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Finance 2.0:

How and when will blockchain technology revolutionise financial markets? How should we regulate the token economy?

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Abstract

This paper aims to outline how blockchain technology is disrupting traditional financial markets through creating a decentralised financial sector. I discuss how the technology works and how it creates value propositions that traditional financial markets cannot offer. Using a model of technological adoption, I estimate a timeframe for blockchain adoption through testing the model empirically using the UK's internet adoption data. I then adjust the input parameters of the model to simulate the adoption of blockchain technology. I predict that blockchain will reach mass adoption (84% adoption) around 2034. Using this timeframe, I discuss how we can expect the use cases of blockchain to evolve over this time and how decentralised financial markets should be regulated to ensure financial stability.

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Glossary

Word	Meaning
Bitcoin	*A peer-to-peer technology which is the first use case of Blockchain technology, invented in 2008 by Satoshi Nakamoto.*
bitcoin	*A digital currency representing an asset on the Bitcoin blockchain.*
Block	*A bundle of transactions, stored together to be added to a blockchain.*
Blockchain	*A system of recording information in a way that makes it difficult or impossible to change, hack or cheat the system (Euromoney).*
Breadth-first	*An algorithm for traversing a network that explores all of the neighbour nodes at the present depth before moving on to the nodes at the next depth level (Wikipedia).*
Cliquish network	*A cliquish network consists of sub-networks where individuals interact extensively with one another (Hanool Choi, 2008).*
Cloud (computing)	*An on-demand availability of computer system resources, especially data storage and computing power without direct active management by the user (Wikipedia).*
Consensus Mechanism	*A fault tolerant mechanism used in blockchain systems to achieve an agreement on the state of the network (Investopedia).*
Cryptocurrency	*A digital or virtual currency that is secured by cryptography, which makes it nearly impossible to counterfeit or double-spend (Investopedia).*
Cryptography	*The practice and study of techniques for secure communication in the presence of third parties called adversaries (Wikipedia).*
Crypto-Token/Token	*A virtual currency representing a fungible, tradable asset or utility that resides on their own blockchain (Investopedia).*
Decentralised applications (Dapps)	*A digital application or program that exists and runs on a blockchain (Investopedia).*
Decentralised finance/DeFi	*A concept where financial products are available on a public decentralised blockchain (Investopedia).*
Diffusion	*The spreading of something more widely, used to describe the spread*

	of technological adoption.
Distributed Ledger	*A database that is shared among many computers acting as nodes on a network, often working towards a common outcome.*
Ethereum	*An all-purpose blockchain that creates an ecosystem for decentralised applications.*
Fiat currency	*Government-issued currency that is not backed by a commodity such as gold (Investopedia).*
Gas	*The fee or pricing value required to successfully conduct a transaction on the Ethereum blockchain (Investopedia).*
Hashing/Cryptographic Hashing	*A hash function is any function that can be used to map data of arbitrary size to fixed size values (Wikipedia).*
Immutable	*Unchanging over time (Dictionary.com).*
Initial Coin Offering (ICO)	*The cryptocurrency industry's equivalent to an initial public offering used to raise funds (Investopedia).*
L2 Scaling	*Solutions designed to help scale an application by handling transactions off the main Ethereum blockchain (Ethereum.org).*
Miner	*Used to verify, authenticate and add the ongoing network transactions to a public ledger (Investopedia).*
Proof of stake (PoS)	*A consensus mechanism allowing a person to mine or validate block transactions according to how many coins they hold (Investopedia).*
Proof of work (PoW)	*A consensus mechanism that requires an amount of effort to mine or validate block transactions.*
Random network/Erdös Rényi network	*A network where the probability of any two nodes being linked is constant.*
Sharding	*A database partitioning technique used by blockchain companies with the purpose of scalability (Investopedia).*
Small-World Network	*A type of network that serves as a hybrid between a cliquish network and a random network.*
Smart Contracts	*A self-executing contract with the terms of the agreement between buyer and seller being directly written into code (Investopedia).*
Software as a Service (SaaS)	*A software licensing and delivery model in which software is licensed on a subscription basis and centrally hosted (Wikipedia).*
Stablecoin	*A class of cryptocurrency that attempts to offer price stability and*

	are generally backed by a reserve asset (Investopedia).
Trustless	*Not requiring trust between any party to come to an optimal consensus.*
Turing-complete	*Colloquially, a Turing-complete computer language can approximately simulate the computational aspects of any other real-world general-purpose computer or computer language (Wikipedia).*
Undirected Network	*A network/graph that is made up of a set of nodes connected by links, where the links have no direction.*
51% attack	*An attack on a blockchain where more than half of the mining network is taken over.*

Chapter 1 - Introduction

Cryptocurrencies such as Bitcoin have been a contentious topic of discussion in the mainstream media due to large price increases and new projects that offer huge returns. However, outside of bullish crypto-markets there is value in the underlying technology that is disrupting the way in which we are able to exchange value within the economy. Blockchain technology allows for the decentralised exchange of digital assets and currencies without the need for an intermediary, which has led to the rise of the decentralised finance (DeFi) industry. This new industry aims to disrupt traditional financial markets by offering services that were previously unavailable.

In this research paper, I begin by outlining crypto-economic literature which focuses on how blockchain technology works and how it provides novel solutions within financial markets. I then discuss the similarities and differences between the internet and blockchain technology to illustrate the disruptive potential of blockchain within the financial services industry. I contribute to the literature by estimating a time period for blockchain adoption since the relevant literature is scarce and unexplored by peer-reviewed papers.

I use a model of technological adoption that aims to estimate a time period for the adoption of blockchain technology. This will be done using a software called Mathematica to model small-world networks that describe social network dynamics in relation to technological adoption. The literature surrounding small-world networks is heavily focused on their existence rather than their application (Hanool Choi, 2008). Rather than focusing on their existence, I aim to further the studies on the implications of small-world network structures on the diffusion of innovations by furthering Choi et al's methodology to model blockchain adoption. Using relevant literature and the time period obtained from the model, I then discuss ways in which financial markets may become decentralised, and how the technology should be regulated to promote a robust financial system that can benefit from blockchain's value propositions. Due to their complexity, I have chosen to omit my research on DeFi paradigms such as flash loans, liquidations and yield farming that deal with new forms of collateralised loans, as well as analysis of their implications on financial stability.

Chapter 2 - Literature Review

The literature regarding blockchain's potential to disrupt financial markets started from the seminal Bitcoin Whitepaper by Satoshi Nakamoto in 2008. Although blockchain has attracted attention from many researchers within both economic and computer science academia, the research still remains for the large part in its infancy.

In this literature review, I outline what blockchain technology is and how it works, I discuss the value propositions of the technology and lastly, I compare blockchain with the internet to justify further comparative analysis throughout this paper.

2.1 What is Blockchain Technology?

2.1.1 What is Blockchain Technology and How Does it Work?

Blockchain technology is a subset of distributed ledger technologies (DLT) and a superset of cryptocurrencies (Anwar, 2019). DLT describes a decentralised database that is shared across multiple computers who act as nodes in a network, often working towards a common outcome (Bashir, 2018). Blockchain is an append-only instance of DLT, meaning that data is added to the database chronologically as it is verified. It is almost impossible to change data on the blockchain once it is added since data is distributed among many nodes in the network, removing the potential for a single point of failure. The blockchain itself is comprised of "blocks" which are batches of transactions that are cryptographically linked to one another. For the sake of research focus, this paper will not go into detail about cryptography, however, it is important to note that it prevents the tampering of block contents and maintains the chain-like structure of the blockchain (see Nakamoto's Bitcoin Whitepaper for a lower-level implementation of cryptographic hashing).

Bitcoin was the first instance of blockchain's use, allowing for the peer-to-peer transfer of assets to exchange value. Therefore, cryptocurrencies are an application of blockchain technology, while blockchain itself can be used to dematerialise any asset and thus as a novel means of exchanging value or information (Kiayias, 2019). An important value proposition of this method of exchange is that it is fully decentralised, meaning that it requires no intermediary such as a bank to complete the transaction, making it fully peer-to-peer

(Nakamoto, 2008). Tapscott & Tapscott explain that for the first time in history, there is a system that prevents double-spending of electronic currency. This means that we no longer need to rely on intermediaries to establish trust between two or more market participants. Instead, the decentralised ledger, network consensus and cryptographic proof can be relied upon for that trust (Tapscott, 2017).

2.1.2 Network Consensus

Consensus mechanisms are required to maintain the legitimacy and verifiability of the ledger by devising a mechanism of verifying data to be added to the blockchain. Firstly, Bitcoin uses the Proof of Work (PoW) mechanism, which requires nodes on the network called miners to solve a cryptographic puzzle to link blocks together, adding transactional data to the blockchain. The PoW mechanism is lottery-based since only one miner is rewarded for solving the puzzle, with one block added to the Bitcoin blockchain every ten minutes (Nakamoto, 2008). The solution is difficult to find, however, once it is found it is easy for other nodes to verify. Once the solution is verified by 51% of the mining network, the miner who solved it is rewarded with a number of tokens (in this case Bitcoin) (Nakamoto, 2008). It is important to note that the number of bitcoins in circulation is capped at 21 million, and as we near the cap; the block reward, which determines the number of tokens rewarded to miners, decreases every 4 years. Once all the tokens have been mined, miners are instead rewarded with transaction fees (Faggart, 2015).

Nakamoto shows using a Binomial Random-Walk that an adversary node is unable (with infinitesimally small probability) to tamper with the contents of a block and rehash the subsequent blocks faster than the current longest chain of the verified ledger. This means that an adversary is only able to alter transaction histories by owning a 51% majority of the mining pool to verify fraudulent transactions. However, it is estimated that it cost around $15 Bn to own the majority of the mining network (bitpanda, n.d.) and once such a compromise has been made, the value of all tokens (e.g. bitcoin) on the network would be undermined. This means that there isn't financial incentive to 51% attack the Bitcoin blockchain, serving as an example of how blockchains use game theory to align incentives and reach a trustless consensus.

Next, Ethereum is an all-purpose blockchain, aiming to apply blockchain technology to use-cases outside of solely payments. It was proposed in 2015, 7 years after the inception of blockchain technology, when Vitalik Buterin published the Ethereum Whitepaper. Using Ethereum, we can leverage the value propositions of blockchain in many different domains, leading to the eventual rise of the DeFi industry and an ecosystem for decentralised applications (Dapps). Ethereum has moved from a PoW consensus mechanism to a Proof of Stake (PoS) mechanism. This is due to environmental and computational scalability issues of the PoW mechanism that are associated with solving cryptographic puzzles. Instead, the PoS mechanism requires validators to stake their Ether tokens to validate transactions. If a validator acts fraudulently, they will lose their stake, creating financial incentive to act in the best interest of the network and disincentivising a 51% attack.

Lastly, there are many consensus mechanisms other than PoW and PoS. Binance Smart Chain is a rival to Ethereum which uses Proof of Staked Authority which is a combination of Delegated Proof of Stake (a more democratic form of PoS) and Proof of Authority (a reputation-based consensus mechanism), allowing a block to be produced every 3 seconds as opposed to Ethereum's approximate 20 seconds and Bitcoin's 10 minutes (Ugochukwu, 2020). It is a highly centralised blockchain due to its consensus mechanism, allowing it to provide lower transaction fees and faster block validation, which may attract more developers in the DeFi industry.

2.1.3 Public, Private and Federated Blockchains

Blockchain networks are categorised by current literature into 3 main groups, public, private and federated blockchains which are classified by the way that they are managed. Bitcoin and Ethereum are the main examples of public/permissionless blockchains, which anyone is able to join as a node; thus, being highly decentralised. Private/permissioned blockchains are a network of whitelisted users, however, since the network is smaller it is possible for nodes to collude creating centralisation. A notable example of a private blockchain is Ripple; a global payments company (Schwartz, 2014). Lastly, a federated/consortium blockchain is a hybrid between a public and private blockchain, where leader nodes verify transactions making the blockchain semi-centralised (Buterin, 2015). JPMorgan's Quorum blockchain is an example of a federated blockchain which aims to reduce cross-border payment fees and transaction times (Arati Baliga, 2018).

2.1.4 Smart Contracts

Ethereum introduced smart contracts which are immutable programs that are written in a Turing-complete programming language, allowing for programs and apps that are able to run autonomously and cannot be removed from the network. However, there is the requirement that "gas" is paid to the smart contract as a fee for the computational work to run the program. Smart contracts allow two or more parties to observe each other's performance of the contract, to guarantee symmetric information to both parties, and be self-enforcing, reducing the need of policing the contracts (Townsend, 2020). This can be used to increase autonomy in financial markets, moving existing financial products to the blockchain. Black Swan Smart Contracts allow users to programmatically select the level of risk in the contract (Melanie Swan, 2019), having revolutionary implications for securities markets and could lead to improved financial stability due to better risk transparency.

2.2. Value Propositions of Blockchain Technology

Now that we have established how blockchain allows for consensus among individuals without the need of a centralised authority, we can discuss how blockchain technology provides value in the economy to further evolve the financial system.

2.2.1 Decentralisation

Heavy centralisation of financial institutions such as banks leads to several inefficiencies. Banks are able to command massive influence on the economy and thus, people's daily lives. Let's take the 2008 financial crisis for instance; it came about through subprime loans particularly within the US housing market where banks were able to over-leverage their capital reserves in an attempt to increase profitability (Krugman, 2008) (Roubini, 2010). The maturity-transformation function of banks, where they lend long and borrow short, leads to the potential for consumers to lose their deposits if the bank goes insolvent. Blockchain can help prevent this financial instability through cutting out rent-seeking institutions in lending markets, reducing the incentives for over-issuing of credit.

Decentralisation is an important value proposition of the technology since financial markets are heavily linked to the sovereign that wields the power to create currency and monetise debts (Philipp Hacker, 2019). Blockchain peer-to-peer loans allow people access to lower interest rates and others to gain higher interest rates on their loans, creating a market that clears without banks taking rents (Khan, 2019). This disintermediation of banking can reduce the influence of central authorities and provide alternative forms of financing that can create the financial stability that traditional rent-seek institutions may be unable to provide.

2.2.2 Borderless Transactions and Reduced Transaction Fees

The bordered nature of transactions leads to inefficiencies in transferring capital across borders (Nakamoto, 2008). Due to strict regulation on the flow of capital in and out of countries, there is a high cost to transacting overseas. This may be through capital tax, delays or fees, costing both time and money. Additionally, the state of cross-border payments is underdeveloped meaning that high costs are exacerbated by inefficiencies in sending money abroad (Rühmann, 2020). Bitcoin proposes a decentralised means of exchange through borderless transactions which allow for low transaction fees and point-to-point exchange, no matter the location, decreasing cross-border transaction times (Duan, 2019).

2.2.3 Financial Inclusion

Blockchain increases financial inclusion. Without the need of banks to act as intermediaries in transactions, the 1.7 billion people globally who are unbanked can have access to financial markets. The barrier to entry is reduced to the price of a smartphone and access to the internet. This allows for a street merchant in Venezuela – a highly financially excluded country – to receive payments electronically or take out a peer-to-peer loan to expand their business (Tapscott, 2017). Blockchain technology is able to provide the institutional support that is lacking in underdeveloped countries, allowing for a means for economic growth and improvement in quality of life through financial inclusion.

2.2.4 Transparency

The Bitcoin Whitepaper details how the distributed ledger allows people to see which addresses have sent X amount of Bitcoin to whom. This enables each user of the system to track the expenditure of the money they have sent to someone else. An example of how this could be used is to verify the legitimacy of a charity's expenditure, increasing financial transparency. Although transactions can only be linked to addresses rather than names, there is concern that public ledgers can create privacy issues where people are able to figure out who is sending how much money to whom (Husam Al Jawaheri, 2019).

The public visibility of smart contracts means that anyone with literacy in programming is able to understand how the contract works and if there are loopholes of entering into a contract. This can prevent problems associated with asymmetric information that occur in financial markets. Consider if the service history of a used car was regularly updated to the blockchain, then the prospective customer will know the exact condition of the car eliminating the adverse selection problem described by George Akerlof's "The Market for Lemons" (Akerlof, 1970). This principle can be applied to many other domains such as insurance and credit markets where the risk of an individual is unknown, helping to prevent adverse selection and moral hazard through eliminating information asymmetry.

2.2.5 Autonomy

Smart contracts allow for the efficient transfer of assets on the blockchain since assets can be signed and given a new owner almost instantaneously as soon as some condition is met, e.g. payment has been received. Avgouleas and Kiayias (2019) describe how the autonomous transfer of assets can revolutionise securities markets. This is through preventing loss of control over securities by the ultimate owner, potential legal uncertainty and the risk that collateral re-use induces credit creation that leads to systemic risk. I will further discuss the application of smart contracts on securities markets in Section 6.3.

2.2.6 Immutability

Immutability is a property of the smart contracts that means that code that is deployed to the blockchain cannot be taken down, this is because it will be stored on the distributed ledger for each node on the network. There are benefits that arise from immutability, such as resistance to failure. Smart contracts only rely on the network (e.g. Ethereum) to be running and gas is paid to run the contract, meaning that so long as those conditions are met, the smart contract will continue to function. Additionally, immutability means that transactions cannot be reversed by an intermediary, making blockchain transactions final.

2.3 The Internet and Blockchain

Now that we understand how blockchain can provide novel solutions in financial markets, I will discuss how it compares to the internet. This will allow us to understand the infrastructural similarities of the internet and blockchain that will have implications on the roadmap to blockchain adoption.

2.3.1 Internet and Blockchain Similarities

Blockchain and the internet hold structural similarities. They both create network effects, meaning that there are positive externalities for multiple users for each new member on the network. This creates adoption externalities due to social marginal benefits exceeding private marginal benefits for each node (Shapiro, 1994). As a result of these network effects, blockchain has been shown by Alabi to follow Metcalfe's Law similarly to the internet (Alabi, 2020). Metcalfe's Law conjectures that the value of a network is proportional to the square of the number of nodes in it. This suggests that the manner in which use cases and the blockchain ecosystem will evolve may parallel that of the internet due to their structural similarities.

2.3.2 Internet and Blockchain Differences

Wiesflecker describes two ways in which blockchain and the internet differ. Firstly, they differ in how they have arisen. The internet was developed by academics with the first message over the internet being sent between UCLA and Stanford researchers. On the other hand, blockchain was developed as an open-source project by Satoshi Nakamoto which subsequently attracted attention from academics in a wide range of fields (Wiesflecker, 2020). The decentralised origins of blockchain may have implications on the development of public blockchains, since funding for research and development may be reliant on decentralised means. Private and federated blockchains will instead be backed by large, centralised institutions such as JPMorgan's Quorum, which might accelerate private/federated blockchain development.

Secondly, Wiesflecker emphasises that the internet revolutionises the exchange of information, whereas blockchain focuses on the exchange of value. Although Wiesflecker does not detail the implications of this distinction, from academic literature it is clear that a new means of exchanging value allows for financial market innovation to be at the forefront of blockchain use-cases.

2.3.3 The evolution and adoption of the Internet

The internet was first developed in 1989, allowing static webpages to dominate until 2005. This is commonly referred to as Web 1.0 where information exchange was predominantly passive due to un-interactive webpages (Patel, 2013) (Ku. Chhaya A. Khanzode, 2016). Subsequently the web evolved to Web 2.0 with the rise of dynamic and interactive web pages, supporting collaboration and facilitating the growth of e-commerce and online business models. During this evolution, the number of global internet users increased from 45 million to over 1 billion (Ku. Chhaya A. Khanzode, 2016). Academic literature suggests that we are currently in a transition phase between Web 2.0 and Web 3.0 (in 2021), where blockchain is a driving factor promoting a decentralised web that allows for freedom of speech due to blockchain's immutability (Massimo Ragneda, 2019).

Fig 2.3.3.1 shows the timeline for different services and technologies that have been involved with the evolution of the web, starting from 1939 up until 2017. We can see the emergence of Software as a Service (SaaS) business models such as YouTube, Twitter and Spotify emerge in the 2000s, which comes at the same time as large cloud service providers such as Heroku and AWS. This shows a clear evolution of the web alongside cloud technologies that allowed online business models to scale to millions of users. Fig 2.3.3.2 shows the number of internet adopters over time, with 4.2 Bn in 2018, clearly showing the rapid technological adoption of the internet in a matter of two decades.

Figure 2.3.3.1 Evolution of the Internet and Blockchain (Source: (Gai, 2019))

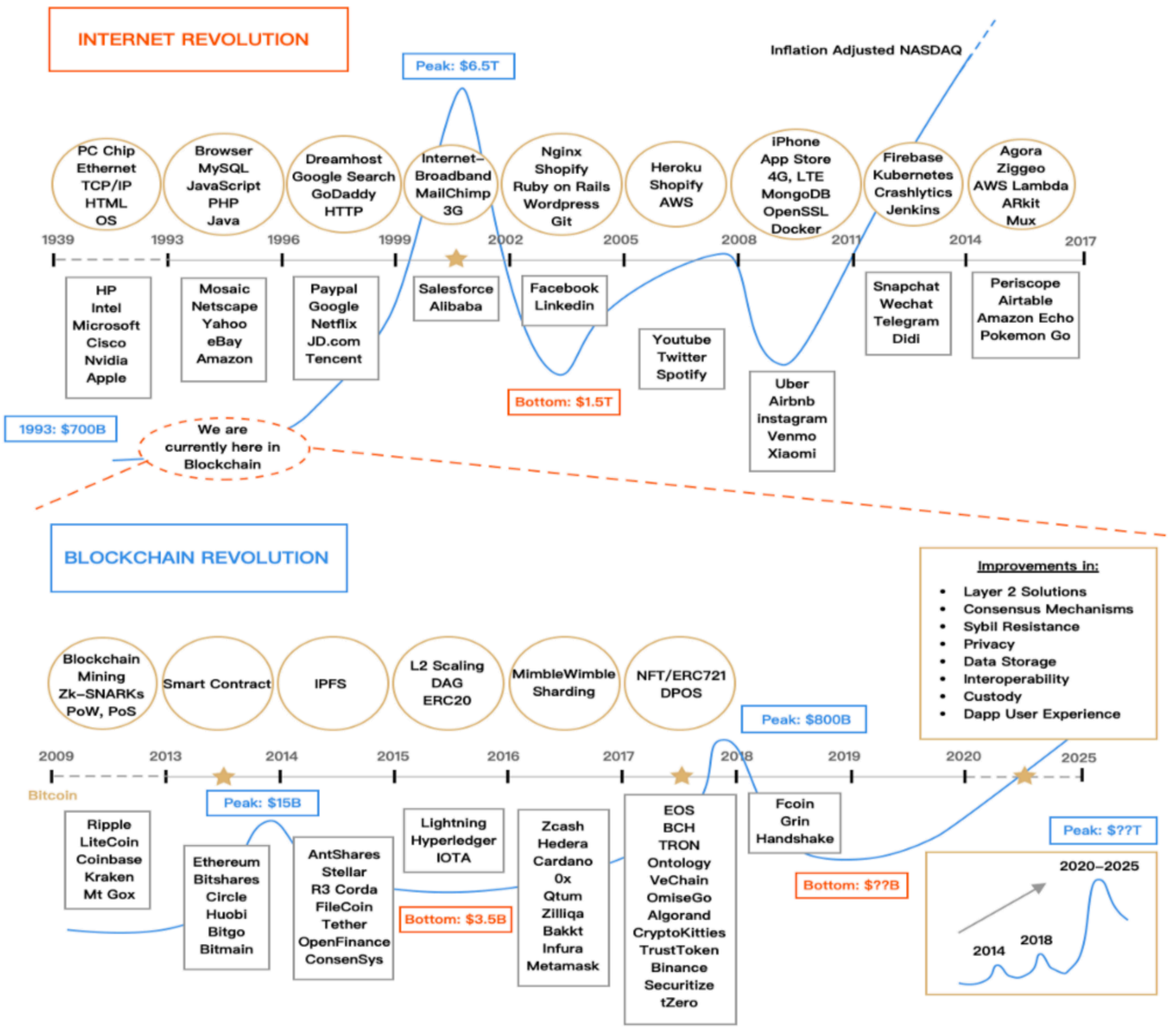


Figure 2.3.3.2 Adoption statistics (Source: (Gai, 2019))

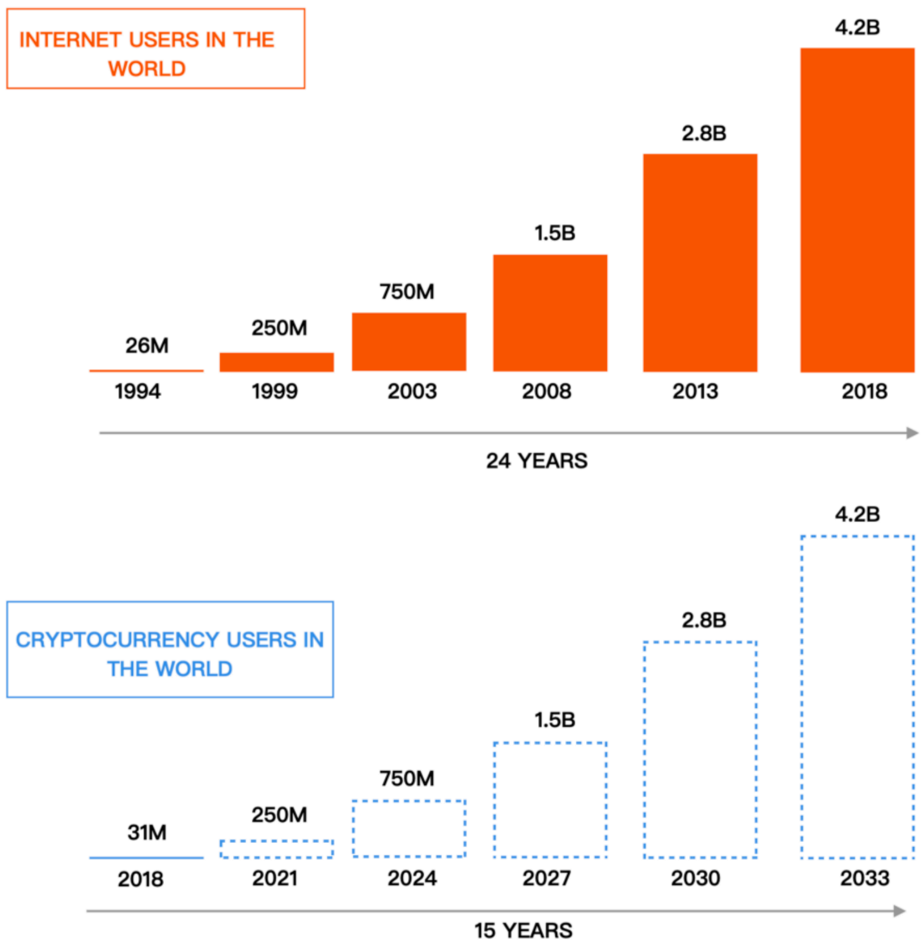
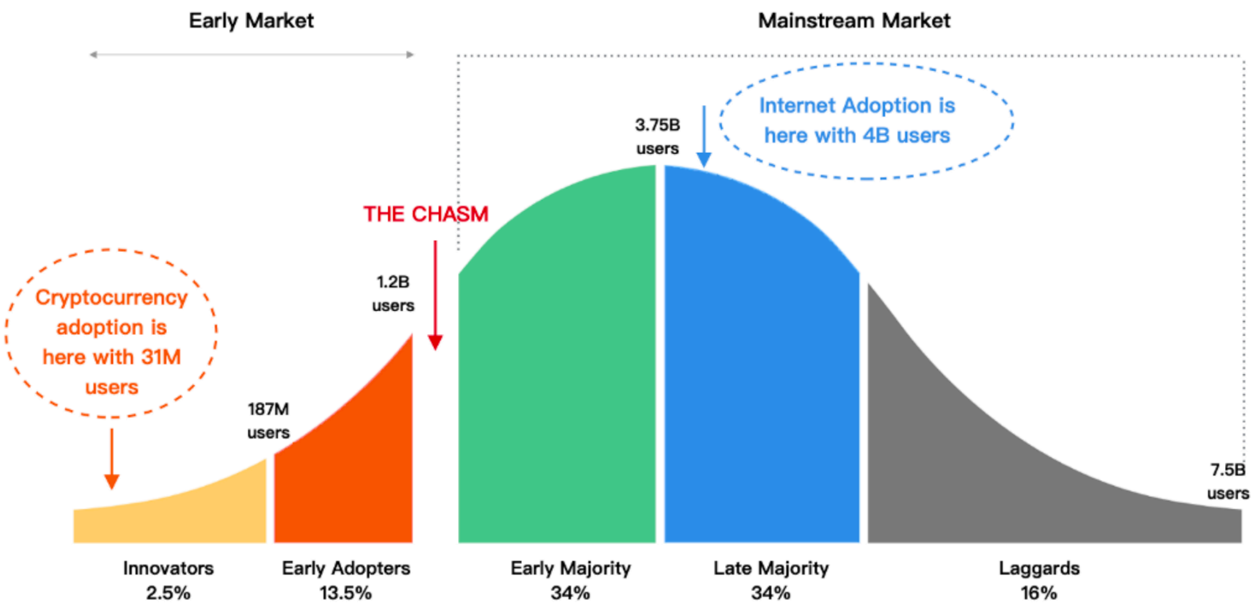


Figure 2.3.3.3 Internet adoption curve (Source: (Gai, 2019))



2.3.4 The evolution and adoption of Blockchain

We can now consider how blockchain adoption might parallel the internet. Figure 2.3.3.1 suggests that the adoption of cryptocurrency adoption is at a similar point to where the internet was in 1994. Blockchain scalability solutions such as sharding and L2 scaling (see glossary) occurred between 2015 and 2017, which provide similar effects to cloud solutions that allowed web services to scale. Although Fig 2.3.3.3 shows that cryptocurrency adoption is in the innovator stage, scalability solutions are occurring at an earlier stage than cloud services did for the internet, suggesting that the timeline for blockchain adoption may be shorter. Fig 2.3.3.2 predicts that by 2033, cryptocurrency adoption will reach a similar level of adoption as the internet in 2018: a shorter 15-year adoption period in comparison to the internet's 24-year timeline. The methodology used to obtain this estimate is unclear from the source, however, it provides a useful ball-park figure for my own methodology in this paper.

Similarly to how the web has evolved, blockchain literature proposes three stages for blockchain evolution: Blockchain 1.0, Blockchain 2.0, and Blockchain 3.0. Blockchain 1.0 refers to the adoption of cryptocurrencies and the use of blockchain to innovate on real-time payments and monetary transactions. Blockchain 2.0 refers to the dematerialisation of asset classes and smart contract innovations, providing robust services such as peer-to-peer lending, mortgages and insurance. Blockchain 3.0 refers to innovations in enterprise blockchain solutions, leading to a broader application of blockchain technology outside of financial markets to innovate in management, big health data and asynchronous space communication (Melanie Swan, 2019).

Chapter 3 – Modelling Technological Adoption

I aim to model blockchain adoption to estimate an adoption timeframe as well as the probability of full diffusion of the technology (at least 84% adoption). There are multiple technological adoption models that I have considered, including Goodhue and Thompson's (1995) Task-Technology Fit model, Fishbein and Ajzen's (1975) Theory of Reasoned Action, Ajzen's (1991) Theory of Planned Behaviour, Taylor and Todd's (1995) Decomposed Theory of Planned Behaviour and Fred Davis' Technology Acceptance Model (1986). However, these models focus on modelling largely behavioural phenomena at a microscopic scale which cannot explain technological adoption at a macroscopic level. I have decided to use

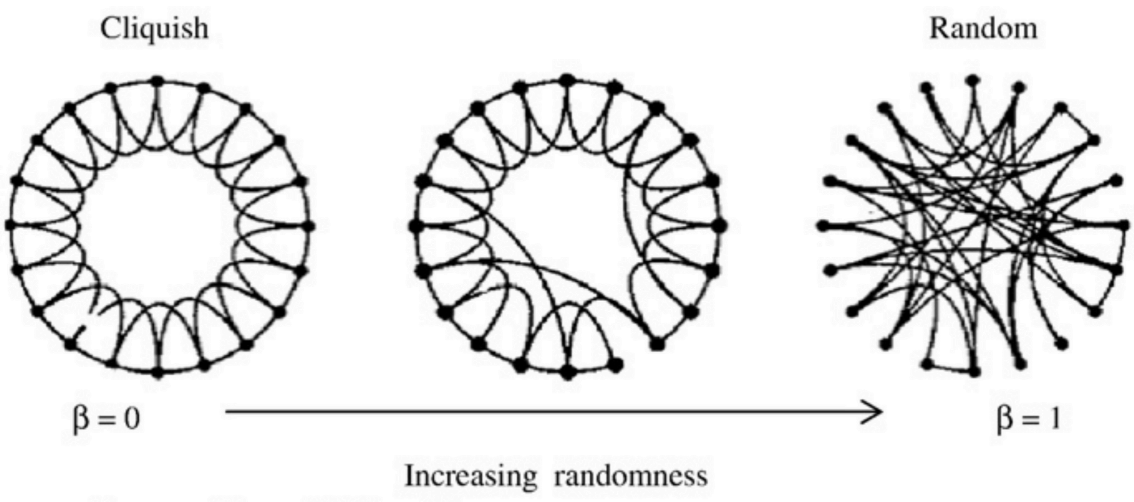
Rogers' (1995) Diffusion of Innovation Theory in combination with Choi et al. and Sabzian et al's small-world network methodology to model the dynamical process of technological adoption. This allows us to model the passage of time through evolving a network, while also describing the dynamics of technological adoption at a higher level and larger scale. Furthermore, this model incorporates behavioural phenomenon such as social influence, while also benefiting from quantitative analysis drawn from network theory.

In this chapter, I present the dynamical model programmed by myself using Mathematica, altering the methodology used by Choi et al's research. This model can be used to describe many dynamical processes such as the adoption of blockchain technologies within a society, the spread of political opinion throughout a country and the spread of a disease throughout a population, drawing similarities to the epidemiological SIR model used by academics to simulate the spread of COVID-19.

3.1 Network Structure

I use a Watts-Strogatz small-world network since they are believed to accurately model societal social networks (Duncan J. Watts, 1998). This type of network, developed in Watts and Strogatz' 1998 paper, serves as a middle-ground between a cliquish network (shown on the left of Figure 3.1.1) and a random/Erdös Rényi network (right of Figure 3.1.1). Granovetter (1973) supports this claim, stating that the structure of social networks is comprised of cliquish sub-networks and bridges (links) between sub-networks. A cliquish network consists of sub-networks where individuals interact extensively with one another (Hanool Choi, 2008), while a random network is a network where the probability that any two nodes are linked is constant. To achieve this hybrid regular-random network, I introduce a rewiring probability parameter $\boldsymbol{\beta}$ which rewires the links of nodes within sub-networks to a randomly selected node within the entire network with probability $\boldsymbol{\beta}$ (Hanool Choi, 2008). This creates bridges between sub-networks, allowing for sub-networks to interact, leading to the small-world phenomenon popularly described as the six-degrees of separation (Duncan J. Watts, 1998).

Figure 3.1.1 Small-world network structure (Source: (Duncan J. Watts, 1998))

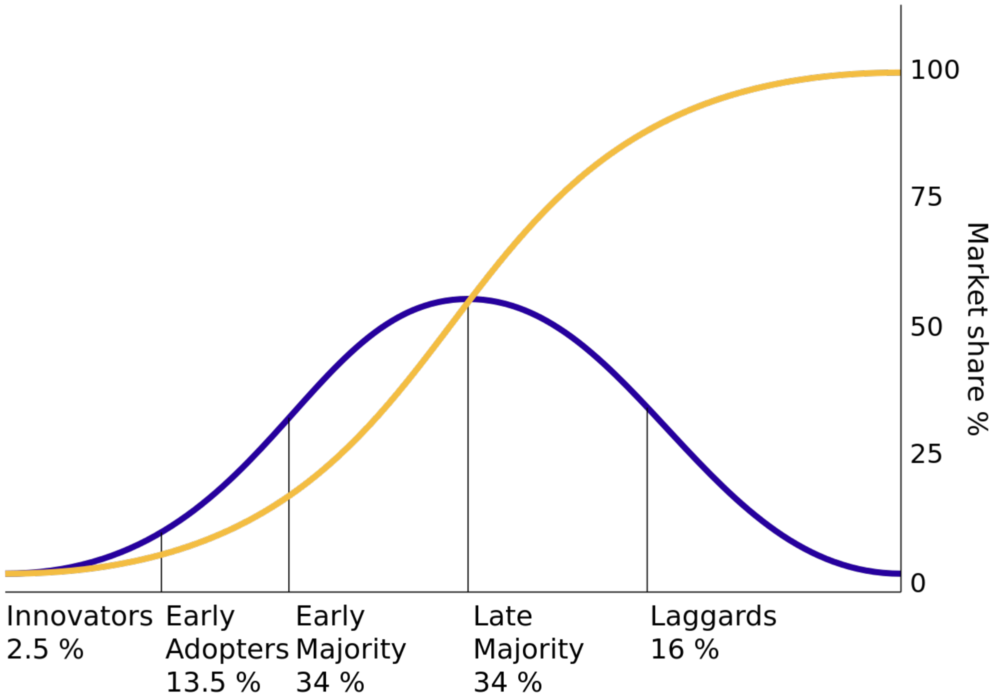


3.2 Agents and Nodes

3.2.1 Agent Types

Agents in the economy are represented by nodes within the network. I categorise them into the five different groups described by Everett Rogers' Diffusion of Innovation Theory in Figure 3.2.1 (Rogers, 2003). These are innovators, early adopters, early majority, late majority and laggards. These types will be assigned to each node in the network and will affect an agent’s likelihood of adopting a technology.

Figure 3.2.1 Rogers' Diffusion of Innovations Theory (Source: (Rogers, 2003))



3.2.2 Utility Function

An agent in the network must individually use cost-benefit analysis to assess if they are willing to adopt the technology, this is determined by their individual utility function. In general, this is given by:

$$\boldsymbol{U_{it} = Q_i + aN_{i(t-1)}}$$

$\boldsymbol{Q_i}$ represents the net value of blockchain technologies to an individual. This encompasses factors such as the technology's intrinsic value to an individual as well as the agent's reluctance to adopt the technology, influenced by the agent's type. It is normally distributed around mean $\boldsymbol{Q_\mu}$ with variance $\boldsymbol{\sigma^2}$.

The term $\boldsymbol{aN_{i(t-1)}}$ describes the positive effects of blockchain technology that arise from network externalities. $\boldsymbol{N_i}$ is the proportion of node i's neighbouring nodes that have adopted the technology, while $\boldsymbol{a}$ is a scaling constant that adjusts the impact of the network effects of neighbouring nodes. This is a simplification of Choi et al's utility function to incorporate agent typing. I initialise these variables $\boldsymbol{Q}_{\mu}$ and $\boldsymbol{\sigma}$ such that approximately 2.5% of agents are innovators who start with a positive utility of adoption without network externalities.

Approximately 2.5% of agents must satisfy:

$$\boldsymbol{U_{it} = Q_{2.5\%} + 0 > 0}$$

$$\text{And thus, } \boldsymbol{Q_{2.5\%} > 0}$$

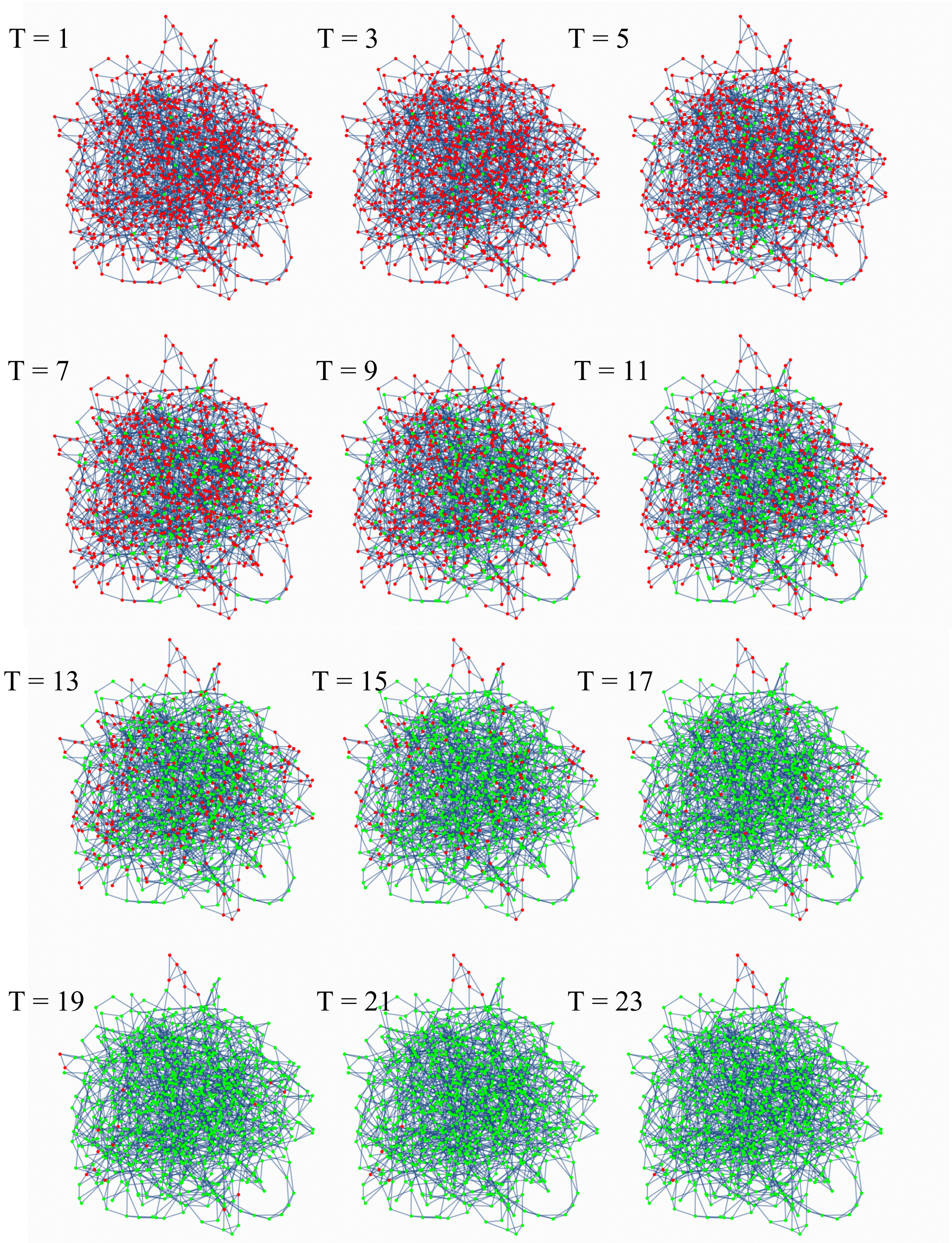
Since the maximum value of $\boldsymbol{N_i}$ is 1, I centre the distribution around $\boldsymbol{Q}_{\mu} = -0.5$ with a standard deviation $\boldsymbol{\sigma} = 0.255$. Thus, $P(\boldsymbol{Q_i} > 0) = P(Z > 1.96) = 2.5\%$. This also means that approximately 2.5% of the population will never adopt the technology, even when $\boldsymbol{N_i} = 1$.

Sabzian et al. (2020) describes early adopters as those whom "possess a higher social status, and are more socially oriented than late adopters". This might describe early-stage investors who are well respected within the technology industry. I use this quality as the basis for the assumption that nodes in the network with higher degree-centrality (a proxy for social orientation) will also have larger $\boldsymbol{Q}_{\mathrm{i}}$ values. I generate the normal distribution of agent opinions and assign the most favourable opinions to nodes in order of highest degree-centrality; this is a measure of node centrality determined by the number of links attached to the node (Warih Maharani, 2014).

3.3 Time Evolution

Now that I have generated a network representing the UK population and I have assigned each node an agent type, I can explain the algorithm used (see Appendix for Mathematica code) to simulate the passage of time through evolving the network. I update agents' opinions, with each evolution modelling the passage of one year. I traverse the network in a breadth-first manner starting from the innovative adopter nodes, adding each node's neighbours to a queue and run the utility function calculation on each node in the queue. If the utility of the node is positive, the agent will change their opinion and adopt the technology with a probability $p = \boldsymbol{N_i}$ (the proportion of neighbouring nodes that have adopted the technology). This way I not only incorporate network externalities, but also describe the effects of social influence within social networks. This leads to the S-shape adoption curve seen in Figure 3.2.1 as theorised by Perez' Technology Surge Cycle (Perez, 2010). This breadth-first traversal is repeated in further time periods until technological adoption stagnates and I end the simulation, yielding the estimated time periods. This allows the program to run with better computational efficiency since I do not need to perform the calculation for every agent in the network each evolution. Figure 3.3.1 depicts the evolution of a network over time, we can see that it starts off with approximately 2.5% of the population adopting the technology, and as the network evolves, more nodes begin to adopt.

Figure 3.3.1 Example model simulation



Chapter 4 - Methodology

In this section I discuss the application of my model to blockchain technologies, using the adoption of the internet as a proxy to test the model as well as to obtain estimates for the model's input parameters $\boldsymbol{\beta}$ and $\boldsymbol{a}$. In Section 2.3 I discussed the similarities between the internet and blockchain to justify this methodological approach. I will discuss methods that I have used to estimate the expected time periods to reach specific milestones in adoption. Additionally, I can obtain probabilities that the technology reaches full diffusion, with both methods being in relation to Choi et al's methodology.

4.1 Parameter Estimation

4.1.1 Data Set

I look to empirically test the model using the adoption of the internet as a proxy for blockchain adoption, which will allow me to approximate the probability that the technology reaches full diffusion as well as to find suitable input parameter values for the model. I use the World Bank's World Development Indicators publication as my source of data shown in Table 1 (The World Bank, 2017). The data details the share of individuals in each country around the world that uses the internet between 1990 and 2017, measuring the proportion of individuals who have used the internet in the last 3 months at the time of collection. This variable has its limitations since penetration (share of households with access to telecommunications) is thought to be a more accurate measure of adoption (The World Bank, 2017). Additionally, some countries have missing data points, so I focus on the United Kingdom for my analysis. This is due to the availability of data as well as the UK's relevance to the targeted reader.

I have considered other data sets such as Statista's UK survey that measures internet adoption rates using penetration (Statista, 2020). However, the data is from a small sample of around 1800 people from 1998 to 2020, meaning that it may be subject to sampling biases that do not reflect the characteristics of the population as a whole. Instead, the World Development Indicators data is obtained from telecommunications operators, meaning that the data is widely available and is sampled from the entire UK population.

4.1.2 Parameter Simulation

I model the UK as a network of 1,000 agents, simply because it is the largest value that I can use given my computational restraints. I aim to obtain values for $\boldsymbol{\beta}$ and $\boldsymbol{a}$ by systematically adjusting each parameter to simulate the UK's internet adoption.

Using the data set, I measure the time between 2.5% adoption to each of the milestones for the sake of consistency with my modelling assumptions. I will be aiming to minimise the errors of three variables: the time taken to reach 16%, 50% and 84% adoption. The significance of these milestones is that they represent the time taken for early adopters, early majority and late majority agents respectively to adopt the internet. This will allow me to discuss the qualitative significance of these milestones more precisely, particularly with regard to blockchain's adoption.

Using mathematical notation, I aim minimise the sum of the squared errors where:

$$SSE = \min \sum \varepsilon_i^2 = \varepsilon_{16}^2 + \varepsilon_{50}^2 + \varepsilon_{84}^2$$

$$\varepsilon_{16} = t_{16} - \tau_{16}$$

$$\varepsilon_{50} = t_{50} - \tau_{50}$$

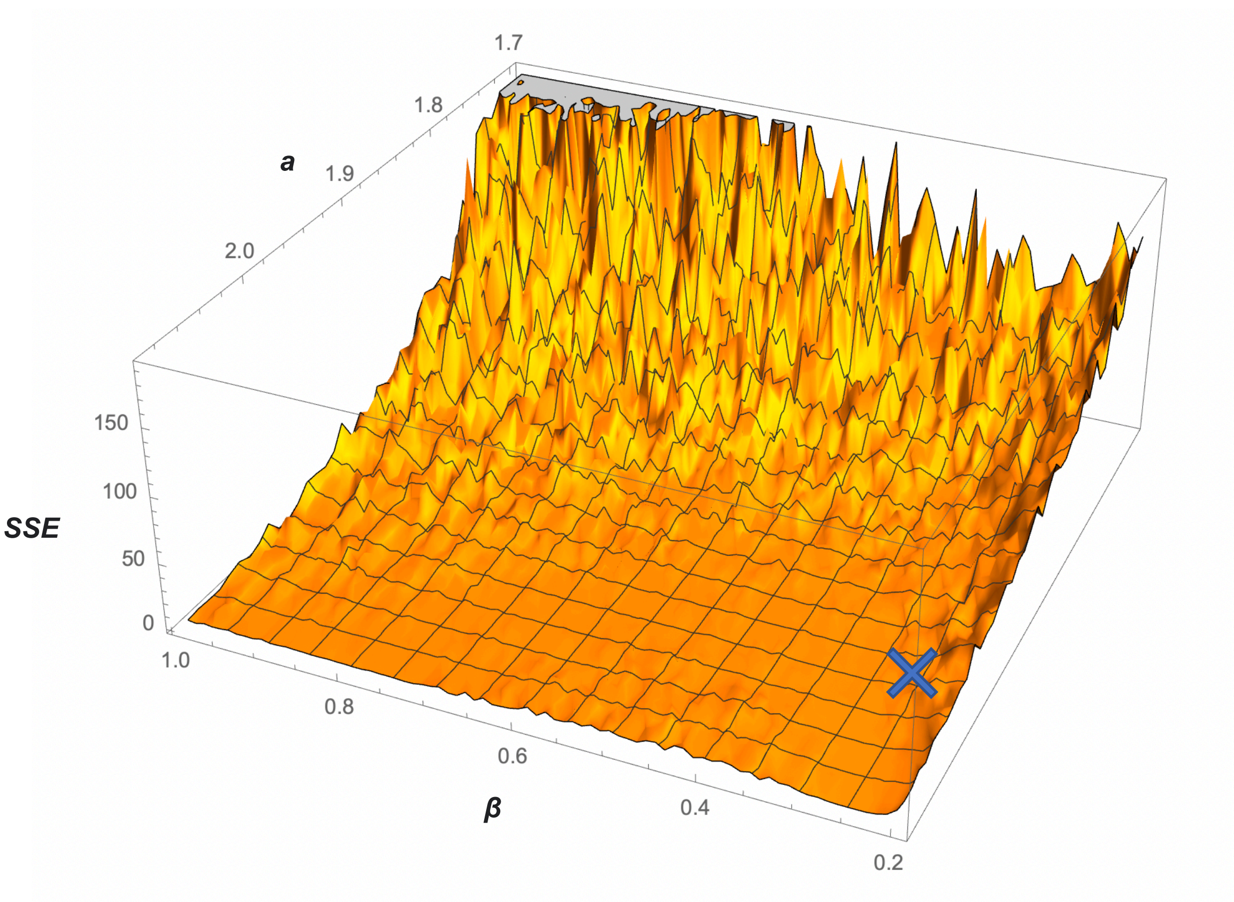
$$\varepsilon_{84} = t_{84} - \tau_{84}$$

$$\boldsymbol{t} \ is\ an\ expected\ time\ to\ reach\ a\ milestone\ yielded\ from\ 10{,}000\ simulations$$

$$\boldsymbol{\tau} \ is\ the\ actual\ time\ to\ reach\ a\ milestone\ (obtained\ from\ the\ World\ Bank\ data\ set)$$

I vary $\boldsymbol{\beta}$ between 0.2 and 1 with a step of 0.01. From initial simulations, I decided to leave out values of $\boldsymbol{\beta}$ between 0 and 0.2 due to large errors caused by failed diffusions. This is because insufficient bridges between sub-networks hinders the adoption of technology. Additionally, I vary $\boldsymbol{a}$ between 1.7 and 2.1 in steps of 0.01. From initial simulations, values of $\boldsymbol{a}$ lower than 1.7 would result in failed diffusions and overestimated timeframes with large errors, while values of ***a*** larger than 2.1 would underestimate timeframes creating large errors. From this methodology, I yield Table 8 and the visualisation Figure 4.1.2.1.

Figure 4.1.2.1 Data visualisation of Table 8



This method of minimising least squares aims to mimic ordinary least squares regression by minimising the error of the estimated timeframes of the simulation. By varying the parameters that I input into the model, I can find the values that yield an adoption curve that resembles the real-world data. This empirical method only aims to minimise the error of three different milestones which means that the simulated adoption curve may not follow the actual data exactly. However, this prevents the issue of overfitting and aims to minimise errors for the timeframes we care about most.

I find that the sum of the square errors is minimised at 0.959 (3 s.f.) when $\boldsymbol{\beta}$ = 0.26 and ***a*** = 2.07. This result is indicated on Figure 4.1.2.1 with a blue cross and a green highlight in Table 8. These results allow me to accurately simulate the adoption of the internet in the UK, and I can use these parameters to help determine how I will model blockchain adoption. A small value of beta implies that social networks are highly cliquish with a small number of bridges, Choi et al. explain that "poor cliquishness with too many bridges hinders an innovation from diffusing throughout the whole population" (Hanool Choi, 2008). This supports my result ($\boldsymbol{\beta}$ = 0.26) and intuition that high levels of cliquishness and a small number of bridges allow for high levels of both intra- and inter-clique adoption. This is because cliques/sub-networks allow for network effects to build, while bridges can allow for adoption to spread to other cliques.

4.2 Parameter Adjustments

In this section, I outline my hypotheses for the values of $\boldsymbol{\beta}$ and $\boldsymbol{a}$ that model blockchain adoption in the UK compared to the values I have obtained to model internet adoption.

4.2.1 Hypotheses

I have two hypotheses:

$$\boldsymbol{Hypothesis\ 1: a_{blockchain} = a_{internet}}$$

$$\boldsymbol{Hypothesis\ 2: \beta_{blockchain} > \beta_{internet}}$$

I cannot empirically test my hypotheses since there is insufficient data on blockchain adoption, however, I can justify my hypotheses qualitatively.

Using the estimates I have obtained for the parameters $\boldsymbol{\beta}$ and $\boldsymbol{a}$, I can discuss how they might vary in the case of blockchain technology. Firstly, looking at the scaling constant ($\boldsymbol{a}$) which weights network effects, it is difficult to make a quantitative assessment on how network effects differ between blockchain and the internet due to insufficient literature. Qualitatively, considering Metcalfe's Law which I have discussed in Section 2.3.1, that postulates that both the internet and blockchain create network effects that are proportional to the square of the number of nodes in the network. This theory supports the hypothesis that the value of $\boldsymbol{a}$ is similar for both technologies, and any deviation from this would require a value judgement on blockchain's inherent value in comparison to the internet, which has not been assessed in the relevant literature.

Considering the parameter $\boldsymbol{\beta}$ which determines the probability of links in the network being rewired, I can adjust it through comparison of social network structures before and after internet adoption. While there is insufficient research regarding the structural changes of social networks, I can use "Dunbar's number" also known as the social brain hypothesis. It postulates that a typical human cannot maintain more than 150 relationships at any one time (Dunbar, 1993). Dunbar explains this is due to cognitive and behavioural constraints of our brainpower, he empirically tests this hypothesis against 2012 internet data, showing that this law holds true. Ultimately, he concludes that internet adoption does not increase the size of our social networks, however, allows us to maintain connections with those whom we cannot physically see face-to-face (Dunbar, 2015). Dunbar's work suggests that following the adoption of the internet, the rewiring parameter ($\boldsymbol{\beta}$) used to describe contemporary social networks is likely to have increased since we are able to maintain relations with people in distant social circles, without increasing the size of our network. In terms of the model, this means that there will be more bridges that connect different sub-networks. Additionally, since we have maintained the size of our social networks, this is further evidence to support that social network effects ($\boldsymbol{a}$) are comparable between the internet and blockchain (post-internet).

4.2.2 Hypothesis Simulation

I now study the effects of upwardly adjusting the $\boldsymbol{\beta}$ parameter on two important variables: the time taken to reach a steady adoption state and the proportion of failed diffusions where there is less than 16% adoption. Choi et al's work conducts a similar systematic assessment of adjusting the rewiring parameter as shown in Figures 4.2.2.1 and 4.2.2.2. Particularly, they find that between 0 and 0.2, increasing $\boldsymbol{\beta}$ has a strong negative effect on average time taken to reach a steady state. Between 0.2 and 1, increasing $\boldsymbol{\beta}$ has marginally positive effect on the average time. Additionally, although increasing $\boldsymbol{\beta}$ leads to an increase in the number of bridges between cliques, this effect is offset by a decrease in cliquishness, leading to a higher chance of failed diffusion shown in Figure 4.2.2.2 (Hanool Choi, 2008).

Figure 4.2.2.1 Effect of changing β on time until stagnation (Source: (Hanool Choi, 2008))

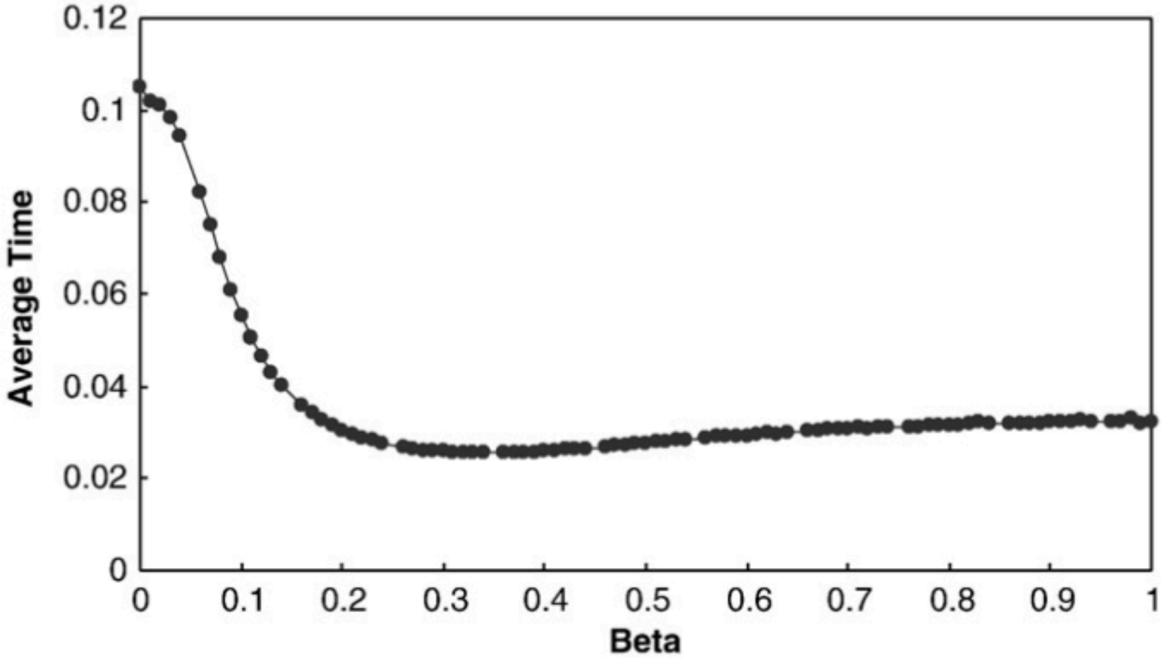
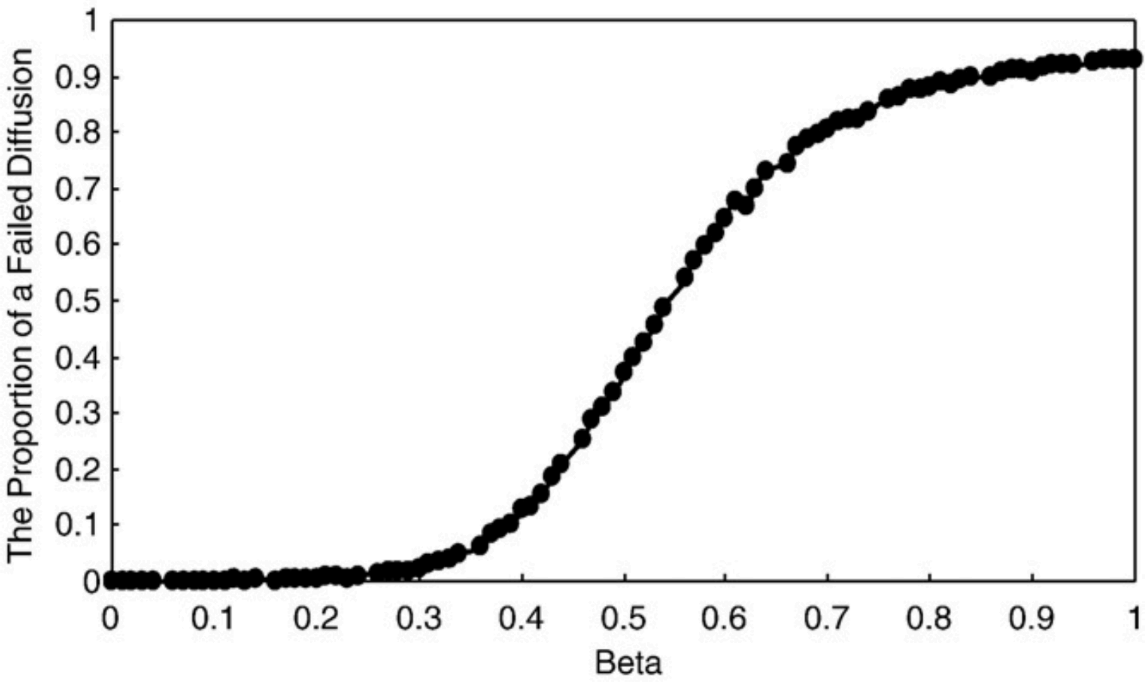


Figure 4.2.2.2 Effect of changing β on proportion of failed distributions (Source: (Hanool Choi, 2008))



By holding $\boldsymbol{a}$ fixed at 2.07 and adjusting $\boldsymbol{\beta}$, I can replicate Choi et al's methodology to assess the effects on the time until stagnation and percentage of failed diffusions. I increment $\boldsymbol{\beta}$ by 0.01 between 0 and 1, finding the proportion of failed diffusions and mean time over 1000 simulations (rather than 10,000 due to computational constraints). I yield the results shown in Figures 4.2.2.3 and 4.2.2.4. Figure 4.2.2.3 shows that as I increase $\boldsymbol{\beta}$ between 0 and 0.3, the average time until reaching a steady state strongly decreases and between 0.3 and 1, it marginally increases. This result is almost identical to that shown by Choi et al. in Figure 4.2.2.1. We can expect that upwardly adjusting $\boldsymbol{\beta}$ from 0.26 will have a small effect on reducing the timeframe for blockchain adoption in the UK. Figure 4.2.2.4 shows the effect of changing $\boldsymbol{\beta}$ on the proportion of failed distributions, giving us an estimate for the probability of mass adoption of blockchain technology. I find that increasing $\boldsymbol{\beta}$ has a negative relationship with the probability of failed diffusion, which is contradictory to the result found by Choi et al. that suggests that lower degrees of cliquishness lead to a higher probability of failed diffusion as shown in Figure 4.2.2.2. This is likely due to my scaling parameter ($\boldsymbol{a}$) being larger than the value used by Choi et al. (which isn't specified). This means that my model likely weights network effects more, meaning that network effects are able to build, even with low levels of cliquishness. This overestimation of $\boldsymbol{a}$ might incorporate the positive effects of omitted variables that are positively correlated to technological adoption. These may include factors such as technological development that occurs over the passage of time, which is a potential cause of omitted variable bias upwardly biasing my estimate of the parameter $\boldsymbol{a}$.

Figure 4.2.2.3 Effect of changing β on time to reach a steady adoption state (Data shown in Table 3)

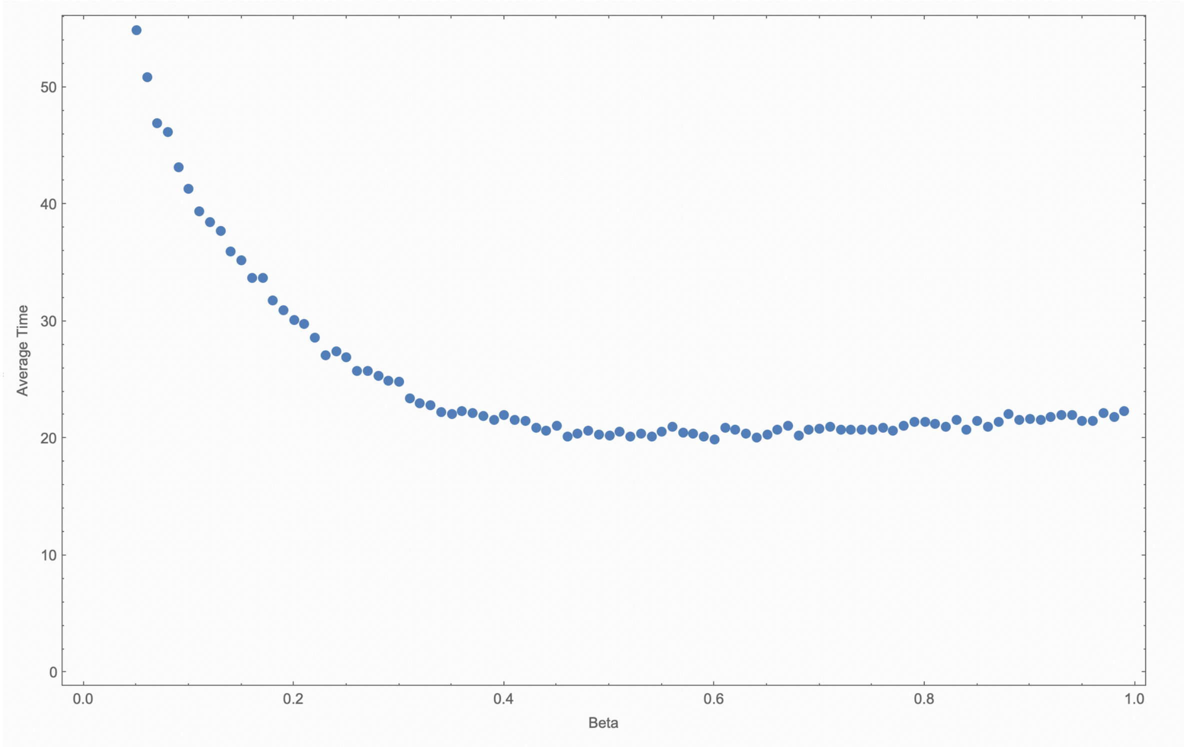


Figure 4.2.2.4 Effect of changing β on proportion of failed distributions using the model (Data shown in Table 4)

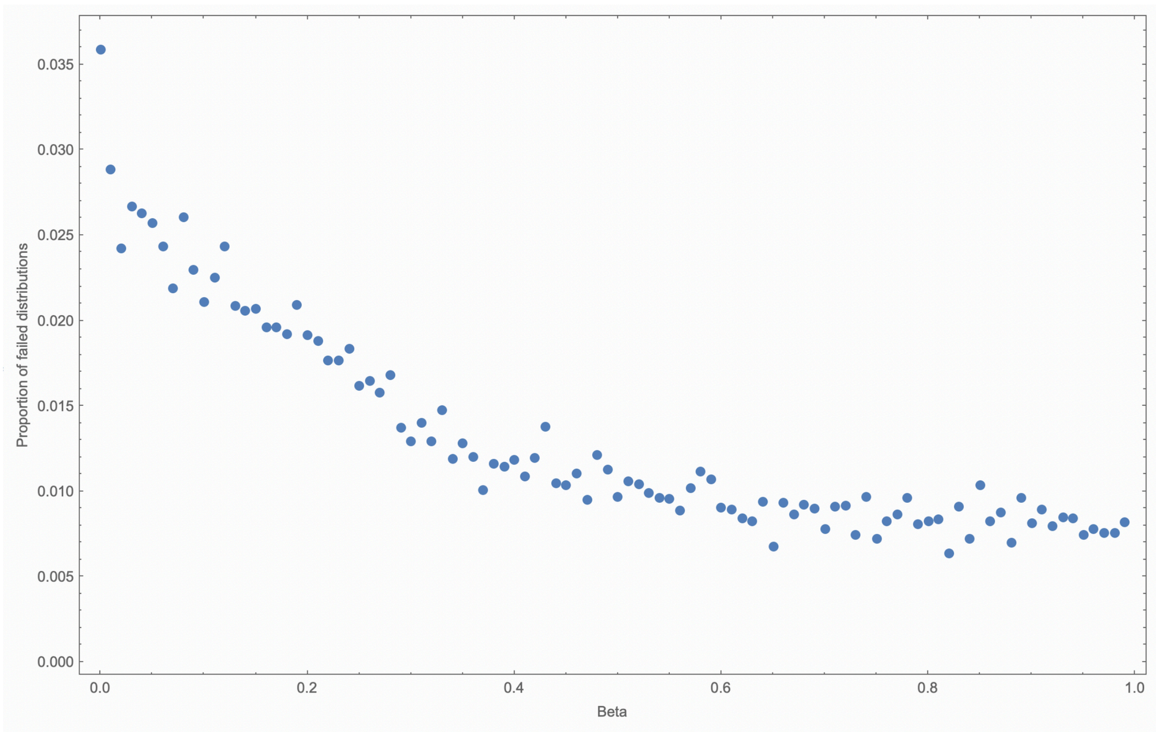
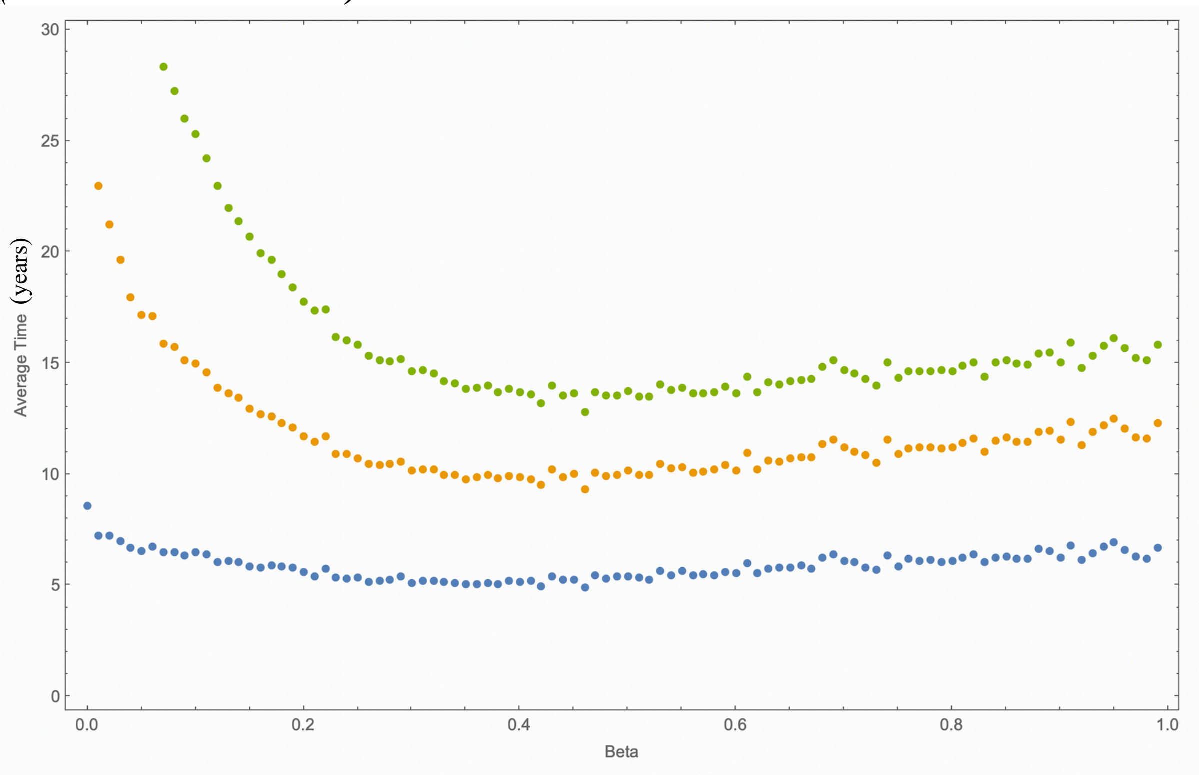


Figure 4.2.2.5 illustrates the variation in adoption milestones as I increase $\boldsymbol{\beta}$. The blue line represents the average time to reach 16% adoption as I vary $\boldsymbol{\beta}$, it remains steady at around 5-7 years for all values of $\boldsymbol{\beta}$. In comparison the orange line representing 50% adoption and the green representing 84% adoption show a similar relationship to the time till stagnation shown in Figure 4.2.2.3. This is characterised by a fall in average time between $\boldsymbol{\beta} = 0$ and 0.3, then as $\boldsymbol{\beta}$ continues to increase, having a small incremental effect on the average time.

Figure 4.2.2.5 Effect of changing β on each milestone's time frame using the model (Data shown in Tables 5-7)



I can now take the maximum and minimum values of the average time to reach each milestone between $\boldsymbol{\beta} = 0.26$ and 1 to obtain three time intervals. Similarly, I can use Figure 4.2.2.4 to obtain an interval for the probability that blockchain technology reaches full diffusion.

The Financial Conduct Authority (FCA) estimate that in the UK, 5.35% of the population hold/have held cryptocurrency in 2020, which is an increase from the estimated 3% in 2019 (Financial Conduct Authority, 2020). These values are sufficiently large to satisfy the modelling assumption that I start the simulation at 2.5% adoption. This means that I can simulate the adoption of blockchain in the UK starting from 2019 (3% ≈ 2.5%).

Chapter 5 – Results and Limitations of the Model

5.1 Results

Using the methodology outlined in Section 4, I have obtained intervals for the time taken until 16%, 50% and 84% blockchain adoption, as well as an interval for the probability of full technological diffusion. Table 2 shows each interval and the median value. Starting the simulation from 2.5% adoption in 2019 (Financial Conduct Authority, 2020) and using the median value of each time interval, I find cryptocurrency and blockchain will take approximately 5.7 years to reach 16% adoption (2025), 10.6 years until 50% adoption (2030), and 14.3 years until 84% adoption (2034). Additionally, from Table 2 I have found that there is a 0.95% chance that blockchain does not reach full diffusion given that internet adoption is a suitable proxy for blockchain adoption. These results show that the adoption of blockchain (14-15 years) will take less time than the internet (18 years after 2.5% adoption) in the UK (The World Bank, 2017). These timeframes support Gai's estimates in Figure 2.3.3.2 that by 2033 there will be 4.2 Bn global cryptocurrency users (between 50% and 84% global adoption).

It is important to note that these estimates are contingent on blockchain technology being accepted by state authorities rather than being outright banned. The decentralised nature of blockchain technology may be an existential threat to governments, particularly in the case that cryptocurrencies cause the state to relinquish monetary sovereignty. Banning blockchain technology altogether would likely hinder Schumpeterian growth (creative destruction) within an economy, thus it is important for proper regulation of the technology to allow for technological growth without anarchy. In the Chapter 6, I further discuss these results to outline a blockchain adoption timeline and discuss crypto-economic regulatory policy.

5.2 Limitations of the Model

In this section I discuss criticisms and limitations of the model to explain the extent to which the assumptions made in my simulation might adversely affect the accuracy of the results.

5.2.1 Network Structure Limitations

There is plenty of literature demonstrating the existence of small-world network structures within a variety of industries. Verspagen and Duysters (2004) show the existence within the chemicals and electronics industries in the 1980/90s, Gay and Dousset (2015) showed this within the biotechnology industry, and Uzzi and Spiro (2005) within the Musical broadway industry. However, Steen et al. (2010) critique the use of small-world networks in innovation studies, supported by evidence from Stuart and Sörenson (2008) suggesting that network research often assumes the exogeneity of network positions. This means that organisational research on network structures ignore the fact that agents choose their links consciously and purposely rather than through the element of randomness. I attempt to treat endogeneity through the assignments of agent types based upon the degree-centrality of nodes in the network, supported by Sabzian et al's (2020) postulation that early adopters are often those who possess higher social status (as mentioned in Section 3.2.2).

A tacit assumption in the model has been that the network is an undirected network, meaning that all connections between nodes are symmetric. However, this assumption may not capture important features of social networks such as relationship asymmetry. For instance, Twitter is an example of a directed social media platform where "following" someone is a one-way relationship. This means that the model ignores the possibility for this type of asymmetric influence that might inhibit technological diffusion since some nodes may be unreachable with no incoming links. The undirected network assumption simplifies the model and allows me to make a ceteris paribus analysis of technological diffusion pre- and post-internet.

5.2.2 Utility Function Limitations

The utility function is a simplification of the cost-benefit analysis an agent must make to decide to adopt a technology. It assumes that the agent's decision to adopt is purely a function of their personality and the influence of their peers, this ignores external factors of influence such as political lobbying, advertisement as well as technological growth such as improved scalability of blockchain technology. Furthermore, it does not take the aforementioned Metcalfe's law (see Section 2.3.1) into account, meaning that an individual agent’s payoff is not determined by the number of adopters in the ecosystem and instead the utility function is heavily socially based. As discussed in Section 4.2.2, this might lead to omitted variable bias, upwardly biasing the estimation of the scaling constant $\boldsymbol{a}$, which would increase social network effects and reduce the estimated timeframes.

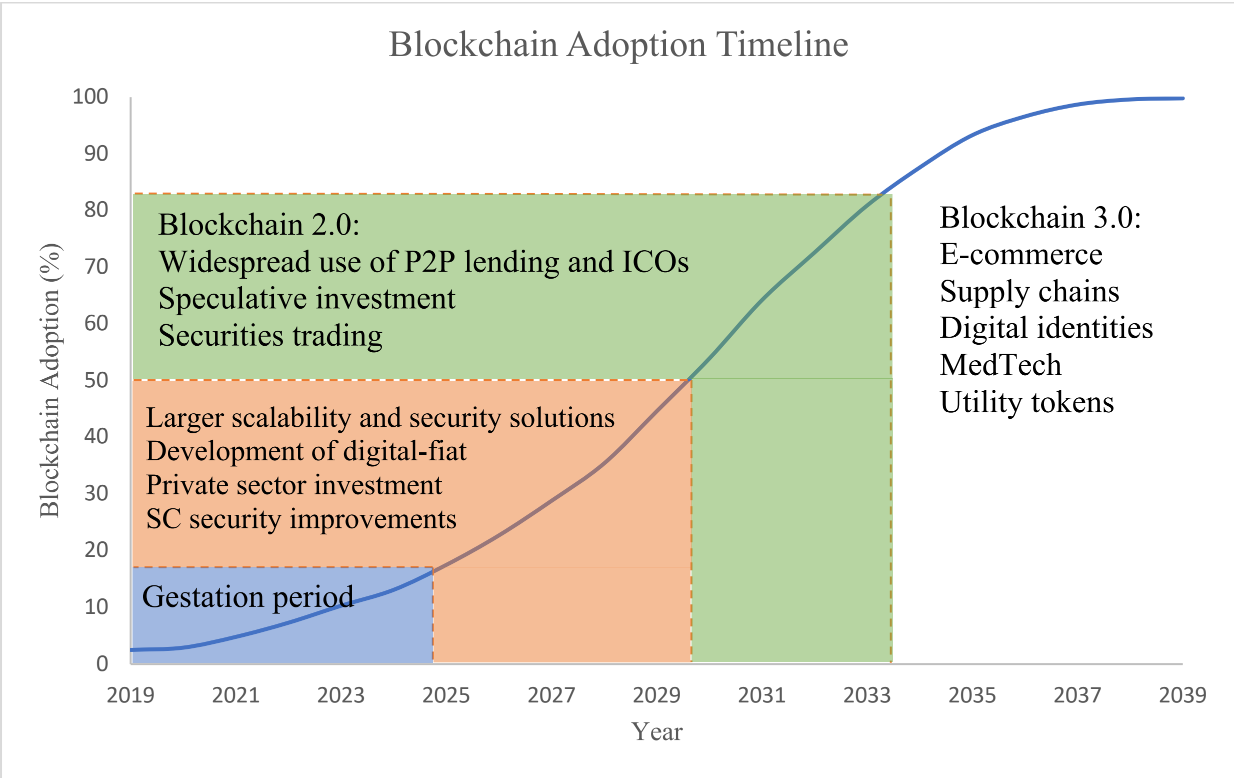
Due to the utility function being a positive and increasing function, the model does not allow agents to adopt the technology then subsequently abandon it. This leads to the result where the simulation ends in either failed or successful diffusion, whereas in practice there is also the scenario of complete abandonment of a technology where adoption rates fall to zero. This might lead to the result for the probability of a successful diffusion to be overestimated and estimated times to be an underestimated since the model does not account for technological abandonment. This would be in the scenario where agents who would actually prefer to abandon the technology create network benefits that propel the simulation to further diffusion. Given more time, I would have liked to have made improvements to the model's utility function to improve the accuracy of my estimated timeframes.

Lastly, the nature of the simulation leads to the discretisation of time since I model the population as an evolving network, with each iteration representing the passage of one year. Rather, the passage of time and adoption of technology behaves in a more continuous manner, whereas my model rounds time to the nearest year. This does not account for agents who are willing to adopt the technology mid-way-through the year, who instead must wait for the end of the year to do so, this may have the effect of slowing down the rate of diffusion. This might upwardly bias the estimate for ***a*** since it must increase to account for the slower diffusion time of a discrete time model.

Chapter 6 – Blockchain Adoption Timeline and Regulation

In this section I outline a timeline for blockchain adoption according to the results of the model, shown in the adoption curve in Figure 6.1. I discuss the technological progression of blockchain during this timeframe through a comparison with internet adoption, explaining how financial markets will likely evolve during each period. Additionally, I comment on regulatory policy that can provide stability to the token economy through regulation of new DeFi paradigms.

Figure 6.1 Blockchain Adoption Curve



6.1 2019-2025

From now until 2025 the model predicts cryptocurrency adoption rates to steadily increase, this is a gestation period where both innovators and early adopters begin to use cryptocurrency as a means of payment. This marks the beginning of the Blockchain 1.0 paradigm that innovates on real-time payments and exchange of value.

6.2 2025-2030

By 2025, the model predicts cryptocurrency to have reached 16% adoption in the UK, and to start to move away from simply being used as a novelty. The UK government may begin to embrace digital currency as the successor of fiat to maintain monetary sovereignty before mass adoption of cryptocurrency. Since borderless cryptocurrency transactions can allow the unregulated flow of capital across borders, countries may be forced to adopt free-capital mobility. The Mundell-Flemming Trilemma states that out of: free capital mobility, exchange-rate management and monetary autonomy, only two out of the three can be maintained at a single time (The Economist, 2016). Using a digital-fiat currency (DFC), capital mobility can be regulated by the state to maintain monetary sovereignty. Furthermore, DFC can meet the three functions outlined by what Söderberg describes as the "functionalism" theory of money. Acting as a medium of exchange, a unit of account and a store of value (Söderberg, 2018) (Smithin, 2002). A DFC allows for a guarantour of value, central regulation, monetary policy sovreignty, while also benefiting from blockchain value propositions such as traceability. Thus, a DFC looks to be the next evolution of money, with China having developed an off-chain digital yuan, and the European Central Bank and Bank of England exploring the possibility of issuing digital-fiat (Philipp Hacker, 2019).

The innovations of Web 2.0 arrived as early adopters began to adopt the internet. This fact and the results of the model suggest that Blockchain 2.0 paradigms will be developed during this timeframe. However, I theorise that blockchain innovation will likely be impeded by regulation to ensure sufficient security and scalability is in place before large transactional volumes can take place on-chain. This is to prevent hacks such as the 2016 DAO hack where around $47 million worth of Ether was siphoned using a smart contract vulnerability from the decentralised venture capital fund (Philipp Hacker, 2019). This form of regulation may come about through more stringent smart contract auditing standards. Furthermore, blockchain scalability solutions will need to improve over this time, to allow blockchain business models to scale to hundreds of millions of users.

The private sector may begin to invest heavily into private blockchain solutions in preparation for Blockchain 2.0. Particularly, investment banks will further embrace blockchain technology to reduce transaction fees in cross-border payments. Blockchain's properties of point-to-point exchange, low transaction fees and borderless transactions make it a suitable vehicle for remittance payments. Bitcoin is restricted to 7 transactions per second, making it a poor choice for remittances, which is why companies such as JPMorgan and Ripple are developing federated/private blockchains to allow for faster, regulated and cheaper cross-border transactions.

Outside of large financial institutions, incumbents from the FinTech industry will further develop novel use-cases for blockchain technology to disrupt financial markets. Particularly, retail banking will likely be disrupted by firms such as Revolut and PayPal who are adopting cryptocurrency as a method of payment which might propel cryptocurrency to mainstream adoption by making the technology easier for anyone to use.

6.3 2030-2034

By 2030, the model predicts cryptocurrency adoption to have reached 50% adoption with the late majority to begin to adopt tokenised forms of currency and assets. Similarly to how Web 2.0 technologies followed Web 1.0, the Blockchain 2.0 wave will likely occur in this time period to provide a robust means of exchanging complex financial products.

Moving securities to the blockchain can reduce the burden on clearinghouses which act as transactional nodes for cleared trades and store information about cleared transactions. This is because they can automate this process more easily due to these transactions being stored automatically to the ledger (Kiayias, 2019). Ultimately, this would reduce transaction fees along with intermediary rents. Clearing and settling times would decrease from around 3 days in the US and 2 days in Europe to almost instantaneous (Philipp Hacker, 2019), creating a more autonomous financial system. Furthermore, smart contracts can automate the coupon and dividend payments of securities which can improve investor confidence by programmatically guaranteeing cash flow. Sophisticated financial products such as mortgages, insurance and derivatives would also be moved to fully or pseudo-autonomous smart contract platforms. These digital exchanges and trading platforms should be subject to anti-money laundering and counter-terrorist laws to prevent under-ground and illicit transactions (Sarah Jane Hughes, 2015).

Peer-to-peer lending will be accelerated by the Blockchain 2.0 paradigm, becoming more ubiquitous, improving the allocation of liquidity in the economy by solving liquidity mismatches without the need of intermediaries. These platforms can be regulated through liquidation regulations to prevent undercollateralised loans, similarly to how capital requirements regulations work (see Robert Leshner (2019) for further detail on liquidations).

Informal financing through Initial Coin Offerings (ICOs) will become more commonly used as an alternative to Initial Public Offerings (IPOs) offered by investment banking services. This provides a method for companies such as an SME (small and medium-sized enterprise) to raise capital by issuing tokens in exchange for other cryptocurrencies or fiat currency, with fewer frictions caused by bureaucracy. To prevent a repeat of 2017, where over half of ICOs failed (Christian Catalini, 2019), ICOs should be subject to tighter regulation. This can be either through deanonymising fundraisers, or through more stringent vetting processes. Furthermore, a framework for crypto-token classification can prevent fraudulent tokens from being issued. Many tokens have similar use-cases to both currencies as well as stocks and securities; this means that they can be more versatile than traditional financial products. However, this leads to a difficulty in categorisation. The US have attempted to subject cryptocurrencies to existing legal frameworks (Xie, 2019). For example, currency tokens designed for payments fall under currency and payments services regulation and tokens designed to provide future cash flow fall under securities laws (Philipp Hacker, 2019). A problem that needs to be resolved is the fact that some tokens have functionalities that don't exist within traditional financial markets, which means that they fall into unknown legal territory. A developed token classification framework can prevent the public from fraudulent ICOs due to more stringent regulation to verify that tokens function as securities, while also allowing SMEs to avoid the due diligence of traditional financing. This way Schumpeterian growth is not hindered, while investor confidence is promoted.

It is highly possible that during this timeframe as Blockchain 2.0 technologies develop, there will be a large amount of speculative investment into blockchain ventures. This might mimic the dot-com bubble that was caused by the adoption of Web 2.0 technologies, causing cryptocurrency price bubbles, similarly to the 2017/18 crash in the price of Bitcoin.

6.4 2034 Onwards

From 2034 onwards, the model predicts mass adoption of cryptocurrency in the UK (>84% adoption). Cryptocurrency payments will be as ubiquitous as credit/debit card services (such as Visa and Mastercard) are currently in 2021, either through providing an alternative or completely replacing the system altogether. Dapps will likely be the vehicle for financial market disruption, with almost any asset being able to be digitised and traded using a dapp (Philipp Hacker, 2019). This affects the way we trade, from e-commerce to the exchange of assets. OpenBazaar is an example of a fully decentralised marketplace with no transaction fees, attracting both buyers and sellers in online retail.

The decentralised finance sector will continue to grow, however, blockchain use-cases outside of financial markets will begin to reach widespread use. Similarly to the late development of Web 3.0 technologies, the Blockchain 3.0 wave will occur, bringing innovation in many other industries, for example, IBM's supply chain blockchain that increases transparency, allowing people to know exactly where their groceries are coming from, who is producing them and allowing them to track their steps along the supply chain

(IBM, n.d.). This might be particularly valuable in industries such as the tobacco industry that requires heavy regulation and quality control. Blockchain based digital identities would benefit from inalterability, allowing the 1.1 Bn people globally without physical forms of identification to begin to legally own property, open bank accounts and find employment (Consensys, 2019). Similarly, medical records could benefit from blockchain technology, providing a patient's unaltered medical history, helping to standardise healthcare practices and lowering administration costs (André Henrique Mayer, 2019). Lastly, utility tokens are tokens that can provide access to a service or platform (Philipp Hacker, 2019). We can expect them to revolutionise subscription services by using smart contracts to prevent spoofing and piracy within online entertainment industries.

Chapter 7 – Concluding Remarks

In this paper, I have outlined how blockchain can create a new infrastructure for decentralised financial markets, allowing for peer-to-peer value exchange. Through cutting out financial intermediaries, the business models in traditional finance are heavily disrupted, paving way for decentralised alternatives in commerce, trading, lending, fundraising and payments. It is important to note that blockchain technology is in its infancy, requiring major solutions to privacy, security and scalability issues to provide the robustness required to support large transactional volumes.

I have used a model that incorporates Rogers' Diffusion of Innovation Theory with Watts Strogatz' small-world networks to model the dynamical process of technological adoption. Through testing my model empirically, I have found input parameters that allow me to precisely model internet adoption in the UK. Subsequently, I have adjusted these parameters to model the adoption of blockchain technology to further the studies on modelling the diffusion of innovations using small-world network structures. In doing so, I approximate that blockchain technology will likely reach mass adoption (84% adoption) by around 2034 in the UK, bringing with it radical changes in financial market structure. This timeline allows regulators and enterprises to prepare for the adoption of decentralised business models and new forms of exchanging value.

Although there are limitations to the results of my model, since they are contingent on multiple factors such as the rate of technological development and state regulation, my results aim to provide academic intuition behind blockchain's adoption timeline. Through outlining a clear timeline for blockchain adoption, I have examined how and when regulators must respond to decentralised business models without relinquishing policy-making power to anarchy. I recommend a digital-fiat system as a response to the growing use of cryptocurrencies as the next form of money. I have also discussed applications of blockchain technology outside of financial markets, with the potential to revolutionise supply chain, healthcare and entertainment industries.

Lastly, there are topics I have researched that lie outside of the scope of this dissertation since they require context in a variety of different fields. I would like to propose these topics as further areas of research that can follow from my work.

1. Firstly, within economics literature, more work can be done to develop a framework for digital-fiat currency. While a digital-fiat regime may provide solutions to existing problems with fiat currency, in practice there are likely many complications with its implementation. For example, the integration of digital-fiat into the existing economy may cause bank runs due to consumers withdrawing their funds to exchange for digital-fiat. Another issue is the logistics behind foreign exchange trading between different digital-fiat currencies that may lie on and off the blockchain.
2. Secondly, there is an interesting intersection between the use of smart contracts and law that can be developed in legal literature. Since code cannot incorporate the nuances of the judiciary system, smart contracts may be subject to legal regulation to remove the blurred lines between code and law.
3. Lastly, I believe that the debate between centralisation and decentralisation can enrich both political and philosophical literature. I have suggested the implementation of government issued digital-fiat, however, such a system can allow the state to infringe on the public's transactional privacy, or to prevent a targeted person from making transactions altogether. While there is economic rationale for peer-to-peer exchange, blockchain creates new institutional frameworks that has widespread socio-economic and political consequences that should be addressed before global embracement.

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Appendix

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Table 1 UK Internet adoption statistics (Source : (The World Bank, 2017))

United Kingdom	GBR	1990	0.087355319	**United Kingdom**	GBR	2004	65.61
United Kingdom	GBR	1991	0.174230922	**United Kingdom**	GBR	2005	70
United Kingdom	GBR	1992	0.260615159	**United Kingdom**	GBR	2006	68.82
United Kingdom	GBR	1993	0.519762001	**United Kingdom**	GBR	2007	75.09
United Kingdom	GBR	1994	1.036609166	**United Kingdom**	GBR	2008	78.39
United Kingdom	GBR	1995	1.895168284	**United Kingdom**	GBR	2009	83.56
United Kingdom	GBR	1996	4.123650336	**United Kingdom**	GBR	2010	85
United Kingdom	GBR	1997	7.385398957	**United Kingdom**	GBR	2011	85.37999855
United Kingdom	GBR	1998	13.6699831	**United Kingdom**	GBR	2012	87.47999842
United Kingdom	GBR	1999	21.29363827	**United Kingdom**	GBR	2013	89.8441
United Kingdom	GBR	2000	26.82175435	**United Kingdom**	GBR	2014	91.61
United Kingdom	GBR	2001	33.48109487	**United Kingdom**	GBR	2015	92.0003
United Kingdom	GBR	2002	56.48	**United Kingdom**	GBR	2016	94.77580063
United Kingdom	GBR	2003	64.82				

Table 2 Model results

Milestone	Lower bound (years)	Upper bound (years)	Median (years)
16% adoption	*4.89*	*6.93*	*5.73*
50% adoption	*9.33*	*12.51*	*10.56*
84% adoption	*12.79*	*16.10*	*14.34*
	Lower bound (%)	**Upper bound (%)**	**Median (%)**
Proportion of failed distributions	*0*	*1.68*	*0.95*

Table 3 Effect of changing β on time to reach a steady adoption state

Steady adoption state							
β	**Years**	**β**	**Years**	**β**	**Years**	**β**	**Years**
0	89.29	0.25	26.9	0.5	20.25	0.75	20.76
0.01	77.74	0.26	25.76	0.51	20.56	0.76	20.9
0.02	67.28	0.27	25.73	0.52	20.19	0.77	20.65
0.03	63.45	0.28	25.32	0.53	20.37	0.78	21.05
0.04	59.96	0.29	24.91	0.54	20.17	0.79	21.41
0.05	54.90	0.3	24.81	0.55	20.55	0.8	21.37
0.06	50.84	0.31	23.39	0.56	20.99	0.81	21.23
0.07	46.89	0.32	22.96	0.57	20.45	0.82	20.98
0.08	46.16	0.33	22.81	0.58	20.38	0.83	21.59
0.09	43.17	0.34	22.21	0.59	20.17	0.84	20.71
0.1	41.33	0.35	22.08	0.6	19.89	0.85	21.47
0.11	39.36	0.36	22.33	0.61	20.94	0.86	21.03
0.12	38.51	0.37	22.2	0.62	20.78	0.87	21.41
0.13	37.68	0.38	21.92	0.63	20.42	0.88	22.11
0.14	35.97	0.39	21.56	0.64	20.05	0.89	21.61
0.15	35.24	0.4	21.98	0.65	20.28	0.9	21.65
0.16	33.67	0.41	21.54	0.66	20.77	0.91	21.59
0.17	33.73	0.42	21.49	0.67	21.06	0.92	21.86
0.18	31.80	0.43	20.93	0.68	20.23	0.93	21.96
0.19	30.92	0.44	20.66	0.69	20.72	0.94	21.98
0.2	30.13	0.45	21.07	0.7	20.8	0.95	21.48
0.21	29.81	0.46	20.12	0.71	20.99	0.96	21.47
0.22	28.62	0.47	20.43	0.72	20.71	0.97	22.14
0.23	27.10	0.48	20.69	0.73	20.71	0.98	21.86
0.24	27.43	0.49	20.32	0.74	20.71	0.99	22.3

Table 4 Effect of changing β on proportion of failed diffusions

Proportion of failed distributions							
β	**π**	**β**	**π**	**β**	**π**	**β**	**π**
0	0.03589801	0.25	0.01616833	0.5	0.00969467	0.75	0.00722784
0.01	0.02886964	0.26	0.01648595	0.51	0.01058434	0.76	0.00825801
0.02	0.02421953	0.27	0.01578655	0.52	0.01039593	0.77	0.00864457
0.03	0.02666518	0.28	0.01682719	0.53	0.00991754	0.78	0.00959607
0.04	0.02628648	0.29	0.01372308	0.54	0.00960036	0.79	0.00808506
0.05	0.02573489	0.3	0.01291041	0.55	0.00953966	0.8	0.00822679
0.06	0.02436593	0.31	0.01400778	0.56	0.00885347	0.81	0.00833982
0.07	0.02186702	0.32	0.01289892	0.57	0.01021201	0.82	0.00634461
0.08	0.0260561	0.33	0.0147305	0.58	0.01114703	0.83	0.00912734
0.09	0.02294862	0.34	0.01188904	0.59	0.01068566	0.84	0.00721021
0.1	0.0210914	0.35	0.01283754	0.6	0.00904977	0.85	0.01034023
0.11	0.02251951	0.36	0.01203611	0.61	0.00895127	0.86	0.00825709
0.12	0.02433063	0.37	0.01009317	0.62	0.00844163	0.87	0.00877096
0.13	0.02085424	0.38	0.01160844	0.63	0.00822222	0.88	0.00699456
0.14	0.02056927	0.39	0.01142287	0.64	0.00940994	0.89	0.00964309
0.15	0.02069958	0.4	0.01186647	0.65	0.006765	0.9	0.00814278
0.16	0.01961865	0.41	0.01087801	0.66	0.00932815	0.91	0.00890403
0.17	0.01962752	0.42	0.01193397	0.67	0.00866474	0.92	0.00797961
0.18	0.01919857	0.43	0.01377013	0.68	0.00919566	0.93	0.00844632
0.19	0.02090787	0.44	0.01045839	0.69	0.00899001	0.94	0.00841919
0.2	0.01914515	0.45	0.01033448	0.7	0.00777432	0.95	0.00743453
0.21	0.01877986	0.46	0.01102204	0.71	0.009101	0.96	0.00777001
0.22	0.01768632	0.47	0.00951222	0.72	0.00914464	0.97	0.00758252
0.23	0.01768738	0.48	0.01213403	0.73	0.0074519	0.98	0.00757238
0.24	0.01837329	0.49	0.01126352	0.74	0.0096613	0.99	0.00820399

Table 5 Early adopter simulation

Early adopters							
β	Σε	β	Σε	β	Σε	β	Σε
0	8.56	0.25	5.34	0.5	5.38	0.75	5.84
0.01	7.25	0.26	5.16	0.51	5.34	0.76	6.17
0.02	7.23	0.27	5.17	0.52	5.24	0.77	6.08
0.03	6.97	0.28	5.22	0.53	5.65	0.78	6.14
0.04	6.69	0.29	5.37	0.54	5.46	0.79	6.03
0.05	6.53	0.3	5.11	0.55	5.62	0.8	6.09
0.06	6.74	0.31	5.2	0.56	5.43	0.81	6.26
0.07	6.47	0.32	5.21	0.57	5.5	0.82	6.38
0.08	6.5	0.33	5.16	0.58	5.46	0.83	6.05
0.09	6.34	0.34	5.08	0.59	5.6	0.84	6.24
0.1	6.5	0.35	5.06	0.6	5.52	0.85	6.28
0.11	6.38	0.36	5.06	0.61	6	0.86	6.17
0.12	6.06	0.37	5.1	0.62	5.53	0.87	6.18
0.13	6.11	0.38	5.07	0.63	5.75	0.88	6.62
0.14	6.02	0.39	5.17	0.64	5.77	0.89	6.52
0.15	5.85	0.4	5.15	0.65	5.8	0.9	6.25
0.16	5.81	0.41	5.18	0.66	5.91	0.91	6.76
0.17	5.89	0.42	4.97	0.67	5.74	0.92	6.12
0.18	5.84	0.43	5.39	0.68	6.22	0.93	6.44
0.19	5.81	0.44	5.22	0.69	6.37	0.94	6.74
0.2	5.58	0.45	5.25	0.7	6.1	0.95	6.93
0.21	5.39	0.46	4.89	0.71	6.03	0.96	6.58
0.22	5.75	0.47	5.42	0.72	5.81	0.97	6.27
0.23	5.36	0.48	5.27	0.73	5.71	0.98	6.21
0.24	5.3	0.49	5.38	0.74	6.32	0.99	6.7

Table 6 Early majority simulation

Early majority							
β	Σε	β	Σε	β	Σε	β	Σε
0	31.24	0.25	10.73	0.5	10.17	0.75	10.89
0.01	22.96	0.26	10.46	0.51	9.98	0.76	11.16
0.02	21.24	0.27	10.4	0.52	9.95	0.77	11.21
0.03	19.63	0.28	10.46	0.53	10.44	0.78	11.19
0.04	17.97	0.29	10.54	0.54	10.25	0.79	11.15
0.05	17.18	0.3	10.16	0.55	10.31	0.8	11.22
0.06	17.11	0.31	10.23	0.56	10.08	0.81	11.38
0.07	15.86	0.32	10.19	0.57	10.1	0.82	11.6
0.08	15.72	0.33	9.96	0.58	10.21	0.83	11
0.09	15.15	0.34	9.94	0.59	10.42	0.84	11.52
0.1	14.98	0.35	9.78	0.6	10.17	0.85	11.66
0.11	14.56	0.36	9.86	0.61	10.94	0.86	11.44
0.12	13.87	0.37	9.97	0.62	10.2	0.87	11.46
0.13	13.64	0.38	9.79	0.63	10.59	0.88	11.91
0.14	13.42	0.39	9.92	0.64	10.57	0.89	11.94
0.15	12.96	0.4	9.84	0.65	10.7	0.9	11.57
0.16	12.67	0.41	9.78	0.66	10.76	0.91	12.36
0.17	12.61	0.42	9.5	0.67	10.74	0.92	11.32
0.18	12.31	0.43	10.2	0.68	11.34	0.93	11.89
0.19	12.09	0.44	9.85	0.69	11.53	0.94	12.19
0.2	11.69	0.45	9.99	0.7	11.18	0.95	12.51
0.21	11.44	0.46	9.33	0.71	11.01	0.96	12.03
0.22	11.7	0.47	10.05	0.72	10.85	0.97	11.67
0.23	10.93	0.48	9.89	0.73	10.53	0.98	11.6
0.24	10.93	0.49	9.95	0.74	11.54	0.99	12.28

Table 7 Late majority simulation

Late majority							
β	Σε	β	Σε	β	Σ	β	Σε
0	77.55	0.25	15.8	0.5	13.74	0.75	14.31
0.01	59.89	0.26	15.34	0.51	13.51	0.76	14.65
0.02	47.77	0.27	15.12	0.52	13.47	0.77	14.64
0.03	40.86	0.28	15.06	0.53	14.03	0.78	14.61
0.04	35.67	0.29	15.2	0.54	13.77	0.79	14.67
0.05	32.25	0.3	14.65	0.55	13.9	0.8	14.65
0.06	31.17	0.31	14.67	0.56	13.63	0.81	14.86
0.07	28.35	0.32	14.52	0.57	13.64	0.82	15.04
0.08	27.25	0.33	14.18	0.58	13.7	0.83	14.4
0.09	25.99	0.34	14.1	0.59	13.91	0.84	15.04
0.1	25.32	0.35	13.82	0.6	13.66	0.85	15.15
0.11	24.22	0.36	13.88	0.61	14.36	0.86	14.99
0.12	22.96	0.37	13.97	0.62	13.67	0.87	14.91
0.13	21.98	0.38	13.71	0.63	14.15	0.88	15.41
0.14	21.38	0.39	13.86	0.64	14.03	0.89	15.48
0.15	20.71	0.4	13.68	0.65	14.17	0.9	15.04
0.16	19.93	0.41	13.6	0.66	14.23	0.91	15.94
0.17	19.63	0.42	13.17	0.67	14.26	0.92	14.79
0.18	18.98	0.43	13.96	0.68	14.81	0.93	15.34
0.19	18.38	0.44	13.55	0.69	15.11	0.94	15.75
0.2	17.78	0.45	13.62	0.7	14.66	0.95	16.1
0.21	17.36	0.46	12.79	0.71	14.51	0.96	15.65
0.22	17.39	0.47	13.71	0.72	14.27	0.97	15.24
0.23	16.16	0.48	13.53	0.73	13.96	0.98	15.14
0.24	16.04	0.49	13.52	0.74	15.04	0.99	15.82

Table 8 Systematic parameter adjustment effect on sum of squared errors

β, a	1.7	1.71	1.72	1.73	1.74	1.75	1.76	1.77	1.78	1.79	1.8	1.81	1.82	1.83	1.84	1.85	1.86	1.87	1.88	1.89
0.2	155.2	147.7	158.5	110.3	105.7	133.5	89.2	86.4	108.0	84.8	98.1	73.1	72.5	64.9	64.7	74.7	64.2	48.5	63.9	53.7
0.21	128.6	134.2	119.2	129.2	111.6	104.4	103.8	106.4	102.4	74.8	73.6	72.3	64.7	64.8	57.4	58.7	53.4	51.8	43.8	35.0
0.22	149.3	120.1	106.9	109.0	97.8	93.2	83.7	83.5	82.2	79.1	69.0	61.1	57.5	58.5	54.2	49.1	44.6	51.6	41.7	35.6
0.23	162.5	143.9	92.7	82.3	92.1	67.5	82.1	83.1	65.7	95.3	56.2	68.4	47.4	57.1	55.7	48.9	44.0	41.7	33.7	38.9
0.24	103.2	123.5	98.3	111.1	105.6	63.3	72.3	67.0	73.0	65.5	57.7	51.3	53.5	47.2	46.7	37.7	35.0	30.3	23.5	28.5
0.25	113.9	99.7	87.1	92.2	71.4	78.9	73.1	67.3	52.9	52.3	51.0	35.6	32.2	32.6	45.9	33.0	32.2	26.8	24.7	30.2
0.26	108.5	107.5	100.1	85.3	75.8	82.1	72.4	61.5	72.1	53.4	66.3	41.7	57.5	44.0	44.0	35.0	23.6	21.0	25.6	16.7
0.27	123.0	85.1	102.5	89.1	82.4	67.2	53.4	44.9	57.2	59.0	48.5	42.9	38.7	41.3	38.0	26.0	24.1	24.9	16.9	17.8
0.28	131.6	93.4	83.6	98.7	77.1	71.3	68.9	66.6	34.8	56.6	41.6	36.2	41.9	39.8	26.7	23.7	15.3	19.1	13.6	13.9
0.29	107.4	94.8	107.1	60.4	54.0	53.0	61.3	54.1	62.4	35.8	45.5	30.1	29.5	35.2	28.1	22.3	21.4	23.0	14.0	14.4
0.3	103.5	75.9	91.9	51.5	56.6	84.4	57.7	64.6	45.5	43.1	36.9	29.4	28.0	19.7	21.3	25.0	19.6	14.1	16.6	11.4
0.31	101.0	97.9	71.9	80.7	73.3	63.0	58.9	42.5	49.9	27.8	39.9	39.1	31.7	21.7	23.3	23.5	12.2	19.3	8.0	12.7
0.32	97.0	108.8	70.4	73.3	69.2	60.2	59.5	48.5	39.6	31.4	57.2	32.2	29.2	24.5	16.1	26.3	12.6	12.2	12.6	10.1
0.33	127.6	94.1	75.2	88.5	75.8	40.7	80.4	54.4	44.9	32.6	33.4	25.4	25.2	15.6	16.0	16.7	14.3	11.9	8.9	13.4
0.34	138.9	112.7	60.7	86.0	86.8	80.8	49.4	50.0	51.1	40.7	46.1	37.1	18.6	27.9	15.8	21.2	15.9	6.9	6.2	8.2
0.35	109.5	133.2	92.5	54.8	59.5	67.2	82.8	45.4	46.0	46.1	19.6	27.2	20.7	15.3	19.0	7.3	9.3	14.4	10.2	6.5
0.36	109.6	82.5	102.5	73.2	75.8	59.8	68.0	41.7	37.8	45.3	32.7	33.0	24.4	16.2	20.7	10.4	6.7	16.5	5.1	7.2
0.37	123.9	76.8	71.9	70.4	63.5	81.9	53.0	36.0	53.9	42.7	35.0	21.6	27.3	20.0	10.3	12.1	19.1	7.2	8.4	4.1
0.38	85.7	154.2	82.1	77.0	74.6	69.7	81.2	50.6	38.6	32.1	25.7	33.2	24.8	12.3	17.2	8.6	7.7	14.2	9.7	5.8
0.39	88.4	119.6	79.5	54.6	93.1	59.2	77.7	44.2	54.6	34.5	28.2	24.7	21.0	19.2	19.1	17.4	5.1	6.5	3.7	10.5
0.4	167.9	93.8	76.8	68.4	77.7	61.1	50.7	41.8	50.4	32.9	28.1	23.1	26.7	17.0	16.9	15.9	13.4	9.8	7.3	3.9
0.41	106.9	137.3	101.3	66.8	71.2	58.1	78.6	50.8	59.2	52.4	28.1	33.5	30.3	31.6	11.2	18.5	13.3	5.6	6.5	5.9
0.42	136.1	91.3	87.9	71.2	71.0	57.5	55.6	48.0	47.6	34.9	23.6	31.5	34.1	22.5	14.5	5.8	3.1	6.1	6.9	5.8
0.43	96.8	115.4	75.4	64.7	70.6	79.2	51.0	43.9	24.9	33.5	34.8	16.9	27.4	17.3	26.4	14.2	12.3	12.5	9.6	4.4
0.44	118.9	109.3	76.6	105.7	64.6	74.5	60.8	67.1	44.1	46.2	33.4	39.3	20.4	21.6	20.6	6.7	10.1	9.2	5.2	2.5
0.45	143.7	120.7	81.5	97.3	72.3	64.2	34.2	59.9	52.7	33.9	36.6	18.1	25.6	24.1	18.8	24.3	9.0	5.3	3.9	1.9

0.46	161.9	132.9	116.4	99.9	57.6	74.1	84.1	46.9	43.5	55.1	30.5	41.3	14.1	24.8	30.7	13.0	12.5	4.8	4.3	4.3
0.47	141.2	129.6	87.0	101.3	90.2	72.5	53.6	58.3	26.8	46.9	44.2	37.3	21.4	13.5	15.7	15.0	5.5	12.1	8.8	5.2
0.48	88.7	125.8	74.3	97.9	59.6	96.0	58.1	44.7	53.1	36.6	24.1	30.0	17.1	35.9	8.5	9.2	15.6	18.3	4.8	4.8
0.49	110.8	97.6	147.8	86.5	75.8	56.2	80.9	41.9	39.2	34.5	38.7	42.4	21.6	23.4	20.8	11.2	9.7	8.6	6.4	8.7
0.5	193.7	159.5	123.1	88.4	124.3	85.0	114.2	55.4	27.6	30.5	24.8	27.1	23.4	10.7	22.9	18.9	10.6	12.1	6.6	5.8
0.51	149.4	99.5	107.1	120.8	83.2	69.5	63.5	74.9	58.3	45.1	41.3	44.6	25.5	13.5	17.9	16.1	14.3	6.5	3.7	6.6
0.52	87.7	106.3	176.6	134.5	127.0	88.1	82.1	61.4	55.5	39.4	32.7	30.8	22.6	46.1	21.7	14.0	5.6	7.7	9.8	2.6
0.53	131.4	138.1	86.5	96.3	79.2	109.9	92.8	60.8	55.7	57.5	26.4	45.7	22.1	22.6	13.5	12.9	8.7	10.9	8.6	16.2
0.54	177.2	115.8	107.7	70.4	82.6	85.0	65.2	67.9	54.3	56.4	35.6	35.0	34.2	20.0	13.8	17.1	9.4	19.8	5.1	17.2
0.55	129.4	134.6	140.0	120.8	88.8	119.3	58.0	61.8	84.6	35.9	61.4	41.0	23.8	37.2	26.3	13.4	12.8	22.6	9.9	6.9
0.56	148.4	178.9	117.7	117.4	108.2	110.9	87.2	54.5	47.4	37.1	56.0	48.7	25.2	12.9	35.7	13.4	25.3	10.7	10.9	19.8
0.57	151.1	145.8	127.3	84.3	87.3	126.5	60.9	47.6	62.6	35.7	52.1	62.2	38.1	26.9	14.8	16.3	35.5	9.0	10.6	7.5
0.58	113.7	144.7	105.3	147.6	91.0	86.6	102.3	82.8	52.9	86.2	45.5	27.1	42.8	24.9	21.2	14.8	18.2	14.6	11.9	8.8
0.59	158.6	123.5	105.0	127.4	151.9	102.2	102.1	66.5	70.9	44.0	50.1	28.3	39.1	25.4	20.8	15.3	16.6	7.9	5.8	6.3
0.6	172.9	154.3	104.3	134.1	109.5	80.8	101.9	76.6	33.2	60.2	59.6	48.0	23.3	25.5	36.5	21.2	18.2	8.1	9.2	6.7
0.61	202.5	138.3	157.0	113.0	118.2	111.4	104.9	59.5	35.1	64.9	52.3	32.6	25.1	30.5	20.3	20.0	13.6	6.9	9.8	9.6
0.62	137.7	172.7	120.1	132.3	91.8	91.7	72.1	104.9	72.4	40.8	45.8	37.5	43.4	16.9	26.4	20.0	8.5	6.4	9.8	19.7
0.63	206.2	209.9	170.9	115.4	87.6	92.8	99.2	33.0	70.6	43.5	55.9	41.5	25.5	27.8	31.3	33.5	16.0	20.8	13.8	7.0
0.64	202.5	161.3	126.7	130.5	158.5	88.8	105.3	59.6	62.5	67.8	39.3	38.9	35.5	23.6	19.9	19.8	28.1	16.0	12.1	7.0
0.65	225.8	132.3	140.3	181.1	76.5	94.9	77.6	90.2	52.6	63.3	64.9	66.3	47.8	40.8	24.7	29.2	16.3	15.6	13.5	6.5
0.66	172.0	179.2	162.1	138.5	135.4	100.6	78.3	86.7	98.3	70.8	40.3	54.4	54.9	39.2	73.8	17.3	24.3	23.6	8.7	15.4
0.67	170.4	112.7	158.5	165.1	102.9	130.2	85.4	81.1	62.4	51.3	55.8	66.4	47.4	19.5	39.3	23.3	16.9	10.9	11.4	12.9
0.68	212.6	174.2	145.5	123.4	78.3	85.2	105.6	49.1	63.5	80.1	48.1	46.8	74.7	50.4	29.1	16.6	15.3	19.9	10.5	14.5
0.69	214.2	165.8	139.1	118.5	127.4	95.8	136.9	74.9	52.7	50.6	104.6	43.6	47.9	60.2	25.6	40.5	22.0	8.6	15.6	17.8
0.7	205.2	154.2	172.0	141.9	87.5	76.2	128.8	70.9	73.4	54.8	53.0	48.4	57.6	39.3	17.0	27.5	36.1	11.0	23.9	19.3
0.71	218.9	184.7	108.4	150.7	126.1	151.6	108.9	133.9	65.1	44.0	45.1	67.2	58.8	42.7	26.3	30.9	27.5	12.4	21.5	28.6
0.72	194.2	114.5	161.0	149.7	132.9	130.7	85.2	99.6	60.7	67.1	75.1	56.2	33.4	31.1	34.7	36.5	23.4	32.6	20.2	15.8
0.73	190.9	184.6	177.2	153.3	107.6	122.6	87.1	70.3	75.4	63.1	46.6	68.0	77.0	26.2	60.9	33.9	36.4	21.5	19.9	22.4

0.74	250.6	197.6	201.3	156.6	102.4	114.4	130.8	77.8	101.9	98.3	103.5	74.6	42.1	38.8	33.7	32.9	34.0	21.2	30.6	23.3
0.75	191.1	171.7	130.0	125.9	107.4	139.1	108.2	94.9	93.0	103.8	70.5	76.5	35.6	58.5	38.8	40.0	20.9	32.9	16.8	21.9
0.76	286.0	289.1	152.4	113.0	126.2	91.6	73.9	98.5	69.2	63.7	62.9	56.8	66.3	27.3	38.1	45.8	28.8	38.4	16.0	31.2
0.77	214.2	209.6	213.6	221.8	203.6	130.2	90.7	126.3	91.1	100.2	59.8	58.1	73.3	45.0	43.1	24.5	34.7	30.3	37.0	16.9
0.78	219.4	193.0	116.0	191.6	130.9	149.0	134.3	80.3	79.3	60.6	81.4	41.5	64.6	42.6	47.5	57.6	24.1	16.1	16.2	16.7
0.79	267.8	241.1	237.5	177.5	145.0	118.6	112.2	82.7	106.4	104.1	68.6	46.8	41.2	55.4	37.0	64.6	29.0	32.1	25.6	13.5
0.8	311.8	180.9	186.3	138.8	210.8	131.1	128.3	88.9	86.9	89.4	71.8	54.1	76.6	59.2	50.3	47.9	24.0	29.8	35.9	25.8
0.81	239.1	168.2	168.8	197.6	174.3	178.2	123.4	165.0	134.2	98.1	84.4	108.3	43.2	45.7	74.7	48.2	42.6	28.1	35.1	23.1
0.82	306.1	251.7	187.9	234.2	178.6	123.2	131.2	145.9	83.6	111.8	75.8	41.5	63.4	42.4	46.1	18.6	34.4	23.3	45.5	23.4
0.83	215.6	272.1	212.1	189.7	152.7	167.6	154.4	145.4	61.9	84.7	63.5	58.6	71.9	55.5	54.5	33.6	41.1	46.7	30.7	31.8
0.84	318.8	236.9	187.5	164.4	172.0	150.2	121.8	125.6	104.5	87.2	88.8	79.9	57.0	59.6	62.4	27.9	38.9	39.9	32.5	29.2
0.85	268.4	268.3	205.4	165.5	224.7	157.7	125.7	124.8	101.3	65.0	68.8	60.1	88.4	72.4	66.0	47.8	41.1	26.7	34.5	26.4
0.86	308.3	209.7	204.0	127.7	163.2	114.8	143.9	153.8	126.5	104.0	92.1	102.4	48.4	42.6	44.6	51.6	64.4	36.7	27.5	20.8
0.87	237.8	235.1	190.3	248.3	132.8	114.8	137.6	97.6	145.8	100.6	100.9	88.7	72.1	58.5	56.4	54.3	25.2	42.3	38.6	20.1
0.88	209.8	235.2	136.0	250.7	179.9	200.1	135.5	114.3	82.7	101.5	108.6	85.2	45.6	67.4	64.9	41.8	49.0	39.8	26.4	49.2
0.89	277.0	257.6	198.7	187.4	202.0	188.1	149.3	110.4	131.8	102.1	77.6	130.2	74.8	55.0	52.9	39.3	58.7	53.0	39.9	30.5
0.9	261.1	247.8	229.6	220.3	147.4	153.3	160.1	118.0	127.0	112.5	112.4	80.3	73.1	72.4	58.7	54.1	39.9	42.5	28.6	31.4
0.91	297.4	277.3	192.6	200.2	249.9	134.6	153.2	125.3	142.7	96.3	65.7	68.3	59.4	59.8	40.8	35.4	35.8	29.7	33.7	29.9
0.92	210.0	218.6	282.0	153.4	204.7	145.0	132.5	139.3	156.8	93.0	111.8	116.0	84.8	121.7	69.9	72.9	39.6	37.3	34.9	31.9
0.93	243.6	267.6	295.0	184.1	198.1	192.8	163.3	87.6	101.3	133.1	105.6	63.5	66.2	55.2	59.2	69.4	40.1	56.1	23.0	59.1
0.94	336.9	318.4	306.9	162.6	169.9	191.8	130.2	152.6	126.3	79.3	98.9	88.6	57.9	64.8	91.7	73.5	38.5	52.7	40.8	50.5
0.95	324.0	258.2	344.5	161.6	157.2	89.2	131.4	161.9	116.7	110.9	74.6	103.1	101.2	81.7	71.6	76.4	49.0	43.0	65.8	21.6
0.96	258.5	267.5	218.2	217.2	213.2	142.5	140.2	165.2	127.3	90.5	117.1	101.7	96.5	74.5	51.8	40.8	69.7	49.0	34.8	30.1
0.97	349.8	231.3	225.2	185.5	173.7	161.9	174.3	101.0	116.6	174.4	74.4	77.1	74.2	82.4	71.0	50.6	65.5	47.6	34.3	50.3
0.98	344.1	173.4	209.0	214.5	170.4	145.8	165.1	144.4	119.6	118.0	114.2	76.1	89.3	87.0	90.3	67.5	61.8	64.5	51.9	32.1
0.99	276.0	245.8	217.5	190.2	176.8	182.7	174.7	99.3	132.1	101.5	78.0	86.7	82.9	85.4	74.3	48.9	50.3	35.5	42.4	46.2

β, *a*	1.9	1.91	1.92	1.93	1.94	1.95	1.96	1.97	1.98	1.99	2	2.01	2.02	2.03	2.04	2.05	2.06	2.07	2.08	2.09
0.2	44.5	44.6	35.5	41.6	35.6	28.2	28.2	24.5	36.3	18.4	19.1	15.5	12.5	14.3	14.7	7.5	11.1	6.5	6.2	9.0
0.21	38.0	46.7	33.0	36.4	29.8	32.2	22.1	26.1	18.8	17.5	16.1	11.8	14.6	7.7	6.7	5.9	4.4	4.5	2.7	4.0
0.22	36.5	28.3	31.5	23.6	24.4	17.2	19.3	22.9	20.6	14.5	11.8	8.2	8.3	5.1	5.9	4.1	3.8	4.1	2.9	2.1
0.23	33.0	27.6	25.4	20.7	15.5	13.4	19.7	18.1	16.0	16.0	15.1	5.2	7.8	3.1	4.6	2.5	1.6	2.0	1.1	1.3
0.24	31.1	24.8	25.7	17.8	18.1	17.7	11.6	11.8	6.4	8.7	9.3	4.8	4.2	3.0	2.6	2.2	2.9	1.8	1.1	1.2
0.25	31.5	17.5	10.5	19.7	19.1	13.4	9.2	6.7	7.4	5.5	8.1	2.5	4.3	3.2	1.3	1.2	1.0	1.5	1.2	1.1
0.26	18.0	13.1	10.5	10.5	10.5	14.8	6.0	7.3	13.3	6.0	3.9	3.8	2.8	1.5	1.8	1.0	1.1	1.0	1.1	1.1
0.27	20.0	13.7	14.8	8.8	5.6	8.6	6.6	5.0	6.4	3.3	2.3	2.0	1.0	1.3	1.0	1.1	1.3	1.1	2.2	1.4
0.28	12.9	10.5	8.9	10.0	5.8	7.4	8.6	6.3	1.3	3.6	2.0	1.2	1.2	1.5	1.4	1.2	1.2	1.7	1.7	2.3
0.29	16.5	8.4	9.2	4.3	11.3	3.2	2.1	4.2	2.2	3.3	1.1	1.8	1.5	1.2	1.3	1.6	1.2	1.5	3.7	2.0
0.3	10.1	12.4	8.5	9.7	3.5	1.6	3.2	1.5	1.6	1.5	1.2	1.5	1.5	1.3	1.3	3.3	1.6	3.6	1.7	3.1
0.31	9.4	7.4	10.6	6.6	2.7	1.6	4.1	1.8	1.6	1.3	1.8	1.1	1.4	1.3	1.6	3.3	3.1	4.7	5.1	5.1
0.32	10.4	6.9	7.1	4.6	2.6	1.9	1.8	1.5	1.2	1.3	1.1	1.9	2.2	1.6	2.9	2.5	3.3	3.7	3.7	4.8
0.33	5.3	8.5	5.1	4.2	2.2	1.7	1.7	1.2	1.3	1.6	1.1	1.3	1.3	2.6	2.9	1.6	3.7	4.2	4.4	7.2
0.34	3.0	5.1	2.6	4.3	3.5	2.1	1.6	1.7	1.2	1.3	1.5	1.3	2.3	3.4	2.6	3.6	4.2	5.1	4.6	3.4
0.35	10.7	5.5	2.0	3.7	1.5	3.5	1.4	1.2	1.7	1.9	1.7	3.7	2.2	3.4	3.1	3.2	8.3	5.9	2.8	7.0
0.36	7.8	8.4	3.5	2.2	3.0	1.2	1.6	1.3	1.5	1.8	2.3	1.9	1.8	2.2	6.1	5.0	3.9	6.4	8.8	5.5
0.37	5.1	3.9	3.5	2.1	1.9	3.5	1.7	1.8	1.9	1.6	2.6	4.5	2.4	1.8	4.0	4.1	5.4	5.9	5.5	8.3
0.38	2.3	3.8	4.9	2.2	3.7	1.9	1.6	1.5	1.6	1.7	2.3	1.9	2.2	3.1	7.0	4.8	6.6	4.2	6.0	9.2
0.39	2.6	2.3	2.4	1.7	1.9	1.6	1.4	3.8	2.9	2.3	2.0	2.0	1.5	5.9	4.3	7.9	3.8	10.2	7.9	7.3
0.4	2.8	6.7	3.5	1.5	3.4	1.8	1.6	2.1	1.7	4.5	3.1	2.6	2.8	3.3	8.6	7.5	4.3	5.9	9.1	8.0
0.41	4.5	4.7	3.0	2.6	1.4	1.5	2.8	1.9	2.6	1.9	1.8	3.9	2.8	6.7	8.3	6.9	8.2	5.4	4.2	6.1
0.42	6.0	1.8	3.3	1.6	1.6	2.4	1.8	2.0	1.7	3.5	3.2	3.4	4.5	6.0	4.2	3.6	5.0	9.1	7.1	11.0
0.43	5.8	1.6	4.3	4.1	2.7	1.6	1.8	1.9	2.1	3.5	2.2	4.1	3.9	4.1	8.6	10.3	7.1	7.0	4.1	11.0
0.44	8.6	2.5	5.1	2.0	1.6	1.9	1.9	2.1	1.9	2.2	3.5	4.3	3.6	3.3	4.9	5.4	8.1	5.6	3.4	5.8
0.45	6.7	3.5	1.9	2.2	1.7	1.7	2.1	1.9	2.2	2.2	3.0	3.8	3.8	3.3	3.7	6.9	4.0	9.8	5.8	9.6

0.46	7.1	2.0	9.8	2.0	2.2	1.6	2.3	2.3	3.0	2.9	2.8	4.0	4.0	3.4	3.8	3.7	9.8	5.4	10.2	8.9
0.47	4.2	2.2	4.4	6.1	3.6	2.1	4.7	3.5	2.1	3.5	4.0	2.5	6.6	4.5	6.4	3.6	7.0	5.5	7.7	5.9
0.48	4.0	2.8	2.1	4.1	4.2	2.5	2.0	2.6	2.5	4.4	3.0	5.1	3.1	3.9	7.9	2.9	8.1	8.0	4.4	6.6
0.49	4.0	2.5	2.1	2.3	2.2	2.0	3.7	2.9	3.6	3.3	3.0	5.4	3.8	2.3	4.6	6.6	6.0	6.4	6.7	6.9
0.5	6.5	3.9	5.8	2.2	3.0	1.8	2.1	2.6	2.1	2.2	2.7	3.2	7.8	4.5	6.5	5.6	7.3	3.9	5.8	8.8
0.51	5.0	2.4	5.0	2.3	3.9	3.0	2.2	2.4	2.2	3.0	2.5	2.7	5.2	4.7	4.0	2.7	4.0	7.1	9.6	6.7
0.52	8.4	3.9	2.5	5.2	2.3	2.0	2.0	3.3	4.5	3.2	3.0	3.4	5.0	3.3	6.6	6.8	6.0	3.3	3.7	9.1
0.53	5.7	2.9	2.7	3.1	2.4	2.4	2.6	3.3	2.9	2.6	3.1	3.5	2.7	4.8	7.1	3.0	6.4	4.6	6.2	6.5
0.54	5.2	8.1	3.5	2.9	2.7	2.2	2.4	2.1	3.0	2.9	3.3	2.7	3.0	5.0	3.1	3.6	5.4	8.3	7.7	7.9
0.55	4.9	4.4	3.5	3.4	2.1	3.3	2.8	2.6	2.8	2.7	5.2	6.4	5.5	3.2	4.2	9.0	3.6	5.2	4.4	6.0
0.56	5.5	4.5	4.4	2.1	3.5	3.7	2.2	4.4	3.1	2.7	2.4	3.3	3.3	5.7	3.9	3.0	6.8	8.7	3.6	5.7
0.57	4.6	3.2	6.9	5.1	7.4	2.9	2.1	2.5	2.6	2.7	4.1	3.5	4.4	4.9	4.2	4.8	2.9	3.8	6.8	9.4
0.58	16.3	3.7	4.1	3.2	3.3	2.5	2.7	2.5	2.8	2.5	2.5	2.8	3.0	3.2	2.9	7.6	6.3	10.5	3.6	5.0
0.59	6.4	7.3	2.8	8.2	6.6	2.3	2.3	3.0	2.3	3.1	4.8	2.7	3.1	3.0	3.0	3.3	7.2	5.9	5.9	9.4
0.6	12.7	9.3	11.2	5.4	4.9	3.6	4.1	3.1	2.9	3.6	2.9	3.0	2.8	3.4	3.2	2.7	5.5	5.9	6.4	6.3
0.61	10.8	8.3	3.4	3.8	3.0	2.9	4.7	3.4	2.8	2.8	2.6	2.7	2.9	4.3	3.2	4.2	7.0	6.3	4.7	4.8
0.62	6.8	8.0	6.6	9.2	10.1	5.2	2.7	2.7	2.8	3.6	3.2	2.7	4.1	2.9	4.4	5.2	4.3	3.3	7.8	4.3
0.63	10.1	13.4	7.3	2.9	5.6	3.6	7.3	3.0	3.2	3.6	2.7	3.2	3.1	3.0	3.0	3.6	4.5	5.2	6.8	3.9
0.64	10.2	9.7	6.6	10.5	2.7	6.6	2.5	6.4	3.4	3.5	3.2	3.0	3.1	3.2	3.8	2.9	3.2	3.5	4.4	6.9
0.65	11.8	24.3	4.8	7.3	6.7	3.3	3.6	6.5	5.0	2.9	3.2	3.2	3.2	2.7	3.5	3.2	4.0	5.2	3.1	3.4
0.66	8.0	6.0	6.9	4.4	5.4	7.8	5.9	2.7	2.5	3.9	2.7	3.4	3.6	2.9	3.6	3.2	3.7	3.3	3.5	7.5
0.67	12.2	5.6	17.7	8.2	7.4	6.4	2.5	4.5	2.9	3.3	3.7	3.0	2.9	4.2	3.1	2.8	4.0	2.9	3.6	3.3
0.68	21.7	6.8	6.7	11.3	4.3	7.0	4.4	4.8	2.8	3.6	4.8	2.9	4.2	3.9	5.7	4.3	3.7	4.1	3.0	3.3
0.69	11.9	13.6	8.0	9.0	3.9	8.1	11.9	6.0	3.9	4.3	3.7	2.7	2.8	3.1	3.1	4.2	3.3	3.9	4.6	6.0
0.7	8.0	14.5	9.9	8.1	9.7	7.2	4.8	6.1	4.1	3.3	3.4	3.5	4.8	3.9	5.5	3.2	3.7	3.1	3.5	4.7
0.71	14.4	11.6	12.5	10.8	7.3	11.2	10.0	5.1	4.4	3.8	3.4	2.8	3.1	2.9	3.5	2.8	5.5	5.4	3.4	4.3
0.72	16.6	13.3	9.8	8.7	9.2	8.3	3.4	6.6	4.9	3.1	5.2	3.2	3.0	2.9	3.1	3.7	3.3	3.4	3.1	3.1
0.73	15.4	4.4	7.3	9.5	6.3	5.9	4.6	4.5	3.9	3.6	4.4	3.2	2.8	3.5	3.7	3.0	3.5	3.8	5.6	2.9

0.74	22.2	11.6	11.2	16.5	8.4	15.3	8.2	9.3	7.9	6.4	2.6	9.4	3.4	3.4	3.1	3.7	3.2	3.5	3.6	3.2
0.75	25.9	9.5	14.1	13.7	7.6	8.4	9.3	4.0	3.4	6.0	4.1	3.3	3.1	3.2	4.0	3.3	4.2	3.2	3.2	3.5
0.76	15.6	21.3	9.7	18.9	15.1	8.6	15.8	4.5	6.3	4.3	6.0	3.1	3.1	2.9	3.5	3.4	3.0	3.5	3.2	3.4
0.77	9.9	14.6	11.9	13.0	10.9	13.0	7.2	4.1	5.7	4.6	8.4	4.1	7.4	3.7	3.6	2.9	3.3	3.3	4.2	3.8
0.78	20.8	16.9	9.1	6.6	5.7	9.9	12.9	8.7	9.7	8.9	2.6	5.2	4.5	3.3	5.2	3.5	3.9	3.2	3.5	3.1
0.79	14.2	17.3	13.5	12.3	17.6	12.3	8.6	5.0	10.5	6.6	7.4	5.2	3.1	4.3	2.8	3.4	3.2	3.6	4.1	3.1
0.8	15.6	13.4	13.7	15.6	11.5	14.5	11.3	9.8	5.1	8.8	7.1	3.9	3.0	5.4	3.1	5.3	3.1	3.8	3.9	3.4
0.81	14.8	18.7	23.9	17.9	6.2	8.6	4.2	8.3	4.7	6.8	7.7	5.4	5.1	3.5	5.0	5.4	3.4	3.4	3.5	3.3
0.82	25.3	32.1	18.1	8.6	12.4	14.1	9.3	14.4	14.0	8.8	4.9	6.8	5.2	3.3	3.6	5.1	3.2	3.0	3.5	3.6
0.83	19.3	14.4	11.7	10.6	15.6	12.1	11.1	13.0	6.4	8.1	4.5	5.1	3.5	4.4	3.3	2.9	3.6	3.0	5.0	3.4
0.84	31.7	14.5	28.9	22.6	20.5	12.2	5.5	5.1	7.7	4.1	4.5	6.2	6.4	5.0	4.0	3.8	3.4	3.9	3.3	3.3
0.85	19.9	25.3	12.8	17.5	8.5	14.7	12.1	10.1	9.4	7.2	5.0	3.1	4.6	4.9	4.0	6.3	4.2	3.6	3.6	3.7
0.86	28.5	22.8	24.2	9.6	13.2	20.1	12.3	6.4	6.7	5.5	5.0	4.1	3.6	7.0	5.1	5.4	3.4	3.3	3.8	3.7
0.87	17.2	31.8	19.8	10.2	25.3	14.4	10.0	10.0	9.3	8.9	7.0	15.0	7.0	3.3	4.0	3.8	6.7	5.8	3.8	4.1
0.88	16.5	35.8	25.5	14.9	24.8	13.0	9.0	13.1	12.4	7.8	6.4	6.5	4.0	3.5	5.6	4.7	3.6	3.5	3.3	3.5
0.89	31.7	29.4	15.7	15.2	24.4	8.9	11.2	11.0	11.0	10.7	4.6	15.6	7.4	5.2	3.9	4.7	3.7	4.0	3.9	3.4
0.9	31.8	24.1	10.2	21.8	16.1	14.4	16.7	12.4	5.8	8.2	15.2	5.2	7.7	6.8	3.6	7.8	3.4	3.0	3.5	4.8
0.91	35.7	27.3	16.4	24.2	13.9	14.9	16.1	19.9	8.6	7.7	12.9	6.9	5.5	3.6	3.0	3.9	3.2	3.3	3.2	3.3
0.92	31.1	20.8	23.7	11.2	14.4	23.2	15.1	6.7	9.0	5.1	4.4	12.8	5.7	3.8	5.7	3.1	4.2	3.4	3.4	3.5
0.93	31.3	25.3	26.9	23.1	25.6	16.9	28.4	17.6	14.9	16.0	8.8	6.7	6.8	4.9	7.5	6.2	3.9	3.6	3.3	3.3
0.94	32.5	25.7	38.9	21.9	16.5	21.5	15.3	14.2	8.0	8.4	11.0	5.0	8.5	3.4	7.7	4.4	3.4	5.1	3.3	4.6
0.95	40.3	24.9	29.7	26.9	11.6	22.7	7.7	8.4	5.8	10.0	7.7	6.0	6.6	9.0	4.0	3.4	3.8	3.5	3.1	3.9
0.96	31.8	25.3	31.3	21.1	19.0	13.6	15.0	13.0	8.0	9.0	11.6	9.7	9.8	5.4	5.2	6.8	5.2	5.5	10.4	3.7
0.97	23.4	28.4	34.6	18.0	27.1	14.8	13.3	13.2	8.0	8.5	18.2	8.2	8.5	15.3	7.6	6.1	7.5	4.5	6.3	4.5
0.98	47.1	40.3	34.1	34.6	24.0	19.0	19.5	14.3	9.7	11.7	18.1	9.7	4.9	4.0	8.1	3.7	5.3	3.1	4.4	3.0
0.99	26.2	38.1	25.4	42.9	26.9	21.2	22.5	22.5	13.2	8.2	7.4	18.4	10.7	7.1	10.7	8.0	3.9	4.1	4.7	3.7

Mathematica Code

```
In[•]:= VecOf1[A_] := Table[1, {j, 1, Length[A]}]
        DC[A_, w_] := If[w == "in", A.VecOf1[A], VecOf1[A].A]

In[•]:= primaryOpinion[agents_] := (agentsCopy = agents; agent = 1;
          Do[If[agentsCopy[[agent]][[2]] > 0, AppendTo[agentsCopy[[agent]], True],
            AppendTo[agentsCopy[[agent]], False]];
           agent++, Length[agents]];
          Return[agentsCopy])

In[•]:= primaryLinks[agents_] := (agentsCopy = agents; agent = 1;
          Do[AppendTo[agentsCopy[[agent]], AdjacencyList[A1, agent]];
           agent++, Length[agents]];
          Return[agentsCopy])

In[•]:= assignTypes[types_, DC_] := (DCCopy = DC;
          sortedDC = Sort[DC, Greater];
          sortedTypes = Sort[types, Greater];
          list = {};
          typesPointer = 1;
          Do[randomNode = RandomChoice[Position[DCCopy, sortedDC[[typesPointer]]]][[1]];
           DCCopy[[randomNode]] = 0;
           AppendTo[list, {randomNode, sortedTypes[[typesPointer]]}];
           typesPointer++
           , Length[types]];
          Return[SortBy[N@ (list), First]])

In[•]:= countAdoptions[list_] := (ele = 1; count = 0;
          Do[If[list[[ele]][[3]] == True, count++, Nothing]; ele++, Length[list]];
          Return[count])

In[•]:= neighbouringOpinions[node_] := (
         nNodes = AdjacencyList[A1, node];
         n = 1;
         false = 0;
         true = 0;
         Do[
          If[updatedAgents[[nNodes[[ n]]]][[3]] == False, false++, true++];
          n++
          , Length[nNodes]]; Return[true / (true + false)]
        )

In[•]:= NodeColour = {Red, Green};
         evolve[N_, β_, a_] := (
           (*generate new network*)
           A1 = RandomGraph[WattsStrogatzGraphDistribution[N, β]];
           A1Adj = Normal[AdjacencyMatrix[A1]];
           (*generate types*)
           QRValues = RandomVariate[NormalDistribution[-0.5, 0.255], N];
           (*calculate degree centrality of nodes*)
           updatedAgents = primaryOpinion[assignTypes[QRValues, DC[A1Adj, "in"]]];

           evolutions = {updatedAgents};
           numberOfAdoptions = {countAdoptions[updatedAgents]};
           Time = 1;
```

```
While[True,
 (*find initial adopters*)
 agent = 1; adopted = {};
 Do[If[updatedAgents[[agent]][[3]] == True, AppendTo[adopted, agent]]
  ; agent ++, Length[updatedAgents]];
 (*find the neighbours of the adopters add to a queue DFS style*)
 adopter = 1; neighbours = {};
 Do[AppendTo[neighbours, AdjacencyList[A1, adopted[[adopter]]]];
  adopter ++, Length[adopted]];
 neighbours = DeleteDuplicates[Flatten[neighbours]];
 (*for each neighbour, check the proportion of adopted neighbours, calculate the utility function*)
 neighbour1 = 1; newAdopters = {};
 Do[neighbourOpinions = neighbouringOpinions[neighbours[[ neighbour1]]];
  utility = updatedAgents[[neighbours[[ neighbour1]]]][[2]] + a neighbourOpinions;

  d = RandomChoice[{neighbourOpinions, 1 - neighbourOpinions} -> {1, 0}];
  (*if all the conditions for adoption are met, set adopted to true*)
  If[(d == 1) && (utility > 0) && (updatedAgents[[neighbours[[ neighbour1]]]][[3]] == False),
   AppendTo[newAdopters, neighbours[[ neighbour1]]], Nothing];
  neighbour1 ++, Length[neighbours]];
 (*if no agents were adopted last period, then break the while loop*)
 If[newAdopters == {}, Break[], Nothing];

  newAdopter = 1;
  Do[updatedAgents[[newAdopters[[newAdopter]]]][[3]] = True;
   newAdopter ++, Length[newAdopters]];
  (*count number of adoptions for listplot*)
  AppendTo[numberOfAdoptions, countAdoptions[updatedAgents]];

  AppendTo[evolutions, updatedAgents];
  Time ++;

 ];

 Return[evolutions];
 Return[updatedAgents];

)
```