout << "\nAnufriev Class Prints" << '\n';
    auto oldVec = this->past_x.getFullSortedSeries().value();
    std::cout << "Series feed (new to old) : ";
    for (const auto& elm : oldVec) {
```

```
        std::cout << elm << '\t';
    }
    std::cout << "\nStored internals of different expectations\n";
    std::cout << "\n0: adaptive, 1: weak trend, 2:strong trend, "
                 "3:anchoring and adjusting\n";
    for (size_t i = 0; i < 4; i++) {
        std::cout << "Expectation Mechanism " << i << " fitness "
                  << this->expectations[i].fitness << " weights "
                  << this->expectations[i].weights << " past_pred "
                  << this->expectations[i].past_pred << '\n';
    }
    std::cout << "Various parameters \n";
    std::cout << "mu " << mu << " lambda " << lambda << " beta " << beta
              << '\n';
    std::cout << "ADA_c " << ADA_c << " WTR_c " << WTR_c << " STR_c " << STR_c
              << " LAA_c " << LAA_c << '\n';
    std::cout << "last expected value of x " << expected_x << '\n';
    std::cout << "Happy coding!!!" << '\n';
}

#endif  // ANUFRIEVEXPECTATION_HPP_
```

A.2 Banking class

```
#ifndef BANK_HPP_
#define BANK_HPP_
#include <optional>

#include "../include/centralBank.hpp"
#include "../include/eNetwork.hpp"
#include "../include/loan.hpp"
#include "../include/network.hpp"
#include "../include/print.hpp"
#include "../include/randomGen.hpp"

class bank {
   public:
    bank(const double bankEquity, const double phi_flex_, const double i_base_,
         const double deposit_i_, const std::string bankNetworkId_)
        : equity(bankEquity),
          bankPurse(bankEquity),
          phi_flex(phi_flex_),
          i_base(i_base_),
          deposit_i(deposit_i_),
          bankNetworkId(bankNetworkId_) {}

    std::string getBankId() const { return bankNetworkId; }

```

```
    // For firm bankruptcy use only. Returns loss for bank
    purse loanBankruptcy(const std::string& loaneeId,
                         const purse& finalPayment);

    void i_base_update(const double policy_rate) {
        i_base = policy_rate * (1 + randomGen::Uni_n(0, bank::xi_bt_max));
    }
    double calPayoff(const double Principal, const double pD, const double i,
                     size_t n, const double delta) const;

    void set_phi_flex(const double phi_flex_) { phi_flex = phi_flex_; }
    double get_i_base() const { return i_base; }
    double getBankLiquidity() const { return bankPurse.balance(); }
    double getBankRetainedEarning() const { return retainedEarning; }
    double getDepositInterest() const { return deposit_i; }
    bool checkCBCreditExpansionLimit(const loan& l_);
    bool checkCBCreditExpansionLimit(const double loanPrincipal);

    double checkRegulatoryLoanSpace() const;

    void updateLoanInterest(const double policy_rate);

    double probLoanDefault(const double cashFlow,
                           const double installment) const;

    std::optional<loan> loanVerification(const double loanPrincipal,
                                         const size_t loanPeriod,
                                         const double cashFlow,
                                         const double interestFirmWedge,
                                         const double recoveryShare);

    // Note use it only for firm initialization. It always disburses loan.
    bool initialLoanDisbursement(const std::string& loaneeUniqueId,
                                 const double loanPrincipal,
                                 const size_t loanPeriod) {
        return applyLoan(loaneeUniqueId, loanPrincipal, loanPeriod,
                         loanPrincipal, 0, 2);
    }
    bool applyLoan(const std::string& loaneeUniqueId,
                   const double loanPrincipal, const size_t loanPeriod,
                   const double cashFlow, const double interestLoaneeWedge,
                   const double recoveryShare);

    // Pay installment amount from depositor's account to the bank. Ensure paid
    // installment amount is available in the account
    void payInstallment(const std::string& loaneeUniqueId,
                        const purse& installmentAmount);
```

```

  // Returns nullopt if user does not have a loan, otherwise loan installment
  std::optional<purse> checkInstallment(
      const std::string& loaneeUniqueId) const;

  // Total principal plus interest payments for last period
  purse checkTotalDebtObligation(const std::string& loaneeUniqueId) const;

  // Put money on the deposit account of a costumer
  void makeDeposit(const std::string& userUniqueId,
                   const purse& depositAmount);

  // Check money on the deposit account of a costumer
  std::optional<purse> checkDeposit(const std::string& userUniqueId) const;

  // Returns amount removed if successful, otherwise nullopt
  std::optional<purse> removeFromDeposit(const std::string& userUniqueId,
                                         const purse& amountToRemove);

  // Pays interest on all deposits in the bank
  void payAllDepositInterest();

  // Returns average interest rate on loan
  double averageLoanInterest() const;

  // Returns total loan
  double totalLoan();

  // Returns total deposit held in the bank
  double totalDeposit();

  // Returns new deposit interest after calculating average loan interest
  double updateDepositInterest();

  void printBalanceSheet();

 private:
  // Loan installment helper function for payInstallment function
  void payInstallmentHelper(loan& loan_);
  double phi_flex{0};
  double i_base{0};
  double deposit_i{0};
  double loan_aggregate{0};
  double deposit_aggregate{0};
  std::string bankNetworkId;
  double retainedEarning{0};
  double equity{0};
```

```cpp
    purse bankPurse{0};

    // static class-wide constants
    static inline double xi_bt_max{0};
    static inline double gamma_size_penalty{0};
    static inline double OCF_DS_threshold{0};
    static inline double lambda_default{4};
    static inline double i_spread{0};

   public:
    // static setters and getters
    static void set_xi_bt_max(const double& xi_bt_max_) {
        xi_bt_max = xi_bt_max_;
    }
    static void set_gamma_size_penalty(const double& gamma_size_penalty_) {
        gamma_size_penalty = gamma_size_penalty_;
    }
    static void set_OCF_DS_threshold(const double& OCF_DS_threshold_) {
        OCF_DS_threshold = OCF_DS_threshold_;
    }
    static void set_lambda_default(const double& lambda_default_) {
        lambda_default = lambda_default_;
    }
    static void set_i_spread(const double& i_spread_) { i_spread = i_spread_; }

    // getters
    static double get_xi_bt_max() { return xi_bt_max; }
    static double get_gamma_size_penalty() { return gamma_size_penalty; }
    static double get_OCF_DS_threshold() { return OCF_DS_threshold; }
    static double get_lambda_default() { return lambda_default; }
    static double get_i_spread() { return i_spread; }
};

double bank::calPayoff(const double Principal, const double pD, const double i,
                       size_t n, const double delta) const {
    double t1{0}, t2{0}, t3{0};
    for (size_t j{0}; j < n; ++j) {
        t1 += std::pow((1 - pD), n) * i * (1 - j / (1.0 * n)) * Principal;
    }
    t2 = pD * Principal;
    for (size_t j{1}; j < n; ++j) {
        double inner_sum{0};
        for (size_t k{0}; k < j; ++k) {
            inner_sum += i * (1 - k / (n * 1.0)) * Principal;
        }
        double inner_term = Principal * (1 - j / (n * 1.0)) * (1 - delta);
        t3 += std::pow((1 - pD), j) * pD * (inner_term - inner_sum);
```

```
    }
    return (t1 - t2 - t3);
}

bool bank::checkCBCreditExpansionLimit(const loan& l_) {
    // Need to check for CB credit expansion
    return checkCBCreditExpansionLimit(l_.check_principal());
}
bool bank::checkCBCreditExpansionLimit(const double loanPrincipal) {
    // Need to check for CB credit expansion
    double loanSpace = checkRegulatoryLoanSpace();
    if (loanSpace >= loanPrincipal) {
        return true;
    }
    return false;
}

double bank::checkRegulatoryLoanSpace() const {
    return centralBank::get_credit_exp_limit() * (deposit_aggregate + equity) -
           loan_aggregate;
}

void bank::updateLoanInterest(const double policy_rate) {
    i_base_update(policy_rate);
    i_base = policy_rate * (1 + randomGen::Uni_n(0, bank::xi_bt_max));
    std::vector<std::string> loanee_ids = eNetwork::Loan.allA_unqIds();
    for (auto l_ids : loanee_ids) {
        if (eNetwork::Loan.areAB_Linked(l_ids, bankNetworkId)) {
            for (loan loan_ :
                 *eNetwork::Loan.getLinkPointer(l_ids, bankNetworkId)) {
                loan_.update_interest(i_base, phi_flex);
            }
        }
    }
}

double bank::probLoanDefault(const double cashFlow,
                             const double installment) const {
    return 1.0 /
           (1 + std::exp(bank::lambda_default *
                         (cashFlow / installment - bank::OCF_DS_threshold)));
}

std::optional<loan> bank::loanVerification(const double loanPrincipal,
                                           const size_t loanPeriod,
                                           const double cashFlow,
                                           const double interestFirmWedge,
```

```
                                           const double recoveryShare) {
    purse lPrincipal(loanPrincipal);
    loan l{i_base, interestFirmWedge, lPrincipal, loanPeriod};
    double probabilityDefault =
        probLoanDefault(cashFlow, l.check_installment().balance());

    double payoff =
        calPayoff(loanPrincipal, probabilityDefault, l.check_interestRate(),
                  loanPeriod, recoveryShare);

    bool grantLoan = false;
    // This third condition is largely a sanity check
    if ((payoff > 0) && (checkRegulatoryLoanSpace() >= l.check_principal()) &&
        (bankPurse.balance() > l.check_principal())) {
        return l;
    } else {
        return std::nullopt;
    }
}

bool bank::applyLoan(const std::string& loaneeUniqueId,
                     const double loanPrincipal, const size_t loanPeriod,
                     const double cashFlow, const double interestLoaneeWedge,
                     const double recoveryShare) {
    auto loanVerified = loanVerification(loanPrincipal, loanPeriod, cashFlow,
                                         interestLoaneeWedge, recoveryShare);

    if (loanVerified) {
        // Loan is verified
        double principal = loanVerified.value().check_principal();
        loan_aggregate += principal;
        bankPurse.Out_checked(principal);
        // put money in loanee account
        makeDeposit(loaneeUniqueId, purse(principal));
        // add loan into loan list
        if (eNetwork::Loan.areAB_Linked(loaneeUniqueId, bankNetworkId)) {
            eNetwork::Loan.getLinkPointer(loaneeUniqueId, bankNetworkId)
                ->emplace_back(loanVerified.value());
        } else {
            std::list<loan> tempList{loanVerified.value()};
            eNetwork::Loan.addLink(loaneeUniqueId, bankNetworkId, tempList);
        }
        return true;
    }
    return false;
}

```

```
void bank::payInstallmentHelper(loan& loan_) {
    std::tuple<purse, purse> installment = loan_.check_installment_i_P();
    purse interestPayment{std::get<0>(installment)};
    purse principalRepayment{std::get<1>(installment)};

    loan_aggregate = loan_aggregate - principalRepayment.balance();

    // It subtracts principal internally
    loan_.pay_installment(loan_.check_installment());
    retainedEarning += interestPayment.balance();
    bankPurse.In(interestPayment);
    bankPurse.In(principalRepayment);
}

purse bank::loanBankruptcy(const std::string& loaneeId,
                           const purse& finalPayment) {
    bool loanExistence = eNetwork::Loan.areAB_Linked(loaneeId, bankNetworkId);
    if (loanExistence && eNetwork::dividendPurse >= finalPayment) {
        purse remaining{finalPayment};
        auto LoanListPointer =
            eNetwork::Loan.getLinkPointer(loaneeId, bankNetworkId);
        purse loss{0};
        for (loan& a : *LoanListPointer) {
            a.reschedule_loan(1);
            std::tuple<purse, purse> installment = a.check_installment_i_P();
            purse interestPayment{std::get<0>(installment)};
            purse principalRepayment{std::get<1>(installment)};
            purse payment{0};
            // Only pay principal
            if (remaining > principalRepayment) {
                payment = principalRepayment;
            } else {
                payment = remaining;
            }
            remaining.Out_checked(payment);
            purse currentLoss = a.defaultOnLoan(payment);
            loss = loss + currentLoss;
            eNetwork::dividendPurse.Out_checked(payment);
            bankPurse.In(payment);
            loan_aggregate = loan_aggregate - principalRepayment.balance();
            retainedEarning = retainedEarning - currentLoss.balance();
        }
        LoanListPointer->remove_if(
            [](const loan& l) { return l.isLoanDead(); });
        if (LoanListPointer->size() == 0) {
            eNetwork::Loan.removeLink(loaneeId, bankNetworkId);
        }
```

```
        return loss;
    }
    return purse{0};
}

void bank::payInstallment(const std::string& loaneeUniqueId,
                          const purse& installmentAmount) {
    if (!removeFromDeposit(loaneeUniqueId, installmentAmount)) {
        assert("Error: can not remove from deposit while paying installment");
    }

    auto required_installment = checkInstallment(loaneeUniqueId).value();
    auto LoanListPointer =
        eNetwork::Loan.getLinkPointer(loaneeUniqueId, bankNetworkId);
    if (required_installment == installmentAmount) {
        // installment is sufficient to pay loan
        for (loan& loan_ : *LoanListPointer) {
            payInstallmentHelper(loan_);
        }

    } else if (required_installment > installmentAmount) {
        // installment provided is insufficient to pay loan
        purse tempBalance(installmentAmount);
        for (loan& loan_ : *LoanListPointer) {
            purse tempInstallment = loan_.check_installment();
            double interestPayment =
                std::get<0>(loan_.check_installment_i_P()).balance();
            if (tempInstallment < tempBalance) {
                // pay installment of this loan
                payInstallmentHelper(loan_);
                tempBalance.Out_checked(tempInstallment);

            } else if (tempInstallment >= tempBalance) {
                // check if it can pay interest
                double shortPrincipalAmort{0};
                double shortInterestPayment{0};
                double interestToPrincipal{0};
                if (tempBalance.balance() >= interestPayment) {
                    shortInterestPayment = interestPayment;
                    shortPrincipalAmort =
                        tempBalance.balance() - interestPayment;
                } else {
                    // can not cover all the interest payment
                    shortInterestPayment = tempBalance.balance();
                    interestToPrincipal =
                        interestPayment - shortInterestPayment;
                }
```

```

                loan_aggregate = loan_aggregate - shortPrincipalAmort;
                loan_.pay_installment(tempBalance);
                retainedEarning += (shortInterestPayment + interestToPrincipal);
                bankPurse.In(tempBalance);
                tempBalance.Out_checked(tempBalance);
            }
        }
    }
    LoanListPointer->remove_if([](const loan& l) { return l.isLoanDead(); });
    if (LoanListPointer->size() == 0) {
        eNetwork::Loan.removeLink(loaneeUniqueId, bankNetworkId);
    }
}

std::optional<purse> bank::checkInstallment(
    const std::string& loaneeUniqueId) const {
    bool loanExistence =
        eNetwork::Loan.areAB_Linked(loaneeUniqueId, bankNetworkId);
    if (loanExistence) {
        purse totalInstallment{0};
        for (const loan a :
             *(eNetwork::Loan.getLinkPointer(loaneeUniqueId, bankNetworkId))) {
            totalInstallment = totalInstallment + a.check_installment();
        }
        return totalInstallment;
    }
    return std::nullopt;
}

purse bank::checkTotalDebtObligation(const std::string& loaneeUniqueId) const {
    bool loanExistence =
        eNetwork::Loan.areAB_Linked(loaneeUniqueId, bankNetworkId);
    if (loanExistence) {
        purse interestPayments{0};
        purse principal{0};
        for (const loan a :
             *(eNetwork::Loan.getLinkPointer(loaneeUniqueId, bankNetworkId))) {
            principal.In(a.check_principal());
            interestPayments.In(std::get<0>(a.check_installment_i_P()));
        }
        return interestPayments + principal;
    }
    return purse{0};
}

```

```cpp
void bank::makeDeposit(const std::string& userUniqueId,
                       const purse& depositAmount) {
    bool Existence =
        eNetwork::Deposit.areAB_Linked(userUniqueId, bankNetworkId);
    if (Existence) {
        // add money in existing deposit
        eNetwork::Deposit.getLinkPointer(userUniqueId, bankNetworkId)
            ->In(depositAmount);

    } else {
        // make new account and add money
        eNetwork::Deposit.addLink(userUniqueId, bankNetworkId, depositAmount);
    }
    bankPurse.In(depositAmount);
    deposit_aggregate += depositAmount.balance();
}

std::optional<purse> bank::checkDeposit(const std::string& userUniqueId) const
↪   {
    bool Existence =
        eNetwork::Deposit.areAB_Linked(userUniqueId, bankNetworkId);
    if (Existence) {
        // add money in existing deposit
        purse deposit{
            eNetwork::Deposit.getLinkPointer(userUniqueId, bankNetworkId)
                ->balance()};
        return deposit;
    }
    return std::nullopt;
}

std::optional<purse> bank::removeFromDeposit(const std::string& userUniqueId,
                                             const purse& amountToRemove) {
    bool Existence =
        eNetwork::Deposit.areAB_Linked(userUniqueId, bankNetworkId);
    if (Existence) {
        // remove from purse
        if (eNetwork::Deposit.getLinkPointer(userUniqueId, bankNetworkId)
                ->isOutFeasible(amountToRemove) &&
            bankPurse.isOutFeasible(amountToRemove)) {
            eNetwork::Deposit.getLinkPointer(userUniqueId, bankNetworkId)
                ->Out_checked(amountToRemove);
            bankPurse.Out_checked(amountToRemove);
            deposit_aggregate -= amountToRemove.balance();
            purse removed{amountToRemove};
            return removed;
        } else {
```

```
            return std::nullopt;
        }
    }
    return std::nullopt;
}

void bank::payAllDepositInterest() {
    std::vector<std::string> depositors_ids = eNetwork::Deposit.allA_unqIds();
    for (auto d_ids : depositors_ids) {
        if (eNetwork::Deposit.areAB_Linked(d_ids, bankNetworkId)) {
            // deposit account exists
            purse interest_payment{
                eNetwork::Deposit.getLinkPointer(d_ids, bankNetworkId)
                    ->balance() *
                deposit_i};
            // remove from bank's purse
            if (bankPurse.isOutFeasible(interest_payment)) {
                bankPurse.Out_checked(interest_payment);
                makeDeposit(d_ids, interest_payment);
                // update retained earnings of depositors
                eNetwork::retainedEarning.addTo(interest_payment, d_ids);

                retainedEarning -= interest_payment.balance();
            } else {
                assert(("Error: Bank can't pay deposit interest"));
            }
        }
    }
}

double bank::averageLoanInterest() const {
    std::vector<std::string> loanee_ids = eNetwork::Loan.allA_unqIds();
    double totalLoan_{0};
    double i_timesLoan{0};
    for (auto l_ids : loanee_ids) {
        if (eNetwork::Loan.areAB_Linked(l_ids, bankNetworkId)) {
            for (loan loan_ :
                 *eNetwork::Loan.getLinkPointer(l_ids, bankNetworkId)) {
                i_timesLoan +=
                    loan_.check_interestRate() * loan_.check_principal();
                totalLoan_ += loan_.check_principal();
            }
        }
    }
    return i_timesLoan / totalLoan_;
}

```

```
double bank::totalLoan() {
    std::vector<std::string> loanee_ids = eNetwork::Loan.allA_unqIds();
    double totalLoan_{0};

    for (auto l_ids : loanee_ids) {
        if (eNetwork::Loan.areAB_Linked(l_ids, bankNetworkId)) {
            for (loan loan_ :
                 *eNetwork::Loan.getLinkPointer(l_ids, bankNetworkId)) {
                totalLoan_ += loan_.check_principal();
            }
        }
    }
    loan_aggregate = totalLoan_;
    return totalLoan_;
}

double bank::totalDeposit() {
    std::vector<std::string> depositor_ids = eNetwork::Deposit.allA_unqIds();
    double totalDeposit{0};

    for (auto d_ids : depositor_ids) {
        if (eNetwork::Deposit.areAB_Linked(d_ids, bankNetworkId)) {
            totalDeposit +=
                eNetwork::Deposit.getLinkPointer(d_ids, bankNetworkId)
                    ->balance();
        }
    }
    deposit_aggregate = totalDeposit;
    return totalDeposit;
}

double bank::updateDepositInterest() {
    deposit_i = averageLoanInterest() - bank::get_i_spread();
    return deposit_i;
}

void bank::printBalanceSheet() {
    FFmt MainNames(30, 2);
    FFmt SubNames(15, 2);
    // width and then //precision
    FFmt Number(15, 2);
    double loan = totalLoan();
    double deposit = totalDeposit();
    double ret_earn = retainedEarning;
    double liquidity = bankPurse.balance();
    double equity_ = equity;
    double sum_asset = loan + liquidity;
```

```
    double sum_liabilities = deposit + ret_earn + equity_;

    std::cout << '\n'
              << MainNames << "----- "
              << "BalanceSheet" << bankNetworkId << " -----" << '\n';
    std::cout << MainNames << "Asset" << MainNames << "Liabilities"
              << "\n";
    std::cout << SubNames << "Loan:" << Number << loan << SubNames
              << "Deposit:" << Number << deposit << '\n';
    std::cout << SubNames << "" << Number << "" << SubNames
              << "Ret.Earn:" << Number << ret_earn << '\n';
    std::cout << SubNames << "Liquidity:" << Number << liquidity << SubNames
              << "Equity:" << Number << equity_ << '\n';
    std::cout << MainNames << "-----"
              << ""
              << "-----" << '\n';
    std::cout << SubNames << "Assets:" << Number << sum_asset << SubNames
              << "Liabilities:" << Number << sum_liabilities << '\n';
    std::cout << MainNames << "-----"
              << "End"
              << "-----" << '\n';
}

#endif  // BANK_HPP_
```