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Design and Development of Smart Contract System for Blockchain Based Applications



A dissertation submitted by

Asma Khatoon

to

Electrical & Electronic Engineering
School of Engineering
College of Science & Engineering
National University of Ireland, Galway

in fulfilment of the requirements for the degree of

Doctor of Philosophy

Supervisor: Prof. Peter Corcoran

Co-Supervisor: Prof. Chris Dainty

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Abstract

The work presented in this thesis describes the design and development of smart contract system for blockchain based applications. The main objective is to investigate the current state of blockchain technology and its implementations and to reveal how main principles of this disruptive technology can reshape "business as normal" activities. This work examines the Blockchain technology as a whole and addresses its potential for the development of distributed applications. Blockchain based smart contract system for different applications that demonstrate a streamlined access management system using Ethereum blockchain has been designed and implemented. Ethereum reinforces the second gen of blockchain technology by providing an open and global computing/environment platform allowing for the exchange of cryptocurrency (Ether) and the creation of self-verified smart contract applications.

Smart contracts provide a framework for the ownership of digital assets and a range of distributed applications in the blockchain region. Ethereum and smart contracts are open, decentralized and unalterable, as such, they are susceptible to vulnerabilities that arise from developers ' simple coding errors.

We have designed and implemented smart contract system for blockchain based applications across healthcare management to Facilitate Medical Ecosystems and Energy systems to increase energy efficiency by designing smart contract system for energy-saving certificates. We also identified key themes, developments and emerging areas of healthcare and energy research.

In this thesis, blockchain technology has been applied in areas such as healthcare and Energy sector. Healthcare applications are the main contribution of this thesis and the work on the Energy systems reflects as an additional contribution of this thesis. Hopefully the work presented in this thesis will give enough motivation towards developing distributed applications (DApps) using blockchain based smart contract system.

List of publications

Peer-Reviewed Journals

- **Asma Khatoon**, Piyush Verma, Jo Southernwood, Beth Massey, Peter Corcoran, "Blockchain in Energy Efficiency: Potential Applications and Benefits," *Energies* 12 (17), 3317 (2019).

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Contributions

A.K. conceived and designed the experiments, prepared the setups on Ethereum platform and ran the Blockchain experiments; P.V. and J.S. provided data on energy efficiency, contributed to the research idea and did energy efficiency market analysis; A.K. wrote the draft, and all the authors discussed the contents of the manuscript; P.C. contributed to the research idea, did supervision of the work, provided feedback on the work, corrected the draft and approved the final version; B.M. revised the content of the paper, provided feedback on the work and improved the final draft of the paper; conceptualization, A.K. and P.V.; data curation, A.K.; formal analysis, A.K.; funding acquisition, P.C.; investigation, A.K.; methodology, A.K.; project administration, P.C.; resources, P.C.; software, A.K.; supervision, P.C.; validation, A.K., P.V., J.S., B.M. and P.C.; visualization, A.K.; writing—original draft, A.K.; and writing—review and editing, P.V., J.S., B.M. and P.C.

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- **Asma Khatoon**, Peter Corcoran, "Android permission system and user privacy — A review of concept and approaches," *IEEE 7th International Conference on Consumer Electronics - Berlin (ICCE-Berlin) (2017), Berlin, Germany.*

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- Maman Ahmad Khan, **Asma Khatoon**, Edidong Bassey, Bilal Amin, Hafiz Hashim Chaudhry, " Smart Metering: A Better Way To Monitor Consumer Electricity Usage," *TechInnovation Symposium 2018, Galway, Ireland.*

Contributions

All Authors contributed equally

Conference Oral & Poster Presentations

- **Asma Khatoon**, Peter Corcoran, "Privacy concerns on Android devices," *IEEE International Conference on Consumer Electronics (ICCE) 2017, Las Vegas, NV, USA.*
- **Asma Khatoon**, Peter Corcoran, "Android permission system and user privacy — A review of concept and approaches," *IEEE 7th International Conference on Consumer Electronics - Berlin (ICCE-Berlin) (2017), Berlin, Germany.*
- Maman Ahmad Khan, **Asma Khatoon**, Edidong Bassey, Bilal Amin, Hafiz Hashim Chaudhry, " Smart Metering: A Better Way To Monitor Consumer Electricity Usage," *TechInnovation Symposium 2018, Galway, Ireland.*

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Asma Khatoun
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Acronyms & Abbreviations

DAPP	Decentralized Application
DFS	Distributed File System
POW	Proof-Of-Work
POS	Proof-Of-Stake
DPOS	Delegated Proof-of-Stake
PBFT	Practical Byzantine Fault Tolerance
EVM	Ethereum Virtual Machine
TX	Transaction
EHRS	Electronic Healthcare Records
NTPF	National Treatment Purchase Fund
HSE	Health Service Executive
OP	Outpatient
IP	Inpatient
IPDC	Inpatient Day Cases
DNS	Domain Name System
ID	Identifier
API	Application Programming Interface
ICTs	Information and Communication Technologies
IOTs	Internet of Things
EV	Electric Vehicle
ESCOs	Energy Service Companies
P2P	Peer to Peer
EPC	Energy Performance Contracting
ACEEE	American Council for Energy Efficient Economy
GoO	Guarantee of Origin
MWh	Mega-Watt hour
EEOS	Energy Efficiency Obligation Schemes
WCS	White Certificate Scheme
DSOs	Distribution System Operators

M&V	Measurement & Verification
NA	National Authority
GWh	Gigawatt hours
JS	Java Script
GETH	Go-Ethereum
SUT	System Under Test
RAM	Random Access Memory
IP	Internet Protocol
ETH-NETSTATS	Ethereum Network Status
EMMC	Embedded Multimedia Card
LPDDR	Low-Power Double Data Rate
SDRAM	Synchronous Dynamic Random Access Memory
mA	Milliampere
mV	Millivolts
SoC	System-on-Chip
VM	Virtual Machine
ECC	Elliptic-curve cryptography
RPC	Remote Procedure Calls
NIST	National Institute of Standards and Technology
ABI	Application Binary Interface
LLL	Low Level Language
IPFS	InterPlanetary File System
ENS	Ethereum Name Service
OOP	Object-oriented Programming
BTC	Bitcoin
ICOs	Initial Coin Offering
ETH	Ether
IoMT	Internet of Medical Things
XRP	Ripple
BCH	Bitcoin Cash
LTC	Litecoin
XLM	Stellar

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Declaration

Design and development of smart contract system for blockchain based applications

Supervisor: Prof. Peter Corcoran

Co-Supervisor: Prof. Chris Dainty

This thesis is presented in fulfilment of the requirements for the degree of
Doctor of Philosophy

I hereby declare that the work in this thesis is based on research carried out at the C3I Imaging Group, Electrical and Electronic Engineering, School of Engineering, National University of Ireland, Galway. It is entirely my own work, and has not been submitted to any other university or higher education institution, or for any academic award in this university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 80,000 words including appendices, bibliography, footnotes, tables and equations and has fewer than 150 figures.

Asma Khatoon
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1 Introduction

Over the past few years there has been an increasingly growing interest in the Bitcoin and distributed ledger technologies. Bitcoin is basically a blockchain technology-based cryptocurrency. Cryptocurrencies are the most common and widespread application of blockchain technologies, although there are different use cases which has been proposed in the recent times. In this thesis, we are going to investigate modern blockchain-based applications with an emphasis on metadata, smart contracts and different access rights. It is important to understand the fundamental concept of the distributed ledger in order to explain the working principles of blockchain technology and its application presented in this thesis.

Blockchain is the technology behind the Bitcoin virtual crypto-currency. The blockchain is a distributed ledger of all authorized, executed, and transmitted transactions between the participating parties. The majority of Network participants validate each transaction. This contains a record of each transaction happening on the network. A blockchain is an immutable collection of verified records, known as blocks which are connected and secured using cryptographic hashes.

Digital virtual currencies store a ledger with a full list of transfer of funds [1]. In such a method, when a consumer chooses to make payments, they create and share a transaction with the required data (e.g. the sum of the currency to be sent and the receiver). In the end, the transaction is put in a new block to be added to the blockchain. Blockchain was first introduced in 2008 by a person named 'Satoshi Nakamoto'. He published a white paper [2] on 'Bitcoin: A peer-to-peer electronic cash system.' Blockchain Technology documents the transaction of digital Ledger that is distributed over the network making it uncorrupted. Any digital assets, such as land resources, vehicles and so on, can be recorded as a Blockchain transaction.

In the simplest possible terms, blockchain can be defined as a data system that holds transactional records while maintaining the security, personal privacy and the principle of decentralization. One could also think of it as a sequence of records stored in block structures

that no central authority controls. It is a distributed ledger which is cryptographically secure and completely open to everyone on the network. Once a data is stored on a distributed ledger, it is extremely difficult to change it or alter it. It is a decentralized digital ledger which includes all the verified interactions in the network. It helps digital currency wallets to measure their available to spend balance in order to check transaction records while ensuring at the same time that they are fully owned by the contributor. Encryption technology enforces the authenticity and chronological order of the block-chain. Crypto wallets hold a hidden piece of data called an encryption keys or pattern being used sign the transactions, offering computational evidence that they came from its account original owner. These cryptographic signature also prohibits someone from modifying the digital transactions once it's released. All the transactions are distributed to the system and typically begin to be validated by a process known as mining as soon as they receive. The process of Mining can be defined as a consensus mechanism which is being used to validate the pending transactions in the blockchain network. It codifies a sequential order in the block chain, maintains network neutrality, and allows multiple processors to settle on the structure of the network. To be authenticated, transactions should be packaged into a block that matches very complex encryption rules which the system can check. Such rules forbid the alteration of subsequent layer, since doing so would disprove all the previous blocks in the chain. The process of mining also produces the essence of a competitive draw, which prohibits any person from effectively introducing new pieces to the network chain consecutively. No one may therefore regulate what would be in the block chain network or substitute segments of a block chain to reinstate their individual spending.

The following section offers a brief introduction of blockchain technology, Ethereum blockchain and smart contracts to understand this chapter and the overall thesis. Blockchain has the potential to be applied in multiple applications such as internet communications networks, public utilities, Supply chain management, the Internet of Things (IoT), and the financial and business systems.

Blockchain technology and cryptocurrencies have gained significant interest in industry and academia. We can define this a fully distributed public ledger and a peer-to-peer digital platform which uses cryptography techniques to host applications, transfer digital currency and digital assets and also store data securely. Bitcoin is one of the most popular and widely used decentralized crypto-currency and has significant importance. Alternatively, the Ethereum platform is also attracting lot of attention due to its smart contract feature and the execution of smart contracts, i.e. programs which are operating in a much decentralized

manner, with its native help and support. Such apps can be either completely new ideas or distributed reworks of existing concepts. It effectively cut off the intermediaries and all the associated costs with third - party service participation.

Ethereum has been taking the digital technologies behind Bitcoin and expanding its functionality significantly. It is an entire network, with its own web browser, programming language, and trading platform. Most notably it helps users to build distributed applications on the Ethereum Blockchain. For instance, the sole benefit that results from people 'sharing' and 'liking' content on the social media platform Facebook from their preferred artist is created by an ad put on their profile, and it transfers straight to the Facebook. The both artists and the viewing public will receive an award for positive coordination and communication in an ethereum variant of such social media network. Ethereum has better infrastructure and more applications than Bitcoin. Due to the fact that Ethereum seems to have more use cases than Bitcoin — and hence serves a broader purpose — It is actually a better Bitcoin substitute ultimately. Blockchain technology is still in its early phase, therefore Ethereum and Bitcoin are receiving constant updates. Yet Ethereum is the clear winner at the moment and the reason is its unique features as Ethereum blockchain uses smart contracts which adds an additional layer of controlled permissions and security features to the platform. Compared to the Bitcoin, it is more developed digital platform. Running transactions on Ethereum platform is much cheaper as compared to the other blockchain platforms. Also the transactions execution process is very quick on Ethereum.

On the basis of current crypto-currency market capitalization, the second most popular and widely used blockchain platform is Ethereum as of November 2017 which is simultaneously the main focus of this research thesis. According to Ethereum's founder, Vitalik Buterin, Ethereum is a blockchain platform that can understand general purpose scripting. As well as acting as a peer-to - peer decentralized cryptocurrency (Ether) trading network [3]. The concept of a Turing-complete blockchain was first implemented by Ethereum. Any device or computer language capable of computing something computable with adequate resources is known as Turing complete. Turing-complete development environment on a blockchain-based platform provides an incentive for a number of decentralized applications to be deployed in different areas.

These decentralized applications are referred to as smart contracts on the Ethereum platform and other blockchain-based networks which enforce Turing-completeness.

As we mentioned earlier, this is the main component that distinguishes Ethereum not only from Bitcoin, but also from other blockchain-based platforms because of its unique features and being the first of its kind in this area. However, Nick Szabo first introduced the concept of smart contracts in 1997, in which he explains the humble vending machine with a real-life scriptural / primitive example [27]. Smart contracts can be defined as a piece of code that runs on EVM. This really is a distributed "computing machine" where all of the peer nodes provide the computational power. All network node that provide computational power are paying in Eth coins for that service. These are called smart contracts, because once the objectives are fulfilled these are automatically enforced. Imagine for instance creating a distributed application regarding fund sourcing using Ethereum blockchain platform. Somebody might set up a smart contract for the Ethereum that would collect cash to give to somebody else. The smart contract might be coded to state it would all be sent off to the receiver once the desired amount would be collected or, if the desired threshold has not been reached within a month, then all money will be returned to the currency's actual owner. This will use Eth tokens, rather than the dollars. All this will happen as per the smart contract rules embedded in the code which implements the transactions automatically with no need for a reliable party party to hold the funds and signing off on the agreement. Smart contracts could be used to create several distributed applications. Coders may build smart contracts that offer other smart contracts features, similar to how different software utilities operate. These smart contracts may potentially be used to store data about the Ethereum blockchain as an app. It has to submit enough Ether as a transaction fee to actually execute smart contract code. This would actually pay for the involvement and the allocation of the computing resources to the ethereum nodes. Ethereum is considered a fairly new and intensely experimental platform, both because of its emergence (July 2015) and for its ability to develop decentralized applications with a Turing-complete scripting language running on a distributed, peer-to - peer platform like blockchain.

1.1 Research objectives

This research work investigates the feasibility of blockchain-based smart contract applications. In particular the main focus of this research work is designing and development of smart

contract system for blockchain-based distributed applications. This thesis main objectives are summarised as follows:

- Adopting the blockchain technology for enhancing the security and auditability of EHRs in current Healthcare systems
- Designing of healthcare smart contracts to facilitate different stakeholders involved in the system and how much computational resources do they consume
- Deployment of a blockchain-supported medical healthcare system which comply with the regulations and estimating the economic costs related to implementation of blockchain based smart contracts
- Trading mechanisms for energy-saving certificates designed to achieve energy efficiency as blockchain applications, and analysing the computing resources they are consuming
- Blockchain-supported local energy market which comply with legislation and can help the local governments to achieve energy efficiency, and analysing the economic cost associated with the real-world implementation
- Building a chain code implementations for the blockchain based smart contracts
- Implementation of the proposed reward system
- Implementing the business logic and processes needed for the blockchain network to remain operational
- Creating a self-contained distributed applications

These research objectives are achieved by designing and development of blockchain based smart contracts for the distributed applications. These have been deployed on a blockchain test networks. Simulations are performed with model cases and tolerance on both the regulatory framework and product architecture. The resulting computational resources are then evaluated which reveals significant parts of the technological feasibility. Furthermore, these scientific findings provide the basis for the research work presented in this thesis.

1.2 Thesis Motivation and Contributions

The emphasis in this dissertation will be on how blockchain technology can be applied to enhance the principles of security and auditability of such systems on top of already existing Healthcare management systems and Energy efficiency domain smart systems. The thesis will provide an implementation of blockchain based smart contracts using the Ethereum blockchain platform as stated in the research objective section. The deployed system would incorporate

the proposed smart contracts in the Healthcare framework for enhancing the security and auditability of the current Healthcare systems and exchanging of energy saving certificates to achieve energy efficiency by introducing a new energy policy regulatory scheme. Smart contracts act as an intelligent representation that links all the stakeholders involved in the system. It Encodes metadata that allows information to be accessed securely only by the authenticated party, unifying access to data across the network. The metadata contains information about ownership, permission and the integrity of the information being requested. The smart contract based framework demonstrates how design concepts of decentralization and blockchain can lead to stable, interoperable systems. These smart contracts are utilized to facilitate a content-control network through various storage and provider sites, authentication log controls access rights while offering full record monitoring, auditability and data sharing to the parties involved. The operational cost has been compiled for deploying smart contracts for the system.

1.3 Thesis organisation

In chronological order, the chapters of this thesis are:

Abstract - Summary of the most important aspects discussed and introduced in the thesis

1 Introduction - Chapter 1 specifies the research objectives and background which will be studied during the whole process to get to the intended logical outcome. It specifies the objectives, thesis motivation, scope and future contribution details.

2 Background - An introduction to the theory and background literature on the blockchain technology has been presented. Different protocols on cryptocurrencies have been explained. An introduction of the Ethereum blockchain, explaining its implementation of smart contracts and definition of participating nodes, including Metamask extension, Etherscan details are included here.

3 Literature Review- Chapter 3 provides a detailed literature review on blockchain based distributed applications in the Healthcare and Energy sector. It also introduces the theory applicable to Blockchain and EHRs. Explanation of the traditional healthcare system vs Blockchain powered medical eco system are included. Existing available Blockchain based distributed applications in healthcare and energy systems have been discussed here.

4 Smart contract framework for healthcare management applications - A presentation of the methods and system implementation details used to design and developed the Healthcare management framework using distributed ledger technology. Chapter 4 provides an explanation of the methods and the implementation details used for medical blockchain. This

includes a description of the components that make up an Ethereum blockchain based smart contract system for healthcare and different medical workflows presented in this chapter.

5 Ethereum smart contract Implementation – In Chapter 5, the detailed explanation and implementation of ethereum smart contract structures and functions along with process flow diagrams have been presented.

6 Blockchain smart contract system for Energy Efficiency applications - In this chapter, we present the blockchain based smart contract solution for Energy Efficiency, obtained results along with a description of how the network is to be configured and deployed correctly.

7 Conclusion - Discussion about the research outcome and conclusions derived from the obtained results. Chapter 7 concludes the thesis with a suggestion for possible future work.

The Journal publications and conference publications associated with this thesis are referred to the chapters as; Blockchain in Energy Efficiency: Potential Applications and Benefits mainly linked to Chapter 6. A Blockchain-based Smart Contract System for Healthcare Management linked to Chapter 4. Privacy concerns on Android devices – A Publication from a side project. Android permission system and user privacy — A review of concept and approaches – Originated from a side project.

2 Background

In this chapter, a brief introduction and discussion of cryptographic algorithms, hashing and consensus algorithm has been given. There is a detailed explanation on the first blockchain Bitcoin and other cryptocurrencies in this chapter. Detailed description of blockchain technology from the technical aspect, Ethereum and smart contracts have been included with some coding example on how to program a smart contract. Different components and structs involved in the contract have been explained in detail.

2.1 Blockchain and cryptocurrencies

Blockchain is defined as a distributed ledger technology which is managed by different nodes on a peer-to-peer network [4]. This system operates without any centralized data storage management or central administrators. Data is commonly distributed across several nodes, and replication and encryption protect the integrity of the data. The idea of blockchain came into being on 31 October 2008 in a white paper, written by Satoshi Nakamoto. He came up with the concept of Bitcoin transactions on a network where payments online could be sent directly from one peer to another without going through a banking institution. Satoshi's main idea was to develop a trust-less ledger [5] which solves the double-spending problem by using peer-to-peer distributed ledger technology and computing the chronological order of digital transactions. When we say blockchain, it refers to a chain containing blocks and each block in a chain stores information about all the transactions which happens at any point of time[6]. Thus every block plays a vital role in linking with the block header, and the proceeding block, as soon as a part of the chain enters the system. Each block has the main role of recording, validating and distributing the transactions among other blocks. This implies that a block in the system cannot be excluded or significantly changed because each subsequent block would be changed [7].

The system is therefore a distributed information system that includes information on all past transactions and continues to operate on a pre-determined protocol defining the direction in which the transactions are carried out and validated, as well as the ability to

function of the entire system and its participants [8]. In addition, this network is generally meant to refer as a decentralized registry, as information is stored on each node allowed to operate for each of the channels.

The group of transactions in the blockchain networks is combined into chain-connected via blocks using the hashes of the previous blocks register [9]. Hence the basic security feature of blockchain networks is enforced as a property of immutability [10]. The more the block is in the chain (the later it is), the more safe from changes are the data contained in it. When an attacker attempts to change some of the keys, the local record will cease to be valid immediately as the hash values inside the next block headers will vary completely based on the cryptographic hash function. [11]. In Figure 2.1, the longest proof of work chain and information contained in each block has been shown.

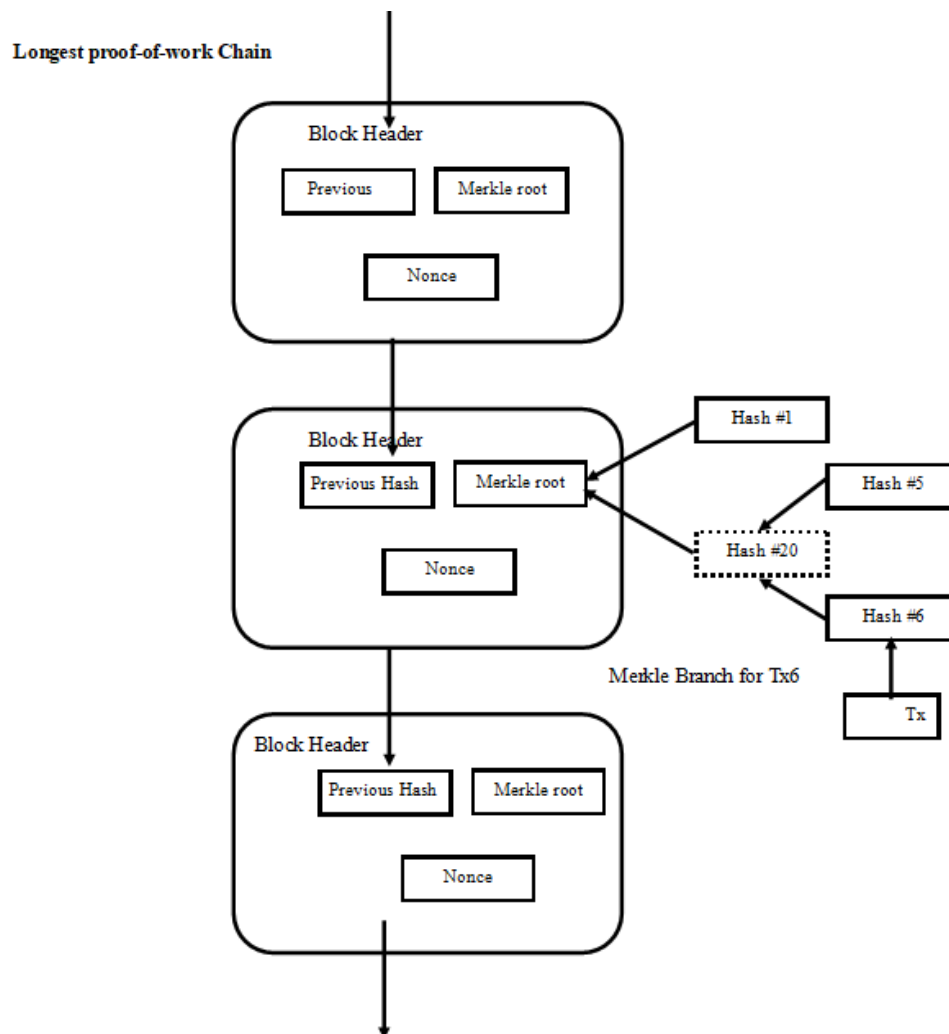


Figure. 2.1 Schematic of a blockchain Proof-of-work.

2.2 First generation of a blockchain technology: The Bitcoin

The Bitcoin, the first and perhaps the most famous cryptocurrency, has attracted considerable attention and the value of academic research on Bitcoin (BTC) continues to develop. The technological advantage of Bitcoin[12] is that it allows for trustworthy exchange processes without the need for central control, even though the system includes unknown participants. Blockchain consists of a chain of blocks tampered with evidence, durability, and time-stamping. Miners do the job of adding new blocks to the network and the overall process is known as mining refers to as the method of creating new blocks. Basically, the process starts with solving of a mathematical puzzle [13], whenever a new block is created and have been added to the chain of existing blocks, a special mechanism takes place which solves a computational puzzle and this is the job which has to be completed by the miners in the network and the whole process is called as the proof of work, which continues in the shape of a chain. We have shown a block diagram in Figure 2.2 which help us to understand the basis of blockchain. Information contained in each block has been shown to understand the overall mechanism.

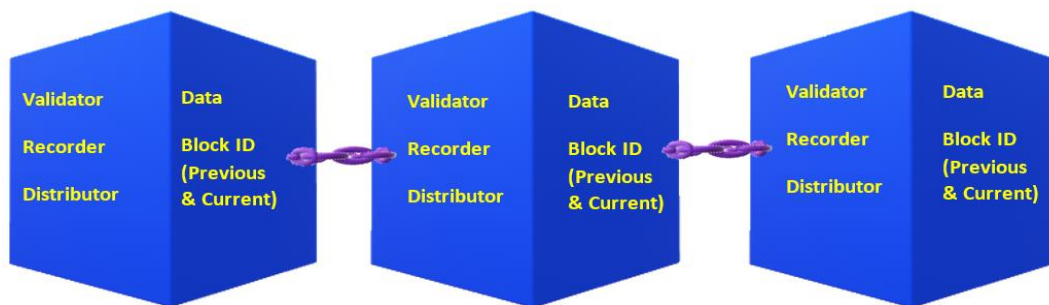


Figure. 2.2 Basic concept of blockchain. Reprinted with permission from Khatoon et al.,
Energies 2019; 12(17), 3317.

2.3 Consensus algorithm and hashing

It is essential to solve a consensus algorithm to start a new block in bitcoin. There are indeed a number of consensus algorithms such as: proof - of - stake; proof- of- burn, proof of time elapsed and proof of work. Bitcoin however is based on proof of work. . The method of solving the difficulty is known as the mining, which is a real challenge, it fails the attempts to create an invalid block in the network but this process is easy and safe to validate the blocks on the

network. A mining process in the blockchain can be seen in figure 2.3. The aim of mining is to generate the safest hash to be formed for next block. A consensus algorithm is a method for organizing users or machines within a distributed environment. It must guarantee that all participants in the system are able to rely on a single source of evidence, even if those peers in the system fail. In short, the system should be immune to faults (fault-tolerance). A single entity has the power over the system in a centralised setup. They could even make major changes as they wish in many other cases – there is no supportive regulatory system among the system-administrators to achieve agreement. But that's a whole different story in a decentralized system. Let say one need may to deal with a distributed system – how do they come to mutual consensus about what records are being linked to? Maybe the most sensitive time opening the way for blockchains was to gain sustainable competitive advantage in a world where random people don't trust one another. In the cryptocurrencies, the balance of participants is registered in a blockchain ledger. It is important that everybody (or, most specifically, each network node) keeps an equivalent copy of the ledger. Otherwise it will easily end up with contradictory details, weakening the cryptocurrency network's overall objective.

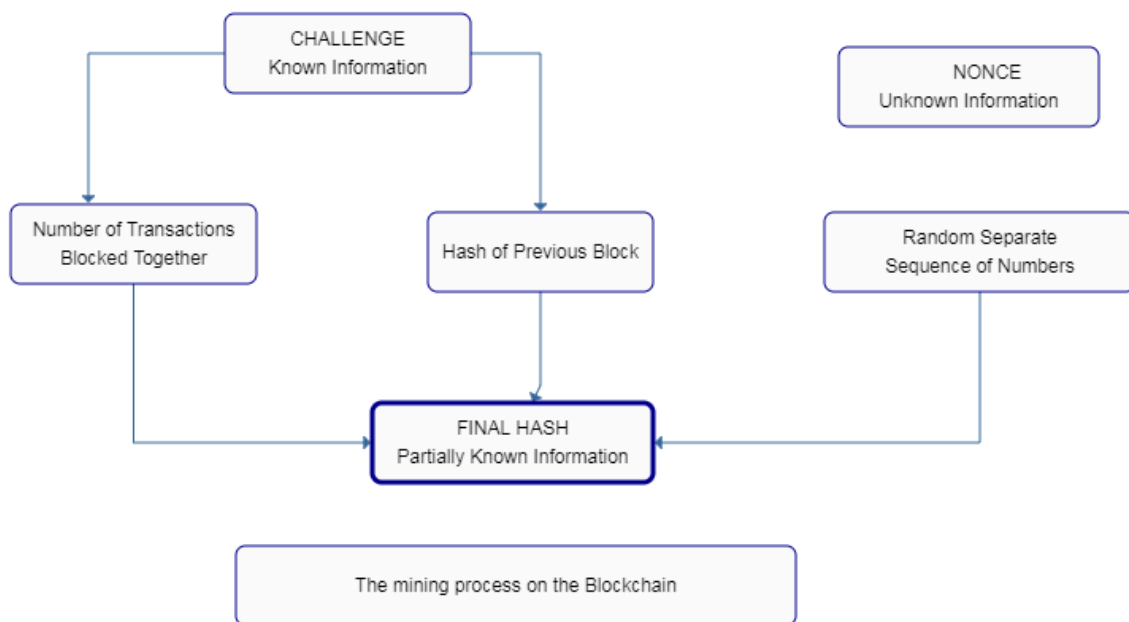


Figure. 2.3 Mining process in a blockchain.

Public-key cryptography determines that participants would not be able to use each other's coin. But also there requires to be a central source of authority on which network

members depend, in order to be able to decide whether the funds are being allocated yet. Bitcoin's founder Satoshi Nakamoto has suggested a Proof of Work method for organizing stakeholders. When we say blockchain is resilient, we means that it is really hard to attack on this system because hacker should have control over 51% of Blockchain to completely hack the system. Proof of Work (PoW) is the real base of consensus algorithms in blockchain. It was first introduced through Bitcoin. In Proof of Work, participating nodes termed as validator nodes (miners) encrypt (generate hash) the data they wish to add when a particular solution is generated.

A hash is apparently a random string of numbers and symbols that would be generated whenever you execute a hash function. And, if you pass through same data again, you'll still finish up with the same results being generated. And change just one item, and the hash will be entirely opposite. There is another very popular consensus algorithm called as proof of stack on which ethereum Blockchain has based [14]. In reality, Proof of stake [15] algorithm works better with 51% attack, it would detects the anomaly in the distributed network and held the value of coins. Exchanging the digital assets is one of the widely used concept and very common application of a Blockchain now a days. Around 2,957 cryptocurrencies [16] are traded with a combined market capitalization of \$221bn (as of Oct 8th 2019). Therefore, the top 10 cryptocurrencies [17] [18] [19]account for about 85% of the overall market cap [20] [21] [22]. The mostly used crypto-currencies are Ethereum, Bitcoin and Litecoin [23] .

There are other features besides the exchange of digital assets and one of the most popular among these is smart contracts. Smart contracts can be described as computer programs that function like the legal contract system and make it easier to check, execute and negotiate legal contracts. They run as blockchain transactions and communicate as a rule defined by the blockchain network participants with crypto-currencies. After the predefined rules / conditions are met, these contracts run autonomously. As we know that these smart contracts operate on Blockchain, they operate as planned without any alteration of the rules laid down before their execution and no third party can interfere with the Ethereum smart contracts network.

Furthermore, implementations of blockchain technology have started to emerge for items other than currencies. It has great potential to handle contracts like digital rights management because of its ability to resist against security attacks and minimise the third part cost as the system works without any central authority.

2.4 Blockchain characteristics and technology types

Basically, there are three major types of blockchain widely discussed as public, private and consortium Blockchain [24]. These types of technology vary in terms of usability, permission management and operating characteristics, such that each type of blockchain can be used in various applications. The most important features of these Blockchain types have been compared and discussed in Table 2.1.

Table 2.1. A summary of the blockchain types and characteristics.

	Public Blockchain	Private Blockchain	Consortium Blockchain
Database	Every participant can access database and store the copy of a transaction and change them.	Central authority who manages the rights to access or change the database.	Open for the public but not all the information is accessible by them.
Secure	Very secure as each block has a copy of individual transaction.	Specific people have access and it is considered secure because all the participants are known.	Provides privacy for the transactions. Known entities and governs the rules who can have access to read the ledger.
Cost	High cost.	Cost lower than public blockchain.	Usually lower cost as compared to public blockchain.
Speed	Slow speed as each transaction has to be validated and synced with each node ¹ .	High speed due to limited number of participants.	High speed compared to public blockchain.
Consensus Protocol ²	Everyone can participate in throughout the consensus process.	Consensus mechanism supports large number of the participants.	The consensus process is controlled via pre-selected nodes.
Network Congestion	High network congestion.	Scales more easily compared there is a controlled process for joining consensus process.	Controlled by enterprise and having lower network congestion.
Block Propagation	The block size keeps increasing.	Few participants are involved.	Block size is controlled as only known participants are involved.

¹ Nodes are the computers/machines which are running the software.

² All the nodes on the network should agree on the state of blockchain that means creating a self-verification network.

Feasibility	Not a very feasible solution in terms of resources consumed and cost.	Easy to maintain and feasible solution in terms of cost and resources.	More feasible in cost but also dependent on the enterprise.
-------------	---	--	---

2.5 Blockchain based smart contracts

A Smart Contract is an integral part of the blockchain-based applications. It is an agreement made between the various parties involved in the defined system. It is a computer protocol that meets specific rules, codes and restrictions agreed upon by all participants in the network. For example, a smart banking transaction or financial purpose contract includes all of the terms and conditions agreed by each stakeholder in that process[25]. Traditional contracts are deemed lengthy and are encountered as a resource-consuming process, either in writing or in any actions.

The term smart contracts is probably a misleading term, because they were neither smart nor contracts in common sense. Smart contracts, in the context of blockchain, are merely logic that is published on a blockchain, can accept or execute transactions such as any address (transactions may be rejected or distinctive arguments may be necessary to function) and can continue serving as an immutable agreement [26]. Smart contracts are intended to serve as a "computerized transaction protocol executing contract terms" (Szabo, 1994), coined for the first time by the cryptographer Nick Szabo. The central concept, and the origin of the contract element in the title, is that some elements of contracts should be incorporated in the code in such a way that violating them is either costly or difficult [27]. Smart contracts are often mistaken for Ricardian contracts (Griggs, 2015), which is the electronic recording system and related to other contract law systems. That's not what smart contracts are meant to mean, because they does not have to be legal or linked to external systems in any way [28]. Nevertheless, in conjunction with the smart contracts system to Ricardian ones, one could easily imagine interest to "outsource" the features of legal contracts to smart contracts. For the access control rights, smart contracts are the best option to consider while deploying distributed applications. In this thesis smart contracts are used to control access rights and manage different permissions on the network.

Thesis logical contracts need to have a few features to be described as a truly smart contracts, according to Szabo definition of smart contracts [29]. These include: transparency, online enforceability, verifiability and confidentiality. Accessibility (Szabo uses the word observability) means contract participants should be able to see the quality of the contract terms

of each other or be able to demonstrate fulfillment of their own conditions to other participants. It also applies to the transparency of the actions taken by the logic in the contract; a point of sale screen showing the amount to be paid to the customer while omitting the fact that the credit card retrieves information is an example of such a secret action. There is a simple example of a smart contract given below in figure 2.4.

```
1 pragma solidity >=0.4.22 <0.7.0;
2
3 contract SimpleSample {
4     uint stateVar;
5
6     function set(uint x) public {
7         stateVar = x;
8     }
9
10    function get() public view returns (uint) {
11        return stateVar;
12    }
13 }
```

Figure. 2.4 Simple example of a smart contract

The version of the solidity can be seen in the first section, pragma. It tells us that this contract will compile between the given versions of a compiler. That line `uint stateVar;` specifies a vector of state named `stateVar`. It could be seen that it is of the `uint` kind, meaning this is an unsigned 256-bit integer. To change `stateVar` it could call functions, or question it. Throughout this example two specified functions can be seen as:

Set the `stateVar`-value changes

Get `stateVar` value retrieved

Smart contracts also need to be verifiable and auditable in the case of a dispute. Eventually, smart contracts should be as private as possible, meaning that information and data access rights in an intelligent contract will only be open to the participants if necessary.

One might find that the objectives of the smart contracts just listed; transparency, online enforceability, verifiability and privacy lead in two separate directions. Privacy exercises control over the contracts with a view to restricting contact with third parties. The other three objectives, transparency, enforceability and verifiability, are diametrically opposed, allowing participants or auditors to have access to contract information. A balance must therefore be found where outsiders are granted as little data and power as possible, but there is

still the possibility of testing, tracking, and implementation. In 1997, Szabo's solution to the optimization issue was to trust an intermediary, a third party, like an auditor, before blockchain technology and developments in zero-knowledge proofs as well as stable multi-party computations.

2.6 Ethereum blockchain

Ethereum is considered to be a promising and relatively new and highly innovative platform, due both to its launch in 2015 and to its ability to create distributed applications with a Turing-complete programming language operating on a decentralized, peer-to-peer network such as blockchains[30]. Accordingly, this field of interest has gained much attention from academia over the past two years. Ethereum is a distributed computing platform based on a public blockchain that provides functionality for smart contracts[31]. It provides a virtual decentralized computer, known as the Ethereum Virtual Machine (EVM), as a runtime framework for smart contract execution [32]. The Ethereum network is a particular blockchain network and a platform for using a virtual machine (Ethereum Virtual Machine, EVM) to run smart contracts. Since the world only functions on the blockchain in the form of a virtual machine, the smart contracts on the node machines are completely isolated from the network, file system or other processes. A high-level, Turing-complete language was developed for the writing of intelligent contracts with Ethereum. Ethereum has been taking the digital technologies behind and expanding its functionality significantly. It is an entire network, with its own web browser, programming language, and trading platform. Most notably it helps users to build distributed applications on the Ethereum Blockchain. Ethereum blockchain is user-friendly when it comes to build Dapps.

Solidity, however, has now become standard for other platforms with smart contract capabilities as well. In syntax, solidity is similar to JavaScript, but written in a different style altogether. It is compiled into EVM bytecode after a contract was written in Solidity and then deployed at a particular Ethereum address. Nonetheless, a special JavaScript RPC-library is used in combination with a web API to deploy and communicate with smart contracts on Ethereum. As smart contract programming originated with Ethereum blockchain technology and Solidity [33] it remains a rising discipline.

2.7 Public key-cryptography

The Ethereum blockchain platform uses a special elliptic curve encryption algorithm for its public key cryptography and a set of various mathematical parameters as specified by the US National Standards and Technology Institute (NIST). Elliptic curve cryptography encryption technique is a powerful cryptographic technique from a very well-known RSA (Rivest–Shamir–Adleman), and an evolutionary method [34]. RSA is a very popular asymmetric algorithm which is developed in 1977. It has been widely used in the network protocols such as SSH and SSL / TLS, and for email encryption, such as OpenPGP and S / MIME. The RSA algorithm is driven by the fact that 2 large numbers are very easy to multiply but it is very difficult to categorize large numbers. The development of the pair of keys is this algorithm's most complicated procedure, and that is what make it so different from the symmetric key encryption. There are the numerical steps for creating the key pair. There is another significant aspect of the RSA algorithm which is its capability to create a message signature digitally. With that kind of function the source of the message can be confirmed. To achieve that, the sender of the message signs the message with its encryption key. The recipient validates the digital certificate with the caller's public key, to validate the source of the text. The very first step of digital signature creation is the formation of a message hash. To build the hash you must apply a hashing algorithm to the text, the most widely used is SHA-256. Once this feature is implemented, the text is simplified to a significant size, 256 bits long. The overview of the encryption and decryption process of RSA algorithm can be seen in figure 2.5.

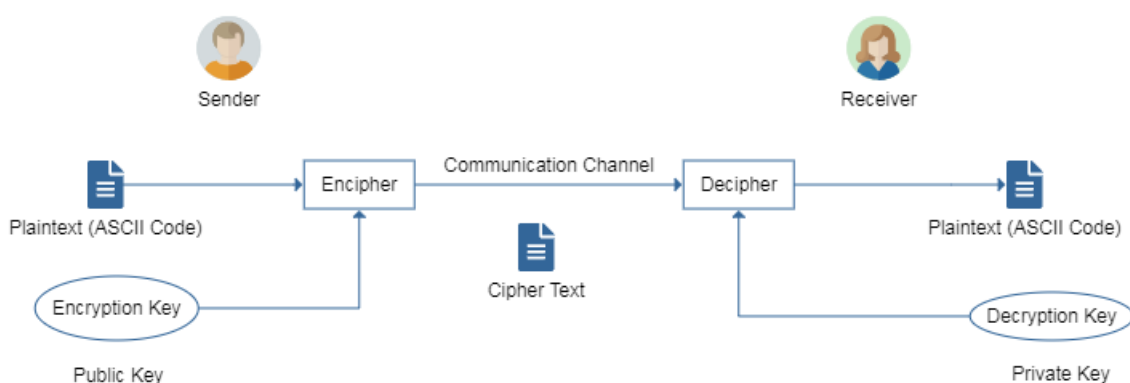


Figure. 2.5 Encryption and Decryption process in RSA algorithm

By using the mathematics behind elliptic curves, a technique used for public key encryption is to establish privacy between key pairs. ECC has grown steadily in popularity due to its potential to provide the same level of security as RSA (Rivest–Shamir–Adleman) with a relatively low key size [35].

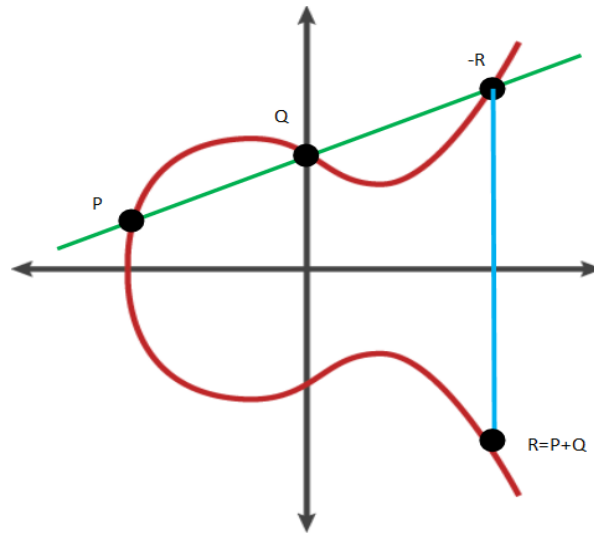


Figure. 2.6 Elliptic Curve (ECC). [39]

When working on the spatial plane, we can describe a group structure at any smooth cubic curve. In Weierstrass's normal form, such a curve will have one additional point at infinite space, O , at the particular emphasis that function as the identity of the group.

If X and Y are two main points on the graph then we can specifically define a third point, $X + Y$ initially, draw the line between X and Y as it can be seen in figure 2.7. This will usually intersect the cubic on a third point, Z as shown in the Figure 2.7.

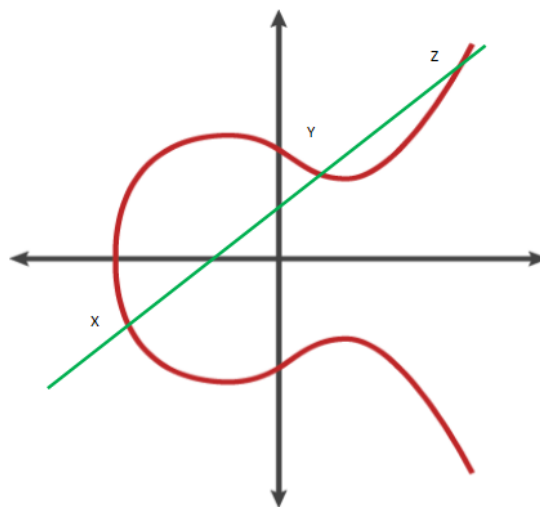


Figure. 2.7 Graph of curves. [39].

2.8 Ethereum virtual machine

The EVM manages the calculations on the blockchain network and contract status and is based on a stack-based language with the predefined set of instructions (opcodes) and arguments. So, in essence, a contract is just a series of opcode statements that the EVM (Ethereum Virtual Machine) executes sequentially. The EVM can be seen as a distributed global computer which is running all the smart contracts. Although it acts like a giant or a super computer, in constant communication it is rather a network of smaller discrete machines.

All transactions on Ethereum network, including the execution of smart contracts, are local and executed in relative synchronization on each node of the blockchain network. Each node validates and integrates transactions sent by users into the specific blocks and attempts to add them to the blockchain network to receive a related reward. This method is called the mining process, and miners are called the participating nodes in the network. Each set of instructions that the EVM executes has a cost associated with it, calculated in gas units, and to ensure proper resource management of the EVM. Operations requiring more computational resources cost more gas than operations requiring less computational resources on the network.

It means that denial-of-service attacks do not interfere with the system, where users seek to overload the network with time-consuming computations. Consequently, the gas purpose is twofold. It encourages developers to write quality apps by avoiding wasteful code, while at the same time ensuring that miners are compensated for their contributed resources by performing the requested operations. When it comes to paying for gas, Ether, the Ethereum network's built-in digital currency, and the token with which miners are rewarded for executing transactions and producing blocks, will charge a transaction fee in small amounts. Ultimately, Ether is known as the Ethereum blockchain platform fuel.

2.9 Ethereum-based smart contracts

Smart contracts are software that are built on the blockchain network and run as part of the verification of the transaction autonomously. A special development transaction will be conducted to create a smart contract in Ethereum platform, which will add a contract to the blockchain network. During this method, a unique address in the form of a 160-bit identifier is allocated to the contract and its code is submitted to the blockchain network [36]. A smart

contract, when successfully established, consists of a contract address, a balance of contracts, predefined executable code, and a state of a contract.

Let us just start with a simple example that determines a variable's value, and enables it to use for other contracts.

```
1 pragma solidity >=0.4.22 <0.7.0;
2
3 /**
4  * @title Storage
5  * @dev Store & retrieve value in a variable
6  */
7 contract Storage {
8
9     uint256 number;
10
11     /**
12     * @dev Store value in variable
13     * @param num value to store
14     */
15     function store(uint256 num) public {
16         number = num;
17     }
18
19     /**
20     * @dev Return value
21     * @return value of 'number'
22     */
23     function retrieve() public view returns (uint256){
24         return number;
25     }
26 }
```

Figure. 2.8 Smart contract code example.

The initializes with the Solidity version and tells that the source code has been written for the solidity version 0.4.22. For scripting languages, Pragma's are standard guidelines on how to handle the code.

A contract throughout the context of solidity is a set of code (its components) and information (its condition) that exists on the Ethereum blockchain at a particular address. In this code the uint establishes a variable of type unsigned 256-bit integer.

Smart contracts are usually implemented by blockchain network nodes, so it is not possible for a single entity to circumvent the rules specified in this code, as most participants would need to agree on this to happen. Smart contracts have the key advantage of being able to simplify the business logic of an enterprise and a system [37]. The move to automation of the contracts, in addition, cancels the consequences of human errors and misunderstandings which can result in legal disputes among different stakeholders involved in the system. Specific interpretations may be subject to a legal contract or statute, but code is deterministic; there is

no space for personal interpretations. A typical structure of a smart contract can be seen in figure 2.10.

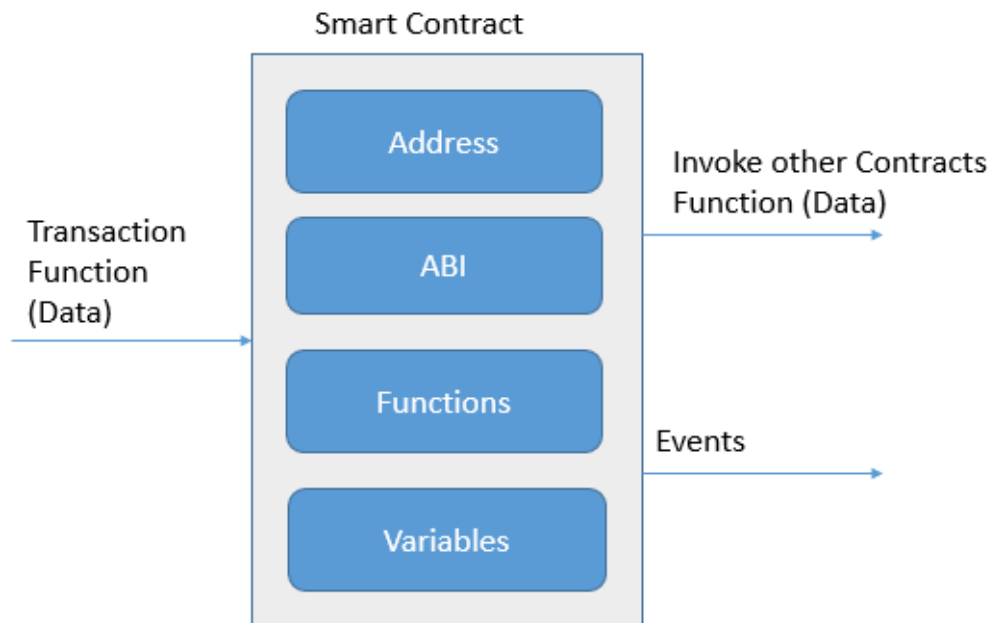


Figure. 2.9 Smart Contract Structure.

Through nodes submitting contract-invoking transactions to a specified contract address, different parties can then communicate with a specific contract. As a result of this, these can trigger any number of actions, such as reading and updating the contract state, interacting and carrying out other contracts, or transferring value to others. A contract-invoking payment must include the execution charge and a transfer of Ether from the caller to the client may also be required. It can also be described as input data for a function invocation. Once a transaction is accepted by the miners, the contract code is executed by all the network participants, taking into account the current blockchain status and input transaction data.

The network then agrees by participating in the consensus protocol on the output and the next contract state. Therefore, Ethereum can be regarded as a transaction-based state machine on a conceptual level, where its state is changed after each transaction happened.

2.10 Solidity

In Ethereum blockchain, smart contracts are typically written in higher-level languages and then converted to the bytecode on the EVM. High-level languages are Serpent which resembles a lot with Python, LLL, Viper (a Python-like language), and Solidity which is very much similar to Javascript [38]. In the early stages of the platform, LLL and Serpent were developed while Viper is currently under development to replace Serpent. Solidity is the most prominent and widely used language for the development of smart contracts [39]. Contracts are designed similar to classes in object-oriented programming languages when using Solidity for contract creation. As in conventional imperative programming, contract code consists of variables and functions that interpret and modify these. The Solidity language has a number of known peculiarities and a list of upcoming changes, meaning software now being written may not be fully functional with the upcoming update. There are a few programming best practices related to the design of smart contracts, gathered in the (relatively) short time Solidity was in use. The coding example of solidity has been given to understand the basic structs and mechanism of solidity program which is as follows;

The very first variable of that we must declare is address in the contract. This has a value of 160-bit, and stores the smart contract address. By accessing the public, it will let the variable access to other contracts that has been declared.

Mapping would then map the uint variables address (unsigned integers assigned to)

```
1 contract cryptoCoin {  
2     address public minter;  
3     mapping (address => uint) public balances;
```

Figure. 2.10 Creation of a contract

The next step is about declaring an event showing in figure 2.11. When the send function needs to execute this will be provoked. Ethereum clients could monitor and track the transactions by listening to these events and receiving arguments.

```
1 event Sent(address from, address to, uint amount);
```

Figure. 2.11 Event declaration in a contract

As shown in figure 2.12, once the contract has been created, the constructor will then execute:

```
1 constructor() public {
2     minter = msg.sender;
3 }
```

Figure. 2.12 Creation of a constructor in a contract

This contract has two functionalities as mint and send. Only one can call mint as the contract-creator. While doing so, one can create a given number of coins and can send them to another address.

The enable function call is to be used to define the constraints under which the adjustments should be switched back. In the figure shown below, it ensures that the minter really is the contract originator and describes the highest number of coins to be sent:

```
1 function mint(address receiver, uint amount) public {
2     require(msg.sender == minter);
3     require(amount < 1e50);
4     balances[receiver] += amount;
5 }
```

Figure. 2.13 Mint and send function

Unlike the mint, sending is accessible to everyone possessing coins. They can send a whole lot of tokens to somebody else by successfully executing it.

Unless the sender attempts to transfer more coins as compared to what they currently own, then the call for the required function will not be executed. An error occurred and the error message would pop up in this situation

```
1 function send(address receiver, uint amount) public {
2     require(amount <= balances[msg.sender], "Balance too low!");
3     balances[msg.sender] -= amount;
4     balances[receiver] += amount;
5     emit Sent(msg.sender, receiver, amount);
6 }
7 }
```

Figure. 2.14 Example of running a contract code

2.11 Smart contracts programming on Ethereum platform

Ethereum blockchain contract development requires a different approach to engineering than most web and mobile developers are familiar with [40]. In contrast to traditional programming languages, which accept a wide range of convenient data types for processing and manipulation, the programmer is responsible for deeper-level internal structure and data manipulation [41]. This implies that details that the developer may not be used to deal with must be addressed. For example, a developer would have to implement a lowercase string method, which are usually tasks that developers don't have to think about in other languages. Here is a simple smart contract example where the contract contains a constructor function and the message in figure 2.16. Function `setMessage` will change the state of message whenever a user wants to change its value.

```
1 contract Hello {
2
3   string public message;
4
5   function Hello(string initialMessage) public {
6     message = initialMessage;
7   }
8
9   function setMessage(string newMessage) public {
10    message = newMessage;
11  }
12 }
```

Figure. 2.15 Simple smart contract example.

In addition, the Ethereum framework and Solidity [42] are constantly evolving at a rapid pace and the developer is facing a continuous transformation of application functionality and the security environment as new instructions are introduced and bugs and safety threats are discovered [43]. Developers need to consider that code written today will probably not be compiled in a couple of months or will need to be refactored at least.

2.12 Metamask

Ethereum has always been about discovering future innovation's potential. If we knew what it was good for, instead of a virtual machine, it would have shipped all those features. And the inventions continued to come. A MetaMask plugin is a script loaded over a protocol such as ENS, IPFS or Swarm that is checked and unauthorized [44]. By default, these scripts have zero rights, but will be able to request from MetaMask a number of important wallet APIs, via a

new API called the wallet API. The wallet API is an expansion of the classic ethereum or web3.currentProvider API, but with some additional features designed to make some of our favorite use cases simpler, such as layer 2 scaling techniques, and even more contract account support features. Metamask has been used to calculate the cost for a specific transaction on the ethereum blockchain for the distributed applications being implemented in this thesis.

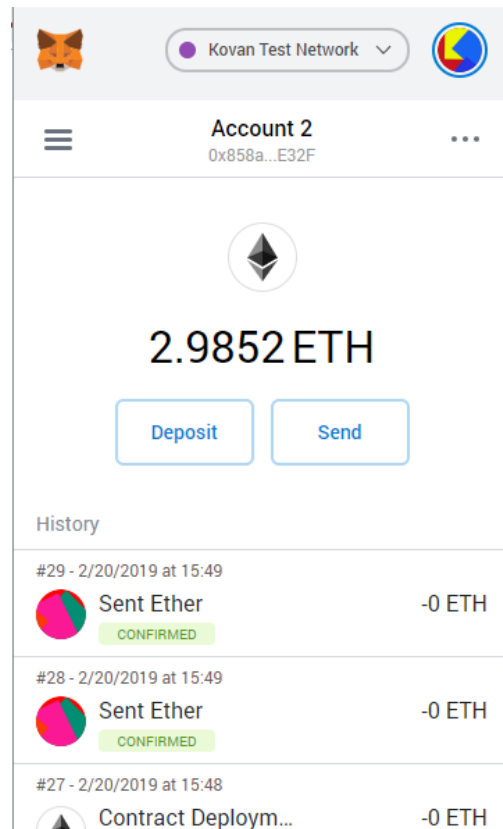


Figure. 2.16 Metamask Extension.

2.13 Etherscan

Etherscan is Ethereum blockchain's pioneer BlockExplorer. A BlockExplorer is essentially a search engine that allow users to search, confirm and verify transactions that happened on the Ethereum Blockchain effectively [45]. Figure 2.18 is an illustration of Etherscan transactions and blocks. In this thesis, Etherscan has been utilized to verify the transactions on the Ethereum Blockchain. Every transaction has been recorded, confirmed and verified using Etherscan for the smart contract applications implemented in the upcoming chapters.

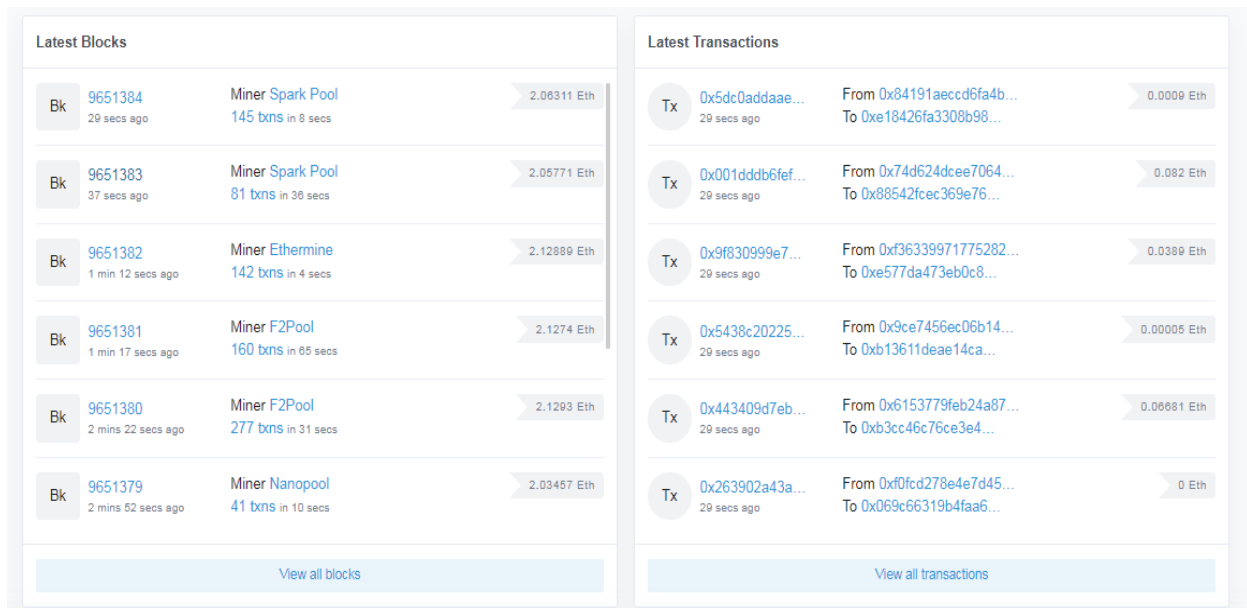


Figure. 2.17 Etherscan Transactions and Blocks.

2.14 Blockchain based smart contract applications

Ethereum blockchain platform makes it possible to develop and test smart contract apps or distributed applications (D-Apps) conveniently [46]. Public smart contracts allow start-ups to raise funds through Initial Coin Os (ICOs). On the other hand, big companies mainly want to take advantage of authorized smart contracts to incorporate their models and enforce enterprise procedures. Some of the common use cases include Fintech industry, Electronic Medical Record (EMR), IoT information management, supply chain and Energy sector. Other interesting applications like smart waste management, real estate, and ride-sharing arcade city are also available.

2.15 Conclusion

In this Chapter, we have briefly given the overview about the basic concepts of blockchain technology along its types and platforms. The foundation of blockchain technology has been discussed in details alongside Ethereum platform, solidity, Metamask, Etherscan and smart contracts. Different components and structures involved in the smart contract have been explained in detail. A brief introduction and explanation of cryptographic algorithms, hashing, and consensus techniques is provided in this chapter. This chapter also provides few examples on blockchain based smart contract applications which will be explained in detailed in the next chapters in terms of Healthcare and energy system application. The concepts presented here

will help to understand the next chapter which provides the literature review on blockchain based distributed applications mainly focused on healthcare applications and energy systems. This is a foundation technique chapter which provides all the details about the tools and techniques utilized in this thesis.

3 Literature review: Blockchain based Distributed applications

In this chapter, literature review has been conducted on existing blockchain based distributed application for Healthcare and Energy Systems. There has been detail provided on gaps in non-blockchain system. The usage of blockchain technology is making transaction histories more transparent. Since blockchain is a distributed ledger, rather than having individual copies of documents, all network participants have access to the same information. Only by consensus can that shared version be updated, which means everyone must agree on it. To amend a single transaction record, all future records would have to be changed as well, and the entire network would have to agree. As a result, data stored on a blockchain is more trustworthy, reliable, and transparent than the information stored in the existing Non-DLT systems. It is also accessible to all participants who have been granted permission. In this chapter we will discuss in details the existing literature on blockchain based applications while at the same time addressing the gaps in the existing non blockchain systems and the motivation to the work we have proposed for blockchain based distributed applications. All the basics concept of smart contracts, distributed applications and the tools and technologies we are using in our work has already been discussed in detail in the previous chapter which is the foundation technique chapter.

3.1 Traditional healthcare system vs Blockchain based healthcare infrastructure

Existing Health record systems were never intended to handle the complications of multi-institutional, lifelong medical records. Individuals' data becomes distributed among numerous organizations as they move between providers, making it difficult to access previous records. Patients encounter significant challenges in reading their results, fixing false data, and disseminating the content because caregivers, not patients, mostly handle the data. The scenario is similar to that of consumer finance, where a person may have multiple bank accounts, debit cards, debts, and investments but no centralized means to access and manage them. However, in the financial services space, there is a system in place to lubricate the rims. With health information systems, we are still lagging behind.

The volume of healthcare information are now steadily growing, yielding the enormous amount of data being generated. This reality relates closely to the emergence of software technologies and smart phones, and of course health records digitisation and clinical documentation. Healthcare data might contain very sensitive and important information. These healthcare data helps in improving healthcare outcomes, anticipating infectious diseases, gaining useful insights, preventing diseases, helping in lowering the healthcare costs and improving the overall quality of life. Keeping in view these aspects, healthcare information needs to be secure.

The emergence of healthcare apps, devices and digital transformation of medical records are rising exponentially. These medical healthcare data are collected, and used in legacy applications, which have serious concerned regarding mishandling of sensitive information. A resolution would then be required and this is where the blockchain technology emerges, as an innovative solution to make things simpler, more confidential and much more efficient.

The recognition of the key benefits of blockchain technology have been growing at a significant rate. This reality contributes in such a growing number of research studies related to the development of blockchain based healthcare applications. In most of these research findings new technologies have been created that can be classified on the basis of their goals such as: improving the insurance pay-outs process; facilitate the delivery of health records; promoting the medical and clinical studies and development of health care applications using the distributed ledger technology. These solutions aim to address emerging problems in conventional health care and data sharing for healthcare systems.

Conventional healthcare systems are centrally controlled: an entity is in place that monitors and manages all the information. Blockchain is built on the principle of consensus algorithm, where each node enables to evaluate the information is being exchanged, to whom and of all, each node does have a copy of all the data and information stored on the blockchain network. Furthermore, distributed systems also helps in reducing the transaction costs.

Medical healthcare information are classified as sensitive information which requires high level of privacy and transparency. Often, though, it is really needed sometimes to share this information with other parties. This can be really challenging in the

existing health-care systems due to a lack of standardization. Most systems do not have compliant data structures which preclude information sharing. Blockchain powered healthcare system improves system-to-system information sharing and is more effective in managing huge data volumes and different parties in the system. Blockchain enable data sharing system helps in the data exchange and integration between distributed apps and other systems efficiently. The blockchain based system allows real time updates in all the network nodes, streamlining the data sharing in the network.

Blockchain based smart contracts play a significant role in maintaining blockchain network's confidentiality and anonymity. There are conflicting rules and privileges in the existing healthcare systems which limit some certain party to access patient's data. A set of rules can be created with "smart contracts" to regulate the information about the patient's records. While doing so, the individual, who owns the health records, may choose to exchange medical-healthcare records with whoever he wants to. In addition, smart contracts are among the main features of blockchain crypto algorithms, which make a contribution pragmatically to the optimization of decentralized management, as it enables regulations and authorizations to be published in the code, thus instantaneously accomplished even without the need of any centralized system.

3.2 Existing blockchain based healthcare solutions and applications

In this section, we have conducted literature of existing Blockchain based healthcare frameworks. Although there are very few implementation of Blockchain based healthcare architectures and there is one very well known among them MedRec, which has been discussed in this chapter. The Legacy systems normally only end up sharing medical and healthcare resources structurally and are not fully compatible with external entities [47]. Nonetheless, there are multiple benefits of integrating these networks for integrated and better wellbeing, calling for interconnections between various organizations for researchers in health information technology [48]. One of most crucial issues is the low- and mid-organizational data exchange, which requires other entities, such as a physician or research institute, to have easily access to medical data obtained by a healthcare provider. Blockchain technology redefines data management and transparency in many Healthcare implementations. This is due to its adaptability and secure exchanging and sharing of medical data. Blockchain technology is at the leading edge of many current developments in the healthcare industry [49].

With developments in electronic health data , cloud storage systems and patient data protection regulations, business challenges for managing health data are opening up, as well as service quality for patients to access and start sharing their health data [50]. Blockchain based applications including data sharing, data management, data storage and EHR are discussed in detail in this section.

Emerging blockchain-based healthcare technologies are conceptually divided into many layers, like data sources, blockchain technology, healthcare implementations and stakeholders. In [51] a healthcare blockchain analysis was conducted where they concluded their discussion about how blockchain technology would allow patient-centric control over institution-centric control of data sharing in healthcare. In their study they explored how blockchain technology transforms the healthcare sector by allowing digital access rights, patient recognition across the network, managing a large volume of healthcare data and immutability of data. In another work [52] on health records using the fabric Hyperledger platform where they sent medical data to the blockchain hyper ledger network. They have used smartphones to collect those medical records. In their research they tried to ensure that health care data were stored with the Blockchain network. There is another work [53] which provided a better way to effectively manage health-care information using blockchain technology. They included different types of studies in their study and most of the work among this study was discussing potential healthcare benefits and limitations of blockchain technology without any evidence or system evaluation being provided. They concluded their discussion on how blockchain could be better suited for managing cloud-based health care records while maintaining data security and privacy at the same time.

There are different blockchain platform including permissioned and permissionless architectures. The authors in [54] identifies an approach to address the limitations of permission and permission less blockchain networks. They have also used an instance of Hyperledger blockchain platform for the patient-controlled health data management system. There are numerous surveys conducted on healthcare blockchain possible solutions. In [55] the authors conducted a literature survey on healthcare management systems while proposing two algorithms for the network security. They have also suggested using a distributed ledger system for the better healthcare data management and to establishing the efficient regulations for the healthcare systems. Blockchain technology and IoT devices are playing very vital role in the healthcare industry. The study in [56] proposes a medical data sharing system using blockchain and peer-to - peer networks named as MedChain. This system was designed for healthcare data

generated through medical assessment and patient data gathered from IoT smart sensors and other mobile applications.

In another work [57] the authors have analyzed different healthcare management system issues, and how blockchain technology could be used to solve them. They have addressed the current healthcare research using distributed ledger technology with some possible cases of medical use where blockchain technology can play an important role in making the process efficient. They also proposed delivery of the IoMT system using networking protocols. Healthcare data privacy and security is very important. Litchfield et al. [58] have addressed different issues regarding healthcare data security and privacy breaches and suggested blockchain as a solution to overcome these issues. They have also conducted a survey on the healthcare issues.

Patient's healthcare data needs to be protected in every situation. In [59] discussed the infringement of patient information, such as name, address etc. This work suggested a system for managing electronic health records through blockchain. The main goal of this paper was to examine the success of their program and see how their proposed solution meets the needs of a patient, clinicians and private entities including third parties. Various healthcare blockchain use cases have been [60] addressed. They have stressed the importance of the blockchain-based healthcare system and how blockchain technology delivers efficient healthcare design. In another work, [61] the authors, mentioned how blockchain technology and smart contracts benefit the healthcare sector by streamlining processes as a whole. In their work, they have mentioned that the management of health care records is extremely important and that blockchain has the potential to reduce the loss and prevent the manufacture of data by securing the ledger information.

Blockchain technology may be a great tool in the standardization of drugs and pharma industry. Jamil et al. highlighted issues regarding drug regulations and how to standardize the overall drug regulation process using blockchain were discussed. Throughout their research, they highlighted the difficulties of detecting counterfeit drugs and suggested blockchain as a way of detecting counterfeit products [62].

Human nails are very distinctive, and reflect the human being's physiological nature. Lee and Yang have worked and studied the fingernail analysis management system using blockchain technology and microscopy sensors. They used microscopic sensors in their work to collect the nail images, and used pre-processing image techniques to obtain clear images. A

deep, neural network was used to monitor an extracting features algorithm's performance. Blockchain technology has been used as a means of protecting user data and providing security and privacy so that any system changes can be tracked and recorded through the Ledger [63].

Ensuring data protection, processing, transactions, and managing their seamless integration is immensely important to any data-driven enterprise, particularly in health care where blockchain technology has the potential to address these critical issues in a robust and efficient manner. In [64] the authors, conducted a comprehensive study of latest literature on blockchain healthcare applications. To answer their research query they selected 65 research articles. Their study indicates that blockchain could be a potential technology for various healthcare case scenarios that includes the supply chain of drugs, clinical research, and electronic healthcare records management. However, they also analyzed the fact that more understanding of blockchain technology still needs to be developed and how it could best fit for different healthcare complex problems.

Innovation in healthcare has been slowed due to inefficiencies and heavy regulatory requirements. Azaria et al. discussed these regulatory issues which cause EMR system inefficiencies [65]. They have recommended blockchain-based solution recognized as MedRec to manage huge quantities of medical data in EMR system. They illustrated an innovative and unique approach to accessing healthcare records which offers a fair access log system for audit access. Using distributed ledger technology, MedRec allowed patients and doctors to share the medical data between different parties. They give people such as researchers, other health individual's incentives to take part in the mining process. MedRec enables the data to be anonymised and available to the miners as a reward for participating in the network.

In [66] the work states that how blockchain based smart contracts have the ability to fix various healthcare concerns. The authors took some initial steps in their work to incorporate blockchain technology for specific healthcare use cases and referred to numerous obstacles in adopting blockchain technology. They also worked out that creating blockchain-based applications will address healthcare problems more effectively.

Blockchain technology has many opportunities for medical scientists, health care practitioners and individuals [74]. It will enable both research and tissue engineering to create a single location for all health data, monitor personalized information directly and set permissions for fine-grained access to data [75]. The work [67] identified different blockchain applications for healthcare system. They outlined problems and challenges with the adoption

of blockchain technology and presented smart contracts for blockchain-based health care system.

Digital security is a big challenge because of hacking motives and privacy breaches. In [68] the authors, formulated consent governance in E-health environments and proposed blockchain as the most stable and reliable solution for handling health data. In this digital world age, access to personal information has become a major concern, with challenging aspects of security and privacy. This is possible in the area of eHealth where the health information management system for patients has to comply with many legislation while remaining accessible to duly authorized healthcare professionals. Because of its most common use-Bitcoin-most in the payment area must have heard of blockchain.

There are many advantages to the blockchain technology and distributed ledger system as discussed briefly in [69] that includes identity management, security of personal data, sensitive handling of information, elimination of third parties. With exception of centralized networks, the capability of the network continues even if single nodes break down. It increases confidence, as individuals do not assess the trustworthiness of the intermediary or other network participants. If people boost confidence within the system itself, that should be enough. The lack of intermediaries also facilitates the data security. As in the current practice of third parties collecting personal data, there is the possibility of security breaches. By using the blockchain, third parties may become redundant and effectively increase user protection. There was a report by the MIT Media Lab [70] highlighting the data protection aspects and the handling of personal information underline all the implementation of blockchain technologies. It is the significance of data processing which is secure – in the sense that it cannot be exploited. The data protection and privacy are another dimension of data security. For instance, Enigma is a decentralized, private information-guaranteed computing platform and a breakthrough on blockchain. Enigma's goal is to enable developers to build an end-to - end digital platform without a trusted intermediary. Enigma is indeed an extension of blockchain technology because processing and data management are not achieved inside the blockchain, rather the blockchain is an "interface" for protected multi - party computations performed by network-participating storage and computing nodes. Relevant data is split between different nodes, and various nodes work together to measure functions without leaking classified information towards the other nodes. In conclusion, "not a single party has any kind of access to the data in its entire duration; instead, each party has a meaningless piece of it (i.e., apparently arbitrary).

Blockchain holds the potential of creating a new data contract, a greater degree of personal data ownership, control and content delivery, through a network that enables the world to benefit from data collection. Within Google Maps, traffic congestion information is a direct example of the advantages of data aggregation: by incorporating location, travel pace and other important personally identifiable information, drivers leverage from the existing data pool to achieve shorter traffic times and avoid traffic jams. But Google attempts to integrate driver's personal location data to do this. BlockVerify, on the other contrary, is an illustration of a start-up using blockchain to assert proprietary information by verifying the origin of luxury goods, physical objects and by investigating the legal status of generic medicines, diamonds and electronics to resolve the issue of counterfeit goods. This type of security occurs because blockchain is decentralized so that it does not rely on a single authority for its maintenance, and therefore a single example of misappropriation that causes a failure does not affect the reliability of the records.

Another study [71] describes blockchain and etherum as a secure platform for handling sensitive information of all kinds. It states that blockchain is a decentralized system. This has significant skill in solving market problems. The encryption secures the data in a blockchain transaction, and each transaction is linked to previous transactions or a database. Blockchain transactions are validated through algorithms on the nodes. A single person might not be able to make a transaction. Blockchains eventually have transparency, allowing each user to track the transactions at any time. Smart contract enforces a secure process which helps to prevent third party interruption. In [72] the authors used the cloud technology scenario and pick the cloud records as a data unit to easily classify user activity from source to collect data. By embedding the data into blockchain transactions, they develop and implement ProvChain, an architecture for cloud data provenance collection and verification. ProvChain operates mainly in three phases such as provenance data collection, origin data storage, and provenance data validation. The results of performance assessments show that ProvChain provides security features for cloud services and applications, including misleading provenance, consumer rights and low overhead durability. There are number of surveys conducted among numerous professionals about the conceptualisation of blockchain and the implementation of blockchain technology in healthcare institutions. Another study in [73] discussed how different business players are pursuing blockchain widely in the healthcare sector to improve their business operations. It can help improve patient outcomes, reduce costs and standardize the whole process.

This systematic review includes all the research studies that create a new blockchain-based solution, algorithm, method, technique, or architecture to healthcare. Also included are review type research, discussion of possible blockchain uses and applications.

3.3 Discussion and motivation for a blockchain powered healthcare infrastructure

Medical researchers need comprehensive data sets to increase understanding of the disease, accelerate medical innovation, track drug development rapidly and design clinical, product life cycle and history care plans for patients [76]. Blockchain's decentralized data network would provide a broad array of data through the inclusion of patients from diverse ethnic and cultural-economic backgrounds and from different economic areas. It offers effective information for clinical studies, since blockchain collects health data over the life of a person [77].

A blockchain in medical care will likely encourage the development of a new breed of "digital" medical provider applications that bypass the latest medical studies and establish tailor-made treatment pathways. Health care professionals and patients would have access to the same information and should participate in a cooperative, informed discussion of research-based treatment options, rather than the best possible case. In this chapter, the existing blockchain based applications for healthcare has been explored. The proposed medical healthcare smart contract system has been presented in the next chapters. In the existing medical blockchain applications, not a single implementation gives complete medical workflows built on distributed ledger technology. The work presented in this thesis gives a Blockchain based framework for the medical workflows involved in the healthcare ecosystem. The exchange of electronic medical data among different stakeholders in the healthcare ecosystem, such as patients, physicians and researchers, will encourage greater and efficient integrated healthcare infrastructure. This private information should be only made available to the approved and authorized users in the system. From the overall associated healthcare data, some users may only want to have access to only certain parts of the information and they might not be needed to have access to the overall healthcare records. The proposed healthcare model in this thesis will help to avoid the risk of exposing all the sensitive information to those users. Other than just accessing such information, peers might also want to upgrade certain information and distribute that information among the other peers of the system, that model will help them in doing so very efficiently by maintaining the privacy and taking care of all the sensitive information in the system at the same time.

3.4 Blockchain based applications for energy Efficiency

Energy efficiency gains must increase by 2030 to meet the Environmental Sustainability Agenda. However, due to a number of market constraints, the adoption of energy efficiency solutions is gradual. By enabling transparent, decentralized, and tamper-resistant systems, blockchain technology has the ability to solve these constraints or perhaps radically revolutionize energy system architecture. A blockchain solution does, however, come with trade-offs that must be considered on a particular scenario. In this section, we address how to overcome the stated challenges to blockchain adoption and emphasize the importance of policy action to accelerate the development of pilot studies. Blockchain allows creative designs that help accelerate the adoption of energy saving initiatives by decentralizing system governance. A thorough literature review has been conducted on existing blockchain based applications in the energy system domain.

The use of Blockchain technology recently emerged as a significant technology in the energy sector's digital revolution and a number of international experts [139] [140] [141] have also identified the blockchain potential use cases for the energy eco-system. In addition, it will also facilitate energy consumers' ability to monetize their excess energy that could have come either from generation or energy savings.

The rapid pace of innovation in communications technology and the growing consumer interest in energy efficiency offer significant opportunities for transformation to a low emission energy system [78]. Distributed ledger technologies, especially blockchain, have recently gained considerable popularity in making the energy sector safer, more transparent and more efficient [79]. Blockchain has been researched as mentioned in the previous section, for several applications in the energy sector. It has been extensively discussed in connection with P2P energy trading and there are a number of articles available that describe this idea [80] [81] [82] [83] [84], a range of early product launches as well as [85] [86] [87] [88]. However, our literature review revealed that blockchain is still just an idea that is yet to be thoroughly investigated in terms of its application to energy efficiency. There is only a limited number of articles on this topic so the purpose of this section is to highlight those key literatures, media articles, blogs or any other relevant writings where the idea has been conceptualized.

Energy Service Companies (ESCOs) are looking for potential blockchain alternatives to overcome the energy performance contracting (EPC) complexity [89]. Over the last couple of years, the prevalence of EPC business models has increased significantly [90] and EPCs have become a popular method for improving energy efficiency in buildings. The problem with the EPC model is that it requires several stakeholders who maintain their own records of energy baseline data, implementation costs of technology, project expenditures, and the amount of energy savings achieved, which can generate conflicts between stakeholders when payment is due. It has even been pointed out that the smart contract functionality will substantially decrease transaction fees, and therefore ESCOs will have the opportunity to pursue smaller projects so the cost and time involved in setting up and administering each EPC will be reduced significantly. It will boost the number of ESCO projects, and the overall amount of energy savings that can be achieved as a result. A study by Gurcan et al. created a practical prototype where blockchain technology was applied to the EPC and removed the need for third-party audit committee to perform large volumes of benchmark and actual consumption data measurement and verification [91].

Ethan has addressed the interesting aspect of how blockchain may improve energy efficiency valuations. This includes a discussion on how to encrypt and share energy savings across a blockchain platform to improve the transparency of the energy efficiency market, information security, and service reliability. The American Council for Energy Efficient Economy (ACEEE) is also investigating how blockchain could be utilized to improve the measurement and verification process and how a more fluid energy market could be facilitated [92]. Toyo [93] stated how the application of blockchain technology could boost energy efficiency in the supply side and how it can tackle energy poverty through a decentralized energy network.

In the scope of energy-related certification schemes, a recent research explored the possibility for using blockchain to trade Certificates of Origin Guarantee (GoO), also referred to as Green Certificates. The regulator awards a green certificate to renewable energy producers for each Mega-Watt hour (MWh) of renewable energy generated from certified sources. Those green certificates document details of when it was produced, where, how, and by whom. This certificate also documents who owns the related renewable assets of the clean energy. The certificates may be transferred, bought, sold or withdrawn, but the processing process for such certificates is slow and opaque. The research carried out by Castellanos et al [94] demonstrates

that blockchain can be used to guarantee the validity of green certificates, increase system transparency and minimize transactional costs by eliminating any need for the third party regulators to manage the scheme.

The existing structure of energy regulation may face new challenges as a result of a decentralized system. The insights provided in this research, reveal that blockchain applications provide innovative organizational forms and advantages that have the potential to greatly alter and transform current energy systems. Blockchain technology could help small and large firms alike deliver energy-efficient products and services, providing innovative business models that could enhance energy efficiency in developing nations. Blockchain can improve accountability and cost-efficiency in these systems by decentralizing power. This research analysis reveals that blockchain technology can solve legacy system design constraints such lack of accountability, asymmetric information, high costs, and limited access to funding that are currently preventing the scaling up of energy efficiency solutions. Finally, whether and how blockchain-based energy solutions emerge in the highly regulated energy industry will be primarily determined by regulators.

3.5 Conclusion

In this chapter, detailed literature review has been conducted on Blockchain based distributed applications in the healthcare and energy sector. Existing available Blockchain based distributed applications in healthcare and energy systems have been discussed here. Using blockchain technology, privacy, security, availability and fine-grained control of data access rights can be ensured. The ultimate goal of using blockchain is to improve processes and thus the overall outcomes of the system. It can be concluded easily from the above discussion in the literature from the perspective of Healthcare and Energy system applications, that blockchain based systems will help in; reducing costs by using smart contracts which are embedded general purpose protocols to simplify procedures, reduce administrative burdens and remove intermediaries provides a better alternative to the non-blockchain systems. This will solve many of the current issues, including high administrative costs, lack of data security, and unaddressed privacy concerns.

4 Smart contract framework for healthcare management applications

Blockchain is transforming into a safe and efficient infrastructure for safe data exchange in applications such as the finance industry, operations management, food processing industry, the energy market, the Internet of Things and healthcare systems. Information sharing among health care and hospital systems is a key utilization of blockchain technologies in the medical eco-system. In this chapter, we have designed multiple healthcare ecosystem workflows using blockchain technology to effectively manage the data and processes. Using the ethereum blockchain, different medical workflows have been designed and implemented. This also involves accessing and managing a considerable amount of medical data. This work would facilitate the delivery of better health care services and cost optimisation whilst also multiple stakeholders involved in the medical system. The detailed implementation of all the medical work flows defining all the coding structures and functions executed in the smart contracts are included in the chapter 5 of this thesis.

In this chapter, using practical clinical databases, we examined the applicability of blockchain to the various healthcare workflows and the viability of existing blockchain implementation in specific healthcare eco-system use cases. Within the implementation of the medical workflows for the healthcare management, the associated costs for this system were estimated in terms of a feasibility study which is presented in this chapter. Blockchain technology has emerged recently as a crucial technology in the healthcare sector 's digital transition and numerous academic studies [131] [132] [133] have identified potential for blockchain in the health care ecological system. It is ready to revolutionize the way in which traditional medical systems and companies have been engaged in the healthcare sector over several years [110]. Information technologies (ICTs) and blockchain are the key technologies that enable healthcare institutions to be decentralized and digitized, and provide patients and service providers with modern and digitized healthcare ecosystems [134]. Blockchain data management applications create utilities for patients , doctors and healthcare institutes in the areas of patient record access and control, claims and payment management , medical IoT security management [135] research data authentication and financial audit exchange [136] and

openness. Real-time updates for distributed and encoded, decentralized blockchain network are done in these applications to understand, track, and manage medical information [137]. This also makes it easier for healthcare providers to restrict the unwanted person's access to confidential information.

Management of healthcare involves a number of activities such as management of finances, personnel, patients, legal issues, logistic support, inventory, etc. Medical workflows also include routine activities related to the treatment of patients, which can be depicted as a sequence of conditional acts. These are designed to provide stronger internal controls, enhance quality, compliance, profitability, and minimize risk, work cycles and overhead costs in hospitals and other providers of health care. In this chapter, multiple medical workflows are designed for various application areas of health care management systems.

This research introduces a smart contract healthcare framework for managing medical data, and streamlining complex medical procedures. We addressed state-of-the-art blockchain work in the field of healthcare, and introduced ethereum-based healthcare management solution. This research work also aims to indicate the prospective use of blockchain in healthcare and to demonstrate the challenges and possible directions of blockchain research.

4.1 System design and implementation framework Ethereum

The aim of our designed system is to facilitate different parties involved in the health care system including medical professionals, patients and healthcare insurance providers. This research thesis proposes an innovative new of decentralized data management framework using blockchain technology for managing Electronic Healthcare Records. The system architecture provides patients with extensive, unalterable logging and accessibility to their health records throughout different facilities and treatment care units. Using specific blockchain properties, this model manages data authentication, data retention, monitor changes for previous data records, updating data for clinicians and patients) and makes efficient data sharing in the system. It manages the records without having any central information repository; the modular framework architecture incorporates existing, local digital storage mechanisms for doctors, enabling interoperability and exchange of data among different stakeholders. Our objective is to develop a system which facilitate patients, providers and other stakeholders, over time, without creating the database that centralized the data and risked creating an attack on patient's information. Patient's electronic healthcare records contains

sensitive information. We have showed the patient EHRs hierarchy in figure 4.2. There are different permissions which shows who have access to what data in the system. Those permissions and the workflows are explained in detailed in this chapter. The detailed implementation of these data access rights and workflows have been given in the chapter 5 of this thesis. The platform implementation will be a decentralized application (DApp) that supports a private blockchain network at the back end, with a distributed file system (DFS). Ethereum has been used to implement a smart contract framework for blockchain in healthcare. This platform is open source, and presently one of the largest public blockchain networks with a community formed and a wide set of public DApps. The platform apparently uses a consensus proof-of - work (PoW) algorithm based Ethash, but in the immediate future, engineers are working to turn it into a proof-of - stake (PoS) scalability algorithm. Ideally a Delegated Proof-of-Stake for the creation of distributed applications, the consensus algorithm (DPoS) or Functional Byzantine Fault Tolerance (PBFT) is suitable. By matching DFS content with ledger registers, the DApp will have the potential to detect irregularities, unauthorized data insertions and missing entities. An Audit Timeline is labeled for each step. Functions, events, state variables, and modifiers are the essential elements of the smart contracts and are written in the language of the solidity programming. Remix and Kovan test network was used to build smart contracts on the testnet and testnet ethers to pay the transaction cost. The creation of smart contracts involves three stages, using Solidity programming to write, compile, and announce the contract on the network. The bytecode is created through the real-time Solidity compiler. Ethereum Wallet was used to announce smart contracts on the Ethereum Blockchain network. Figure 4.1 shows the overall mechanism of a smart contracts with Ethereum blockchain network, where the mining process has been excluded for the purpose of simplification. This smart contract has been constructed into machine-level byte code in which each byte reflects a function, and then posted as an EVM-1 transaction to the blockchain. A miner then picks it up, and confirms Block-1. When a user processes the response through the web interface, the EVM-2 queries and embeds the web-based data into Transaction tx and deploys it to the blockchain. In Block-2 the transaction tx status is changed. If node 3 decides to test the states that are stored in the contract, then it must synchronize the changes that tx triggers up to at least Block -2.

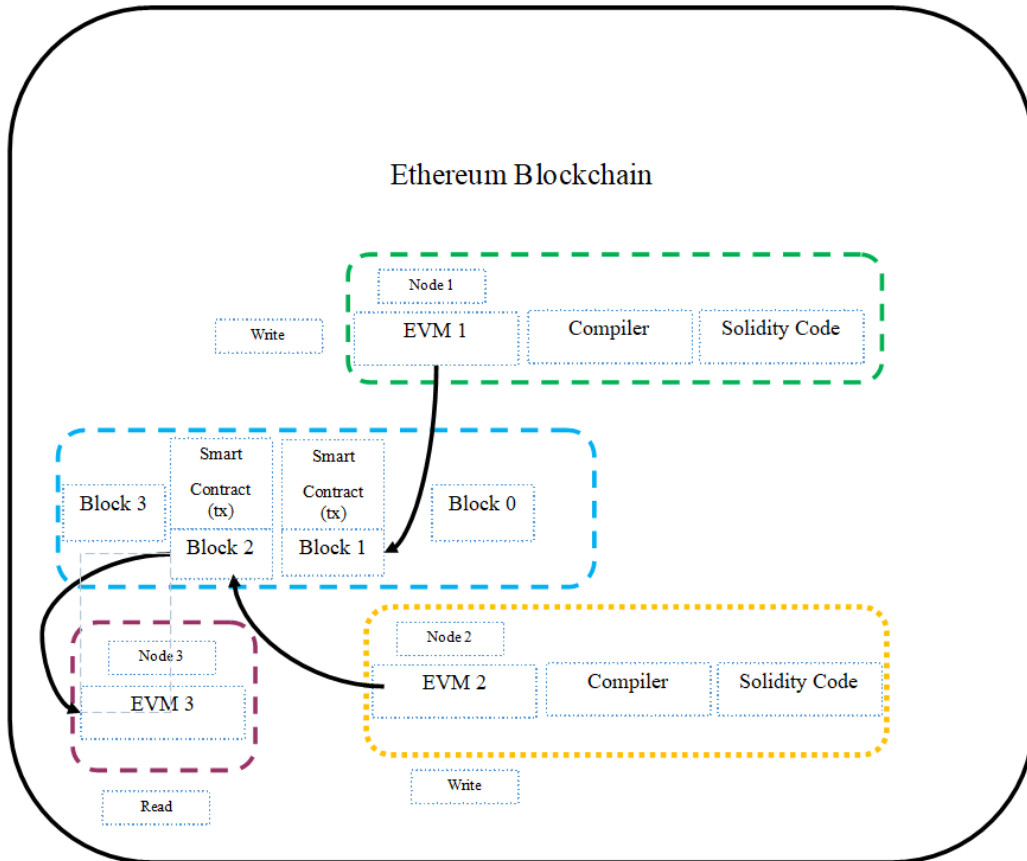


Figure. 4.1 Ethereum Smart Contract Mechanism. Reprinted with permission from Khatoun, A., Electronics 2020, 9(1), 94.

4.2 Medical Blockchain smart contracts

We leverage Ethereum's smart contracts to construct digital representations of actual medical records that are stored within individual nodes on the network. We are building contracts to include metadata, permissions and data validity of record ownership. Blockchain transactions of our network hold cryptographically signed instructions to handle certain properties. The contract's State-transition functions execute policies only through valid transactions that enforce data alternation. Such laws can be designed to implement any set of rules governing a specific medical record as long as it can be interpreted in a computational way. For example, a policy may involve the sending of separate consent transactions from patients and healthcare professionals before granting permission to a third party to access. Smart contracts were designed for different medical workflows and then data access permissions were managed between different entities in the healthcare ecosystem using Ethereum blockchain network. In

our system, we are managing an off-chain local database for the healthcare records. Hierarchy of electronic healthcare records (EHRs) can be seen in the figure 4.2.

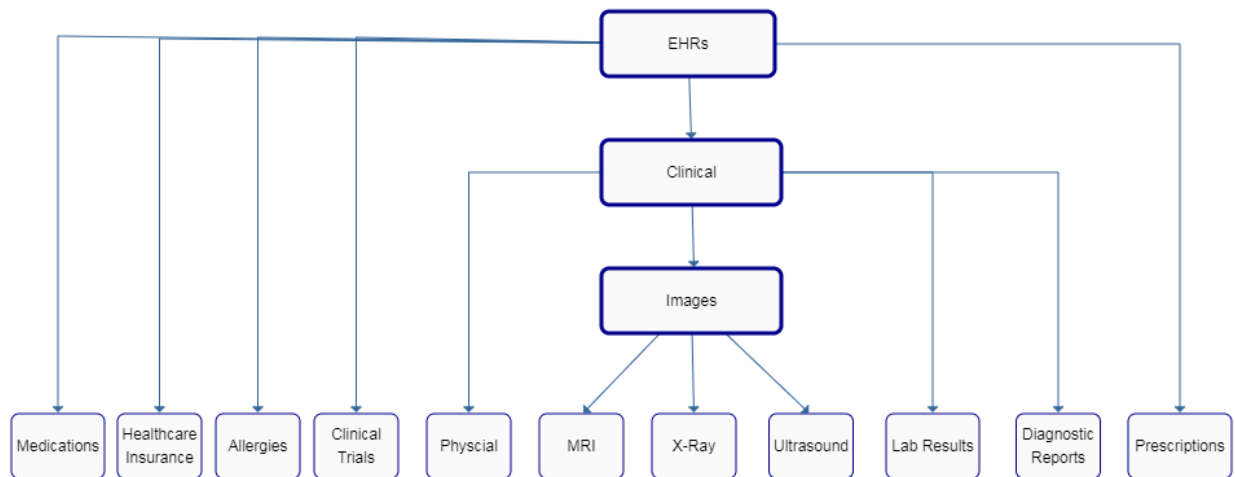


Figure. 4.2 Electronic Healthcare Records.

A smart contract, stored on blockchain technology has been developed and tested that have all the conditions from managing different permissions to accessing data as shown in Figure 4.3 and it can be seen that a number of stakeholders are involved in this scheme trying to perform various activities. This will create stronger interactions between patients and doctors with the help of smart contracts. The rules on data access rights are incorporated into smart contracts. This can also help monitor all behaviors with specific ids from their origin to their surrender. There will be no need for a centralized body to oversee and authorize the project because it can be handled directly via the smart contract that will greatly reduce the management process administration costs. All medical record data is stored in local database storage in order to preserve efficiency and economic viability, and the data hash is the data item of the chain's block.

The information transactions shall be signed with the private key (patient or doctor) of the owner. Data ownership and access rights exchanged by users of a peer-to-peer private network are the block material for the program. Blockchain technology encourages the use of smart contracts that allow us to automate and monitor such state changes (such as a shift in accessing rights or the birth of a new system record). We sign patient-provider relationships on an Ethereum blockchain via smart contracts that combine a medical record with accessing

permission rights and via providing data retrieval instructions (essentially information pointers and metadata) for the outside server execution to prevent tampering, we include a cryptographic hash of the blockchain record to ensure data integrity.

Providers may attach a record number associated with a particular patient, and patients can require sharing of records between providers. In both cases, the party receiving new information receives an automatic notification and may check the submitted record before approving or rejecting the data. That keeps the participants informed and engaged in the evolution of their records. This system prioritizes usability by also offering an assigned contract that aggregates links to all a user's patient-provider relationships, thus creating a new reference point for checking for any updates in medical history. We are using public key cryptography technique for the management of identity verification and using a DNS-like implementation structure that is mapping an already existing and widely accepted form of ID as person's name or their social security number to the Ethereum blockchain address of the user. After referring to the blockchain network to confirm different permissions via our system such as database authentication server, then a syncing algorithm will handle "off-the-chain" data exchange between patient's database and a provider's database.

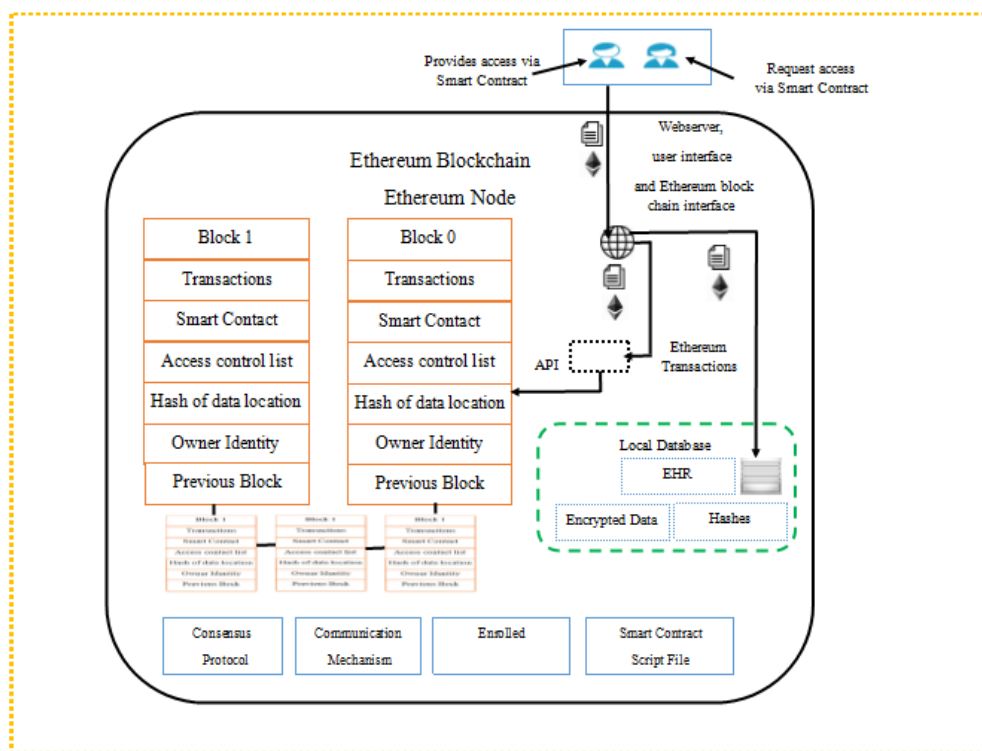


Figure. 4.3 The Schematic of the System workflow with smart contract controlled access.

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4.3 System design and development

Different medical workflows were developed and enforced via the blockchain smart contract framework, involving unique medical procedures. This include the issuance of specific medical prescription for the treatment of complex diseases and their procedure such as care protocol for patients under surgery. The purpose of designing these smart medical contracts is to facilitate the overcoming of administrative inefficiencies for the patients, doctors and healthcare organization. This system will help in the collection, analysis and management of complex data and procedures in healthcare.

Algorithm 4.1: Patient Monitoring and updating records

Input: Ethereum address of the patient and all the other stakeholders involved in the system

Initialization of the process = Access approved

If Enrolment stage is finished

Then

 Allow all the transactions to be added in the network

 Mapping of data to the respective address

end

else

 Don't allow/accept unauthorized transactions

End

If Patient drop outs

Then Stop processing that further

 Update the records

 Notify/update the other peers in the network about the progress

End

Algorithm 4.2: Patient Monitoring in the event of Emergency

Input: Emergency case reported

If during the monitoring phase an emergency occurs
& Ethereum Address = Primary doctor's EA /GP

Then
Allow the Input details to be included as a valid transaction

End

else
Don't allow/accept unauthorized transactions

End

If Ethereum Address = Specialist
Approve the transaction from valid EA

End

else
Don't accept unauthorized transactions

End

Algorithm 4.3: Reporting and Analysis

Input: Finalized the reports and update the EHRs

If Analysis and reporting is completed
Accept the input as valid transaction

End

else
Don't allow/accept unauthorized transactions

End

If Primary doctor/GP = EA **then**

```
    Allow the accept/reject decision for the reports and analysis
else
    Don't accept unauthorized transactions
End
```

4.3.1 The process flow of a smart contract for medical prescriptions

The key purpose is to improve the process of medical prescription handling by eliminating the long waiting period cycle, removing the fraud factor from the system and the human error rate caused by misunderstandings by the doctors. A doctor to write a prescription for the patient and needs to put it through a smart contract into the patient's healthcare records. The pharmacy then utilizes this prescription through the Ethereum blockchain smart contract, with the permission of the primary providers and the patients. After obtaining the prescription, the pharmacy then assigns the medication to the patient's healthcare records through smart contracts along its expiry date and dosage use, and then the medication is ready for patient selection. Medicine satisfaction among doctors and drug stores is generally coordinated by the smart contract app. Doctors spend less time discussing demands for medications or speaking directly to drug stores during a patient's visit.

As shown in Figure 4.4. data flow for the issuance of a medical prescription includes patient, primary doctor (GP), and pharmacy. It also contains prescription details which would include the medicine Id, date of expiry and patient Id.

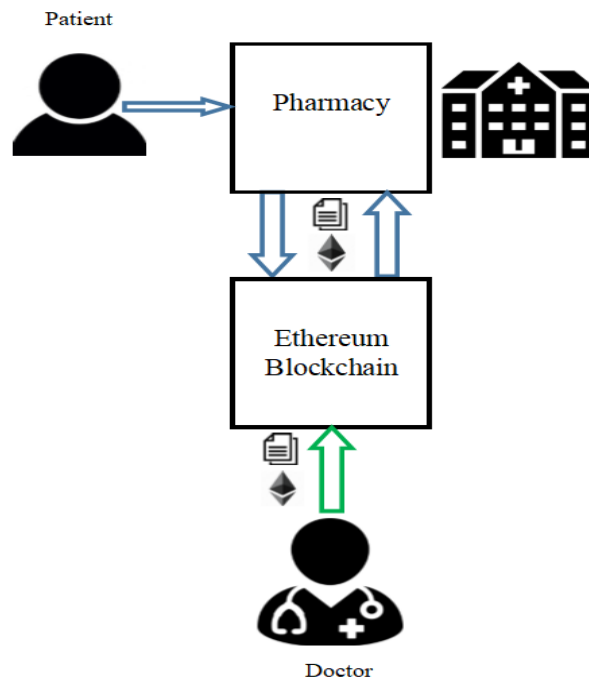


Figure. 4.4 The Smart contract for issuing and filing of medical prescriptions. Reprinted with permission from Khatoon, A., *Electronics* 2020, 9(1), 94.

4.3.2 Laboratory Test Results

The main goal is to share the information through smart blockchain contracts by allowing laboratories, doctors, emergency clinics and different parties involved in the system to effectively access and share the therapeutic information of a patient among different stakeholders as shown in Figure 4.5.

Here we consider a use-case in which a patient has to visits a blood test laboratory. After processing, the laboratory will put the outcomes into the patient records, the patient receives these information updates via Ethereum blockchain, a notification that now the test's processed results are available, and can either choose to enable the laboratory to encode the relevant information and place it on Ethereum blockchain. The patient grants approval to post the details on the blockchain. In the case of an emergency with the patient where he is unconscious, the emergency department may easily access patient details through Ethereum blockchain and provide personalized care.

By having allowed patient records to be posted on healthcare blockchain, a patient avoids having to either carry the laboratory results on their own or arrange for records to be faxed to various care providers. He also makes sure all of his health care professionals have the knowledge available to deliver the best medical treatment. Laboratories minimize printing

and mail or fax regulatory expenses for each test result to singular distributors. In addition, laboratories and patients have access to the healthcare blockchain, where they may obtain installments from protective firms advising the transferred information to process claims or from pharmaceutical organizations selecting the information to be used in contemplates. Consultants and emergency departments have free access to gather restorative information about their patients, reducing authoritative research and costs.

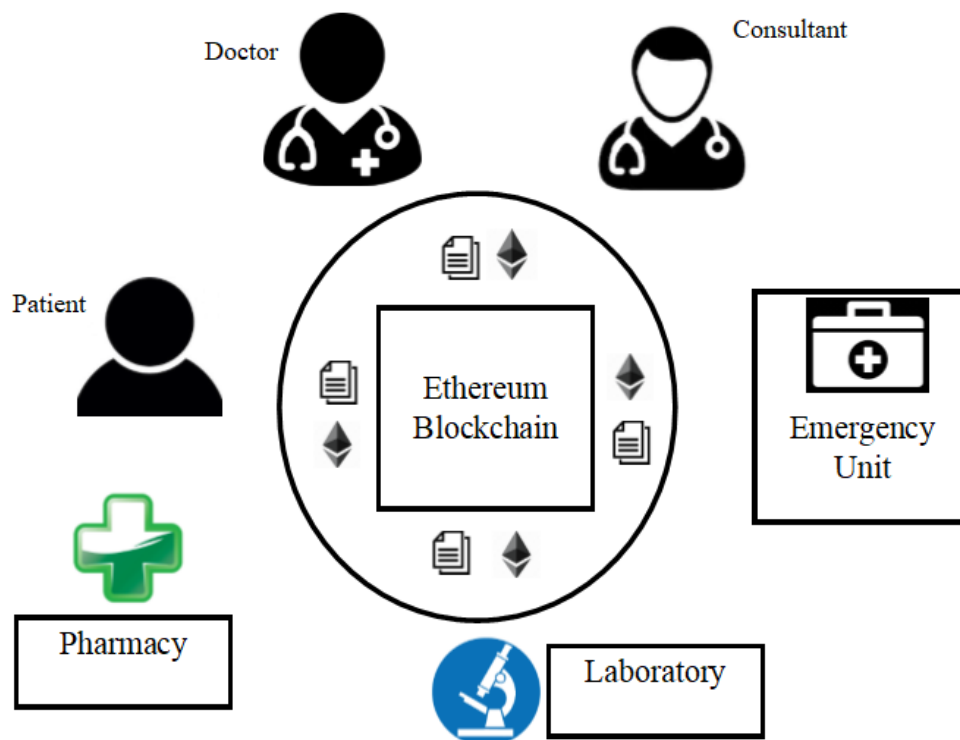


Figure. 4.5 Smart contract for sharing lab results. Reprinted with permission from Khatoun, A., *Electronics* 2020, 9(1), 94.

4.3.3 Communication between Patients and Service Providers

Under this use-case, as seen in Figure 4.6 the patient submits an application for a medical condition. It automatically adds that request through the smart contract system to the primary doctor. A doctor must consider the request and respond with a recommendation, and, where appropriate, refer the patients to the specialist for further care. Any patient information regarding treatment history should be reported on the EHR. Please note that patient records are maintained by a local database, where there are specific rules that can access the record to what extent and to what extent these rules are governed by the Ethereum blockchain smart contracts.

Another case in which the patient submits an application for a particular medical procedure. Accordingly, the strict structure of the agreement sends this application to the appropriate specialist. A doctor acknowledges the demand and respond appropriately with a recommendation, and where patients are forwarded with the specialist for further care. Any patient information about treatment history must be recorded on the EHR. Notice that a local database holds patient records where there are clear rules which can approach the record to what degree and how well these guidelines are implemented through the competent Ethereum blockchain contracts.

Patients who are seeking health information on a particular topic receive recommendations that are much more customized than those offered by a web search. Senior doctors are finding a new way to monetize their experience without having to overbook their schedules, whereas junior doctors can enter a new potential customer audience and develop their brand within their specialization. Payments motivate patients to receive Junior Physician recommendations.

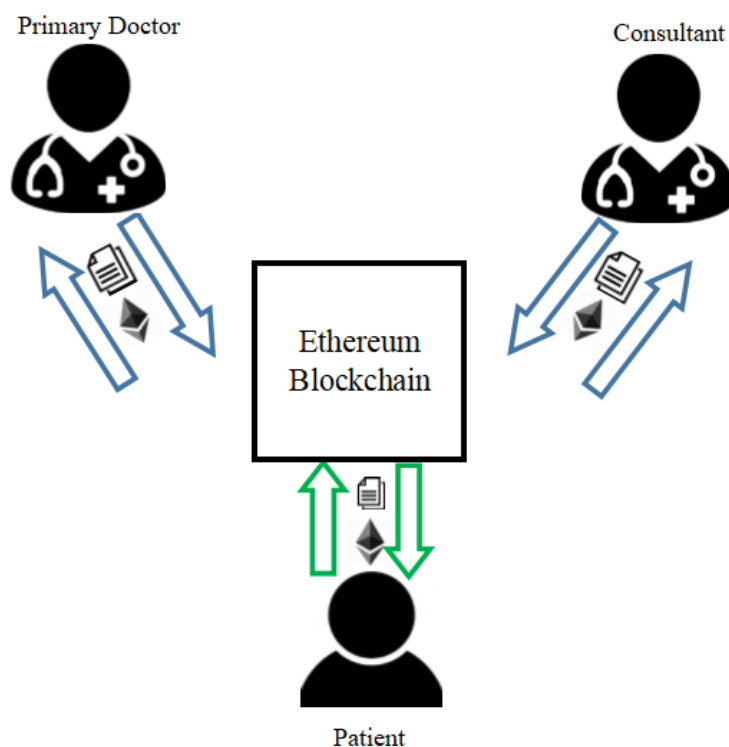


Figure. 4.6 Smart contract for enabling communication between patient and service provider. Reprinted with permission from Khatoon, A., Electronics 2020, 9(1), 94.

4.3.4 Healthcare reimbursement

The main aim is to speed up the reimbursement process for the medical healthcare system. In this, doctors will be able to continue to proceed with treatment quickly, instead of having to put their patient's treatment on hold while waiting for the payer to respond. Automated smart contract execution will supervise the entire process. Reducing-and eventually eliminating-the human effort to manually monitor and respond to inquiries for prior authorisation, and reducing appeals caused by misinterpretation of manually written prior authorisation forms.

Health Insurance Companies posts its policies through smart blockchain contracts which contain the policies used to ascertain authorization. A supplier then lodges a request for prior authorisation for a consultant appointment, treatment or prescription via Ethereum blockchain network. The payer's smart contract for a health policy automatically decides authorization using the patient's medical details processed by Ethereum blockchain and the request details. Authentication data are then immediately returned to the provider. Further, the patient, as well as any laboratories, pharmacies, specialist doctors and other stakeholder's involved in the system to whom the patient has delegated access, will also verify the authorization for insurance in real time. The whole process can be seen in Figure 4.7.

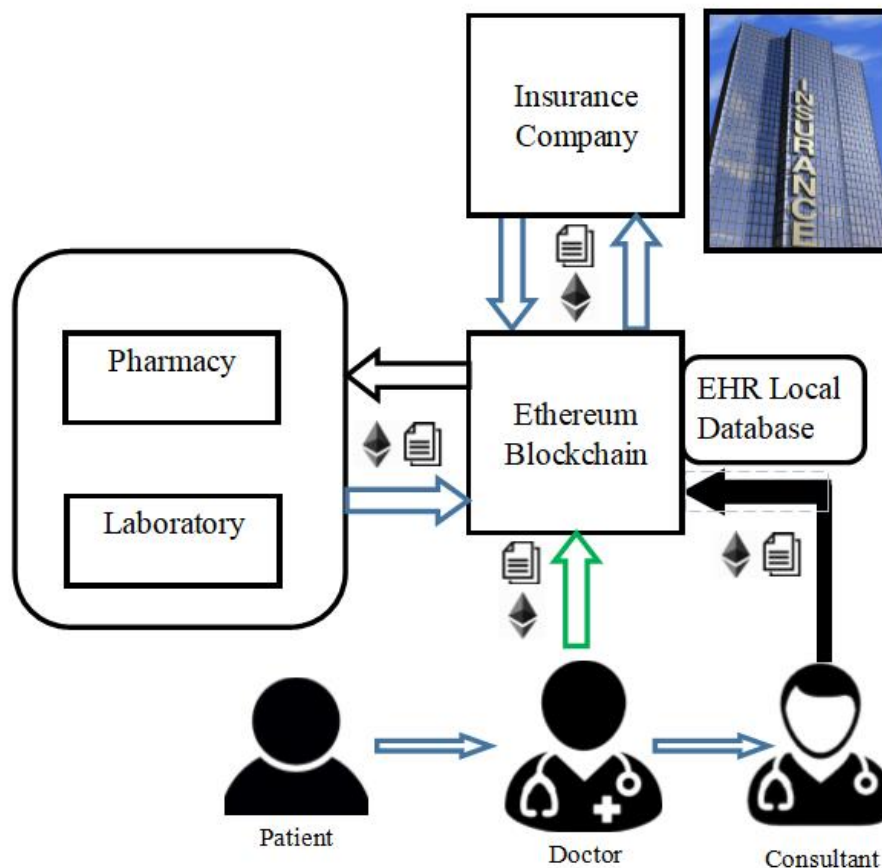


Figure. 4.7 Smart contracts for healthcare reimbursement. Reprinted with permission from Khatoun, A., *Electronics* 2020, 9(1), 94.

The automated prior authorisation process will result in considerable cost savings for payers, which already spends large sums on manually monitoring and responding to requests. Doctors can proceed with treatment quickly, rather than having to stop their patient's care while waiting for the payer's response. In fact, patients will be spared concerned about how their insurance will cover the medication their doctor recommends. With instant prior authorisation information available, doctors and patients can work easily with a care plan specially tailored to the patient's needs and adequate medical insurance coverage.

4.3.5 Ethereum Blockchain contracts for clinical trials

Providing healthcare, medical technology manufacturers and all the multiple stakeholders involves in the system throughout the processes of initialization, verification and validation of a trial with a quicker and more cost-effective alternative to the existing recruitment in the process of conducting clinical trials. This will also entails substantial expenditures in

purchasing patient contact information from independent data suppliers and carrying out extensive pull-marketing campaigns.

The main objective is to allow users to run clinical trial-related smart contracts on an Ethereum network leading to safer medicines and increased public interest in medical research. We will handle metadata in this process including protocol registration, pre-set study information, screening and enrolment logs through smart contracts.

A pharmaceutical company is searching for metadata stored on the Ethereum blockchain to identify possible patients for clinical trial inclusion as shown in Figure 4.8. The organization then sends a letter, including an application to read access to their medical records, to selected patients, including any related laboratory test results. If the patient provides access, a pharmaceutical company bill will be processed via smart contracts, awarding the patient part of the fee paid, and another portion to the laboratories which recorded the patient's correct test results.

Drug and medical device manufacturers will significantly reduce spending on data purchases and marketing efforts through direct targeting of qualifying customers. Patients, meanwhile, will gain access to alternative care options, in addition to obtaining compensation for engaging in trials. Laboratories responsible for delivering results would have a new way to monetize their data. The whole clinical trial processes includes different parties such as Review Board, FDA, Sponsor, Primary Investigator and lab scientist throughout the process.

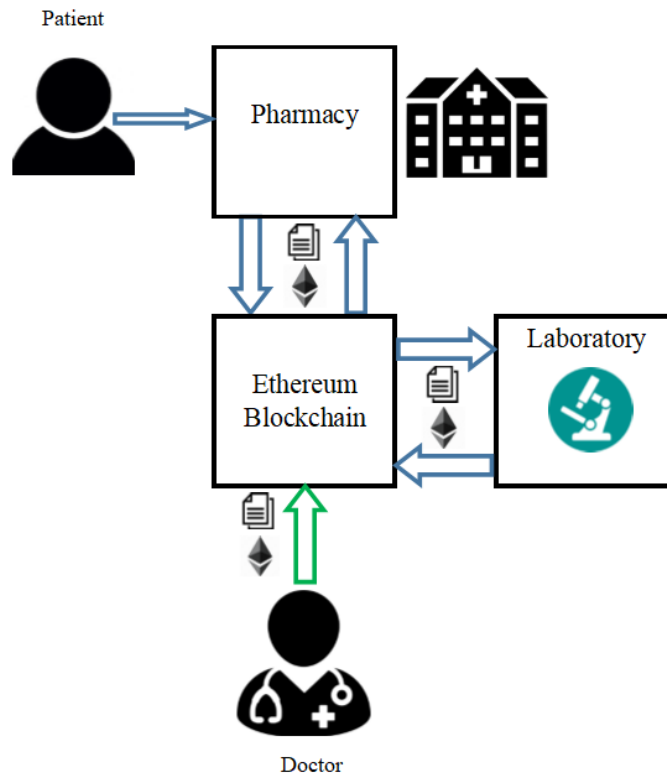


Figure. 4.8 Schematic diagram of Smart contracts for conducting clinical trials. Reprinted with permission from Khatoon, A., *Electronics* 2020, 9(1), 94.

4.3.6 Surgical procedure via smart contracts

In a busy clinical process, the procedure associated with surgery can be a huge burden. The EHR Surgical Workflow System addresses the needs of busy practices and converts a dynamic process into a simplified, all-in-one workflow. The practice could be fully integrated with EHR Surgical Workflow system via Ethereum blockchain smart contracts. This also allows administrators, billing, front desk operations, and other tasks to accomplish things from pre-operative medication care to post-operative patient management to support the overall workflow. Then, the details are seamlessly inserted into the patient's prior surgical record. Patient consent taking and initial assessment of the patient could be recorded through the smart contract features. Our process workflow consists of different activities associated throughout the patient surgery process. This requires pre-approval, medical certification, scheduling of surgical operations, pre-operative testing and consent to record. The visit is documented in the process, and treatment is registered and compensated. This would be useful

in revising the past surgical cases or the cancelled surgical procedures. Figure 4.9 and Figure 4.10 respectively display algorithmic workflow and the solidity smart contract components.

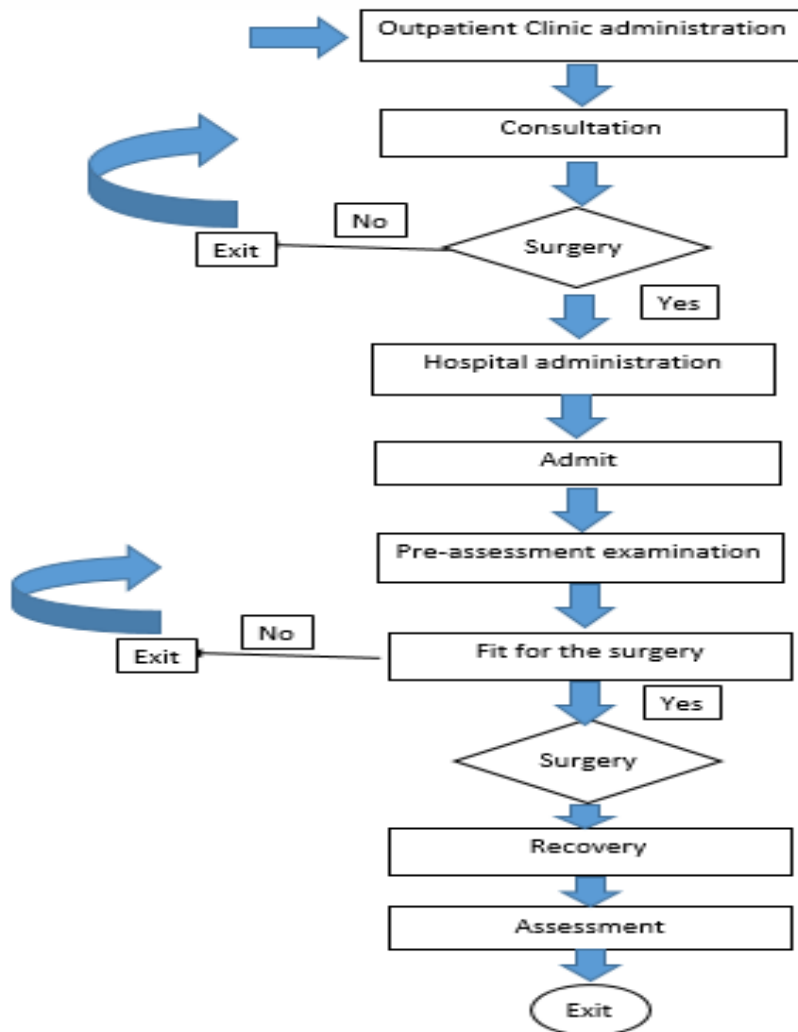


Figure. 4.9 Algorithmic workflow for a smart contract with surgery patients. Reprinted with permission from Khatoon, A., Electronics 2020, 9(1), 94.

```

1 //Contract Surgery
2 pragma solidity ^0.4.18;
3 contract Surgery {
4     address [] public consultant;
5     bool [] public consultantEnabled;
6     address [] public realtionships;
7     address public surgicalteam;
8     bool public sugicalteamEnabled;
9     address public patient;
10    bool public patientEnabled;
11    address public anesthesiologist;
12    bool public anesthesiologistEnabled;
13    modifier isowner () {
14        bool enable;
15        if (agentEnabled && msg.sender == agent) enable = true;
16        for (unit i = 0; i < consultant.length; i++) {
17            if (consultantEnabled [i] ) && msg.sender == consultant[i]) {

```

Figure. 4.10 Smart contract surgery.

4.4 Cost estimation

In terms of setting up and deploying a medical blockchain, an estimate of the costs associated with deploying smart contracts for healthcare needs to be made. The ultimate aim is to develop a program with all the advantages of blockchain that can offer a feasible electronic health system. In Ethereum blockchain, all programmable computations and calculations cost some sort of fees to avoid network abuse and to resolve other computational related problems. The fee is listed as gas in Ethereum blockchain to run all kinds of transactions. Gas in the Ethereum blockchain network refers to the payment or price value necessary for a successful transaction or contract execution on the Ethereum blockchain platform. The exact and accurate gas price is determined and calculated by the miners of the network, who could refuse to validate a transaction if the gas price does not meet their limit. All operations running on the Ethereum also including computations, message calls, smart contract creation / deployment and storage on Ethereum Virtual Machine (EVM) therefore require gas to perform all of these multiple tasks. To perform transactions on Ethereum virtual machine, if anyone wants to do some kind of activity on EVM, they must have unique amount of gas in their account. With any transaction there is a gas cap, and if there is any remaining gas it will return to the user account after the transaction has been completed. If a user has no valid balance account, he is unable to carry out any type of operation and is therefore considered invalid. In EVM Ethers, gas is purchased and the users on the network running the transactions can set their account gas limit for that particular transaction. But then again if they tend to approve and endorse the transaction or not, it is on the miner again. When a sender wants low gas price, charging for the gas will cost them high price and miners would be able to get great value and would be rewarded for the transactions. A miner then performs the computation to add that transaction to a block. A miner can then transmit the new block to the network after the successful execution of transactions. The gas utilizes during the broadcasting of smart contract depends on how complex the function of that specific smart contract is and also the number of stakeholders and interaction involved in the system.

4.5 Validation of the workflows with HSE datasets

We have used our smart contract workflow processes built to estimate the cost of implementation using actual healthcare datasets which we have taken from HSE Ireland. In ethereum, details of the blockchain transaction can be seen in Figure 4.11. The datasets are described in section A. In section B, using the actual datasets, the cost of deployment is calculated and plotted for different factors.

4.5.1 HSE Dataset

Datasets have been taken from the Health Service Executive (HSE)Ireland from their different archive system (<https://data.ehealthireland.ie/>) [138]. The Health Service Executive is responsible for delivering public funding for all people living in Ireland to the health and personal social services. In this work, all the outpatients, the waiting list of hospitals across different departments / hospital in Ireland were considered to be used. The waiting lists for the outpatient, hospital and day cases are managed by the National Treatment Purchase Fund (NTPF) from data collection to its validation phase. The OP's Waiting List study reveals the cumulative number of patients waiting for a first consultation appointment at a consultant-led outpatient clinic in the different time ranges. Each individual report is composed of the numbers waiting in each specialty per hospital. The numbers were aggregated under a 'Small Volume' heading to protect the confidentiality of individuals where < 5 patients are waiting in a particular specialty / hospital. All reports consist of monthly data over the course of a year.

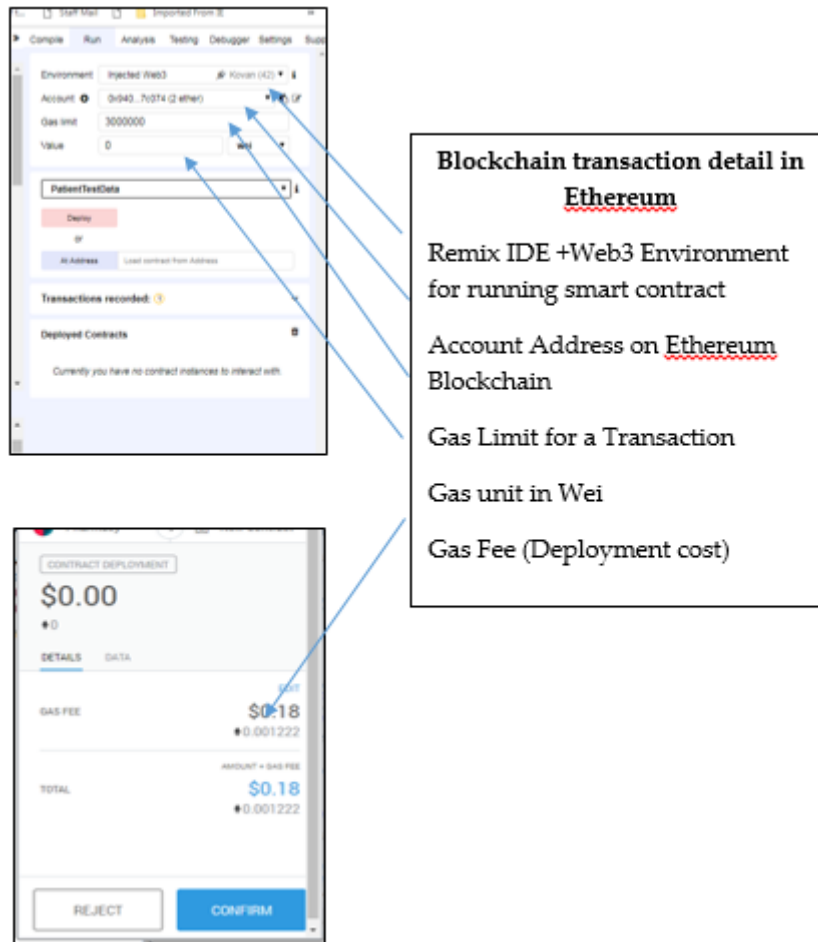


Figure. 4.11 Metamask extension for calculating smart contract cost.

The cost of creating, deploying and running of a smart contract needs ethers as a gas as seen in the figure 4.11. Whenever we need to broadcast a transaction on the network it needs a gas which can be measured in wei units. We are paying for the gas needed to run the transaction and function of a smart contract on the ethereum blockchain network via ethers using Metamask. MetaMask calls `eth_estimateGas` on the Ethereum node. `eth_estimateGas` basically measures the amount of gas used to run the transaction. It also depend on the block hash and block number that how much gas would be needed to run the specific smart contract transaction on ethereum blockchain.

Figure 4.12 below shows the county wise number of pharmacies, Figure 4.13 shows the number of transactions for different departments.

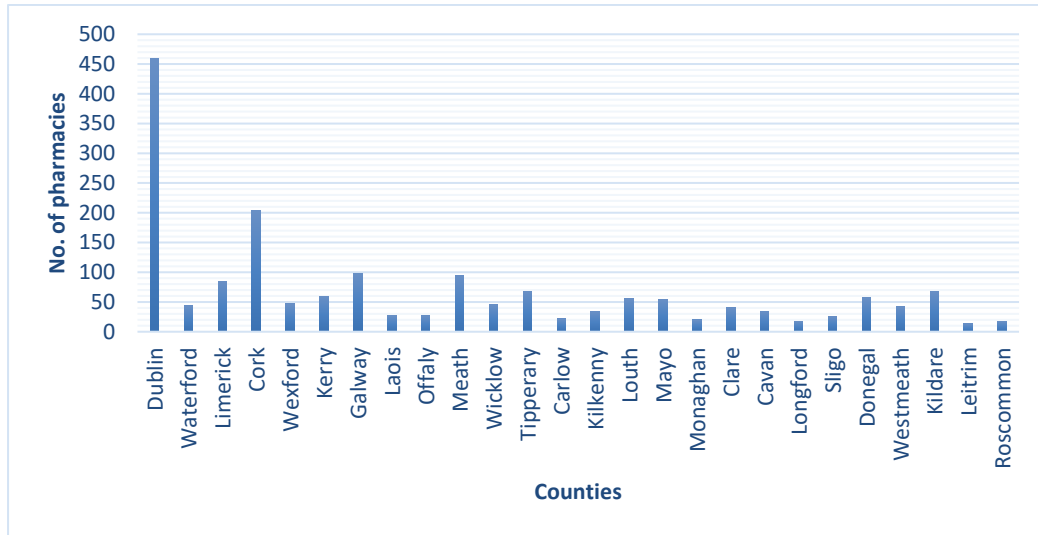


Figure. 4.12 Plot showing county wise pharmacy list from Ireland.

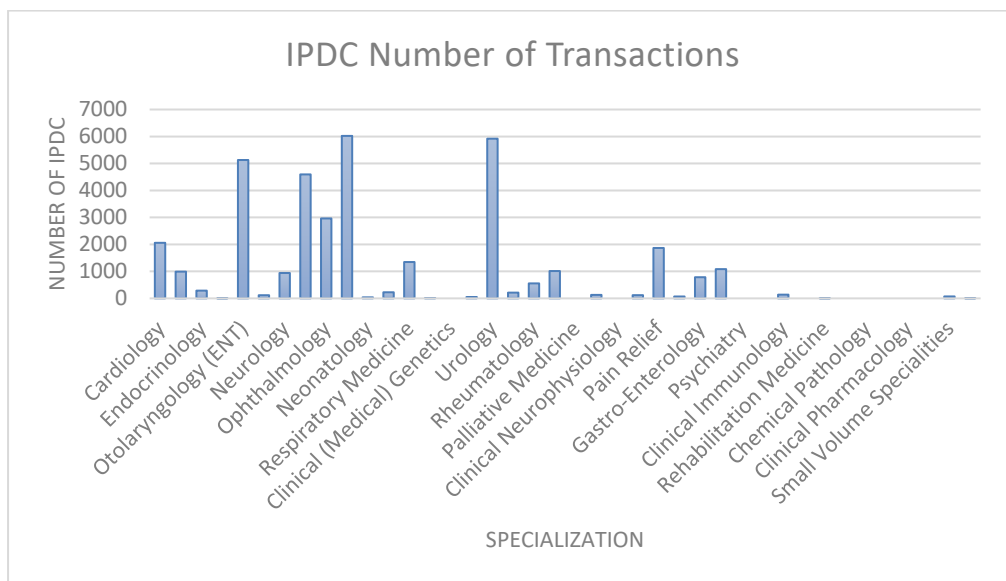


Figure. 4.13 Number of IPDC and their transaction across different departments/specialty.

4.5.2 Cost estimation using real datasets

The costs associated with implementing smart healthcare contracts need to be calculated in terms of the deployment of healthcare blockchain. The ultimate goal is to develop a system that will provide a sustainable electronic health network with all the advantages of blockchain. All

programmable calculations in Ethereum blockchain cost some fees to prevent network misuse and to solve other computational related problems. All activities, multiple computations, message calls, intelligent contract creation / deployment and storage on Ethereum Virtual Machine (EVM) therefore involves gas to perform all these certain tasks and activities.

The cost to deploy smart contracts for a healthcare management system has been compiled. There is cost known as Gas for running an operation on the Ethereum blockchain. All the transactions require 21,000 gas as the basic operational requirement. If a user interacts with Ethereum's smart contract, an additional gas associated with running and execution of those specific smart contract transactions will require 21,000 of the gas. The gas was compiled for medical smart contracts to enable contract deployment to communicate with the different contracts. More complex the smart contract functions / operations use more electricity, resulting in more fees. From the point of view of feasibility, it is very much clear and obvious from the results that the cost of smart contract deployment for healthcare management system is extremely low. As far as medical system is concerned, this expense is very affordable and everybody would like to pay this small charge to have control of their EHR and retain their medical data for life. Figure 4.14 indicates the expense of deploying smart contracts for each pharmacy, as our program estimates.

We have calculated the costs for patients in the general outpatients, paediatric clinic and surgical patients. The number of smart contract transactions and their related costs as calculated by our method are shown below in the Figures 4.14–4.29.

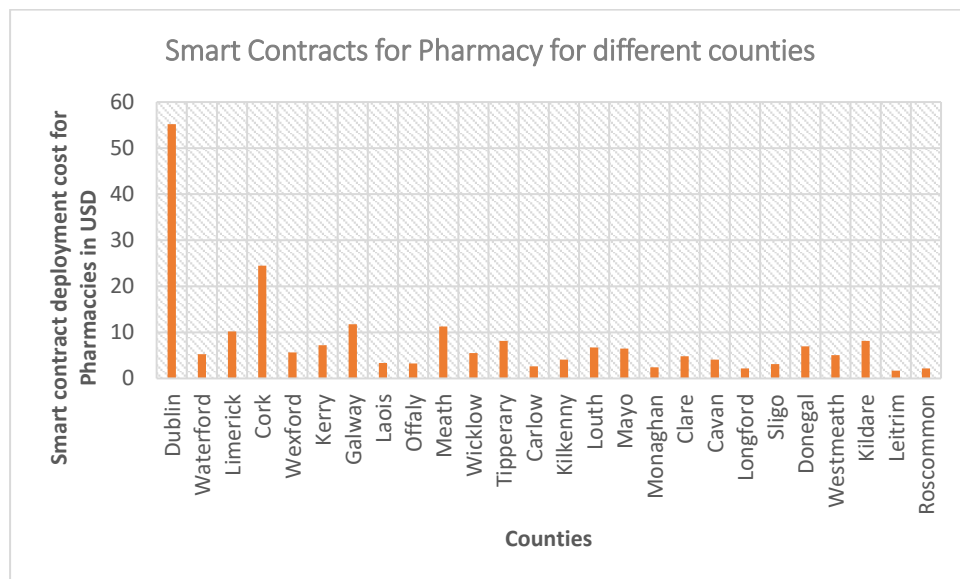


Figure. 4.14 Plot showing smart contract deployment cost for countywise pharmacies in Ireland.

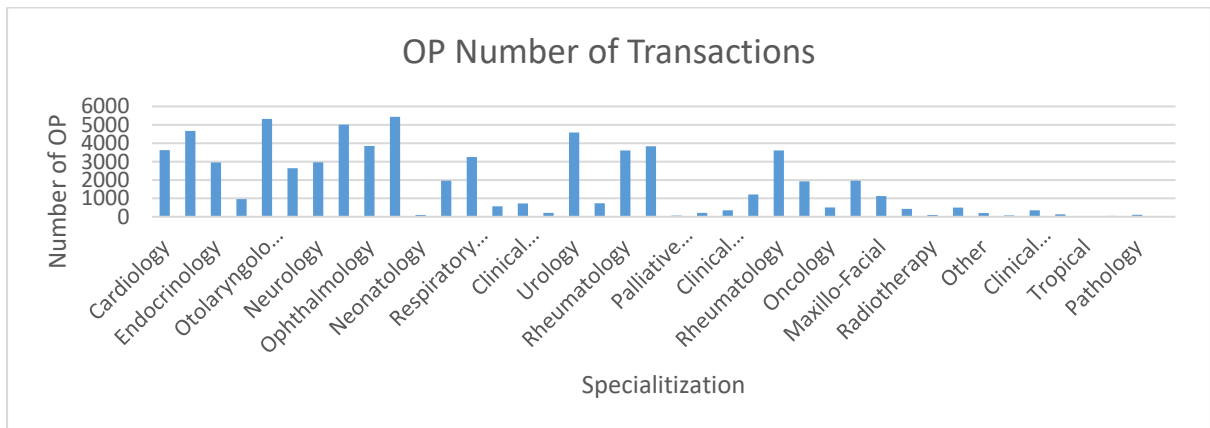


Figure. 4.15 Cost comparison among different smart contracts and entities.

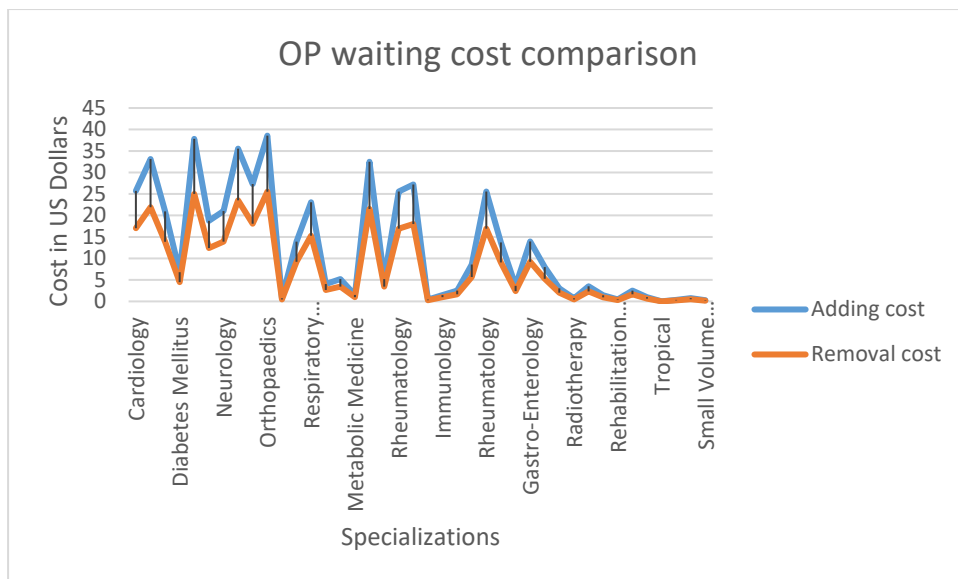


Figure. 4.16 Adding and removing entity cost for waiting list outpatients (OP) in the system across different departments/specialities.

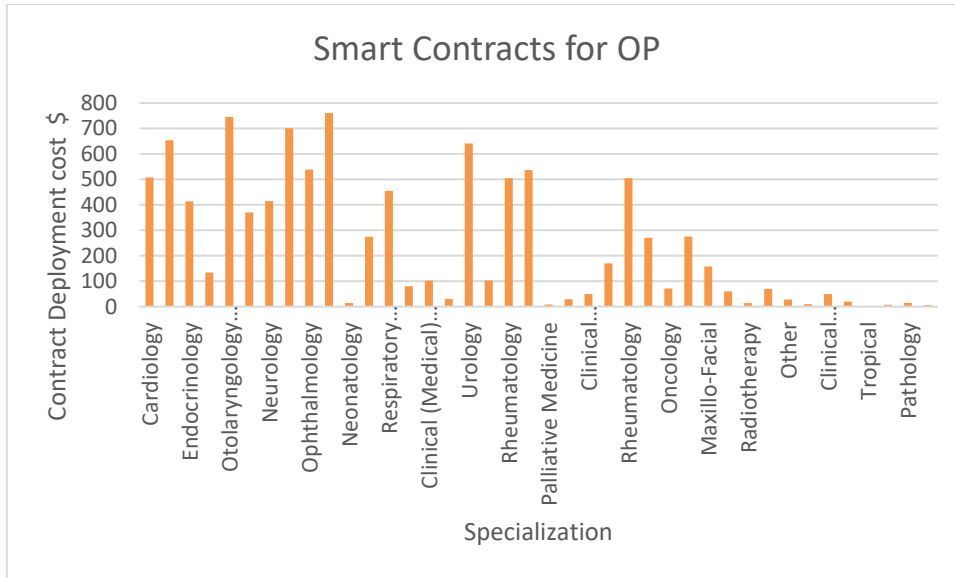


Figure. 4.17 Smart contract deployment cost for Outpatients (OP) across different departments/specialities.

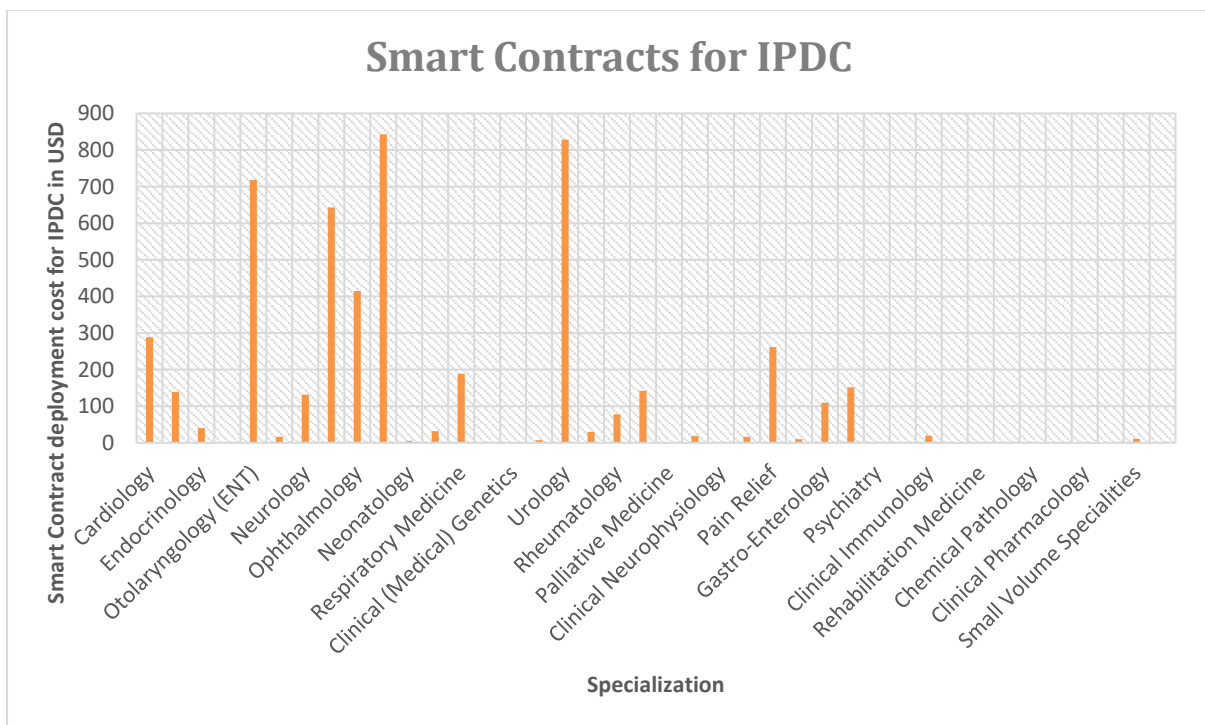


Figure. 4.18 Smart contract deployment cost for Inpatients and Day cases (IPDC) across different departments/specialities.

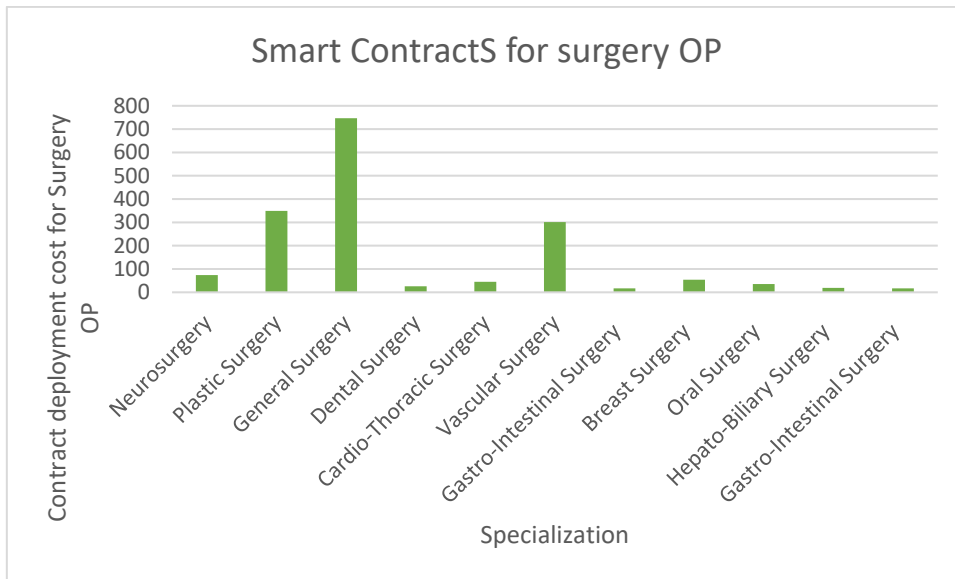


Figure. 4.19 Smart contract deployment cost for surgery outpatients across different departments/specialities.

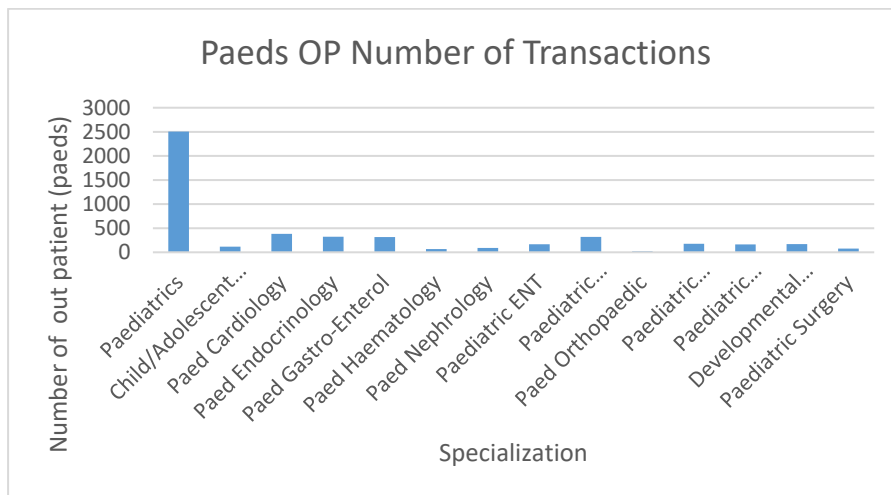


Figure. 4.20 Number of paed outpatients (OP) and their transaction detail across different departments/specialities.

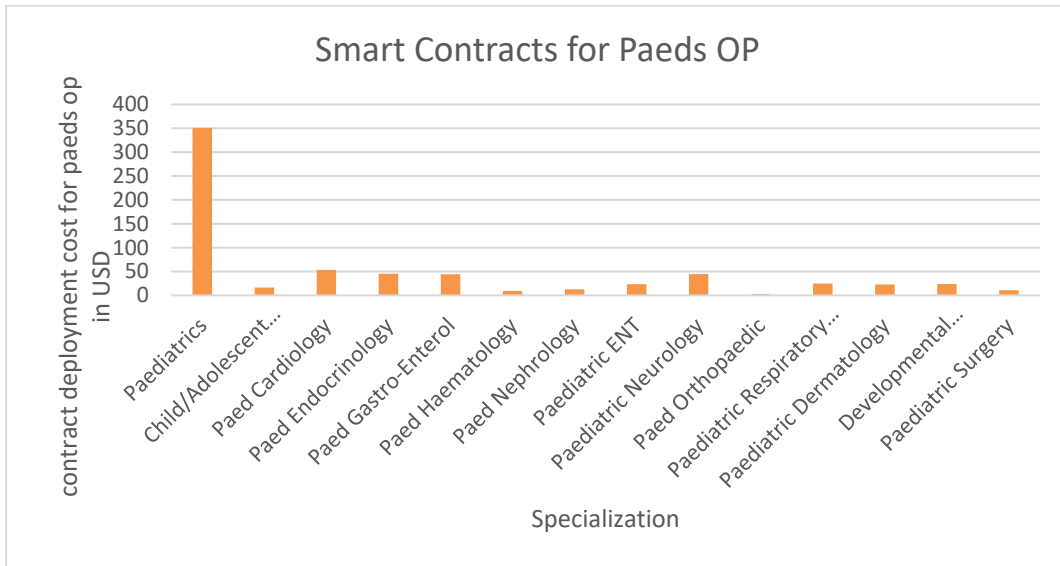


Figure. 4.21 Smart contract deployment cost for paed outpatient (OP) across different departments/specialities.

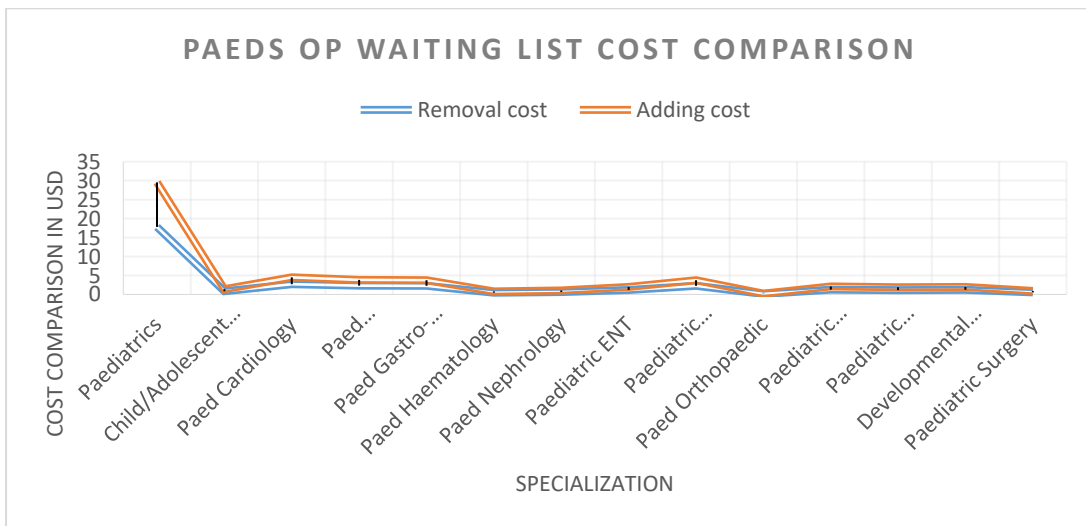


Figure. 4.22 Adding and removing entity cost for Paeds outpatients (OP) in the system across different departments/specialities.

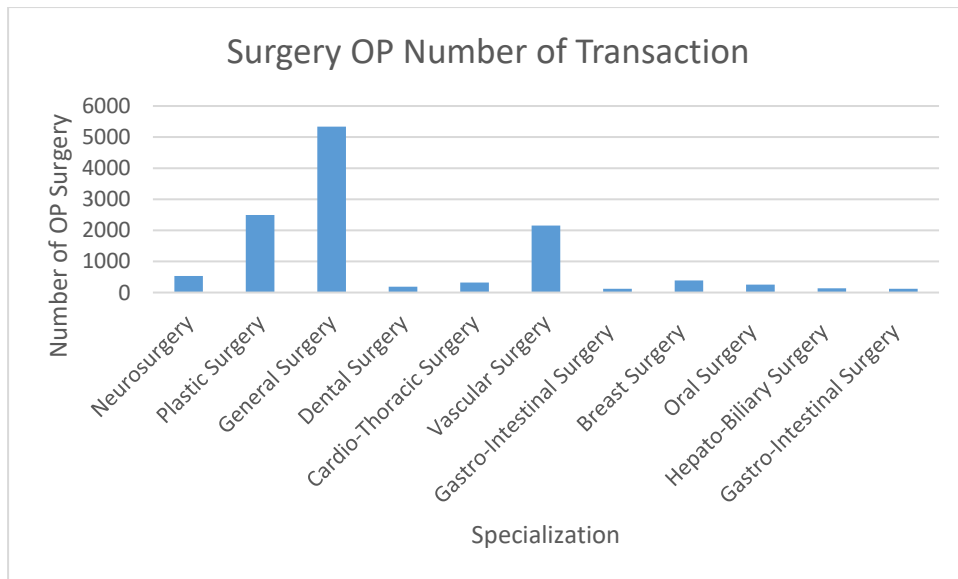


Figure. 4.23 Number of Outpatients (OP Surgery), smart contract deployment and their transaction detail across different departments/specialities.

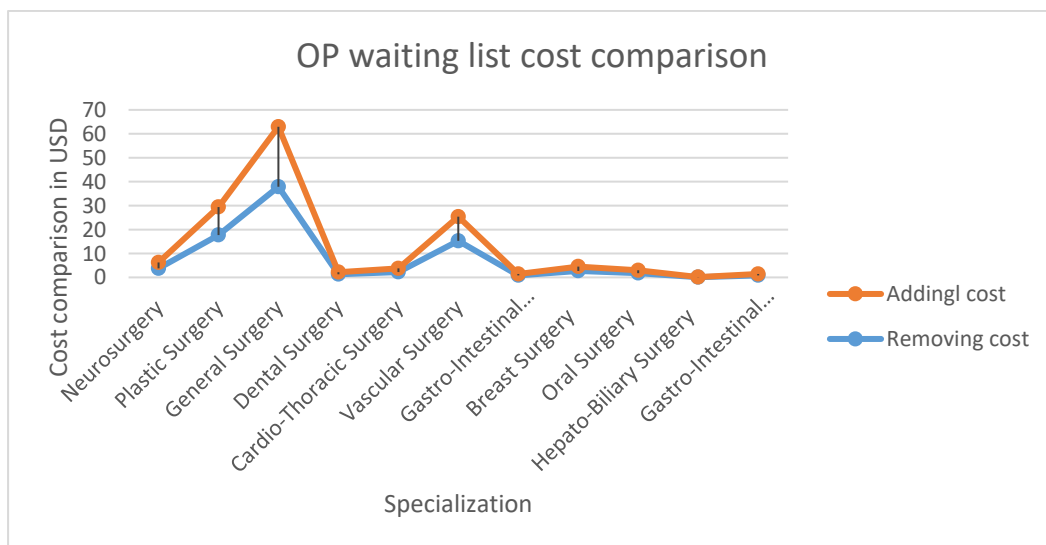


Figure. 4.24 Smart contract deployment cost comparison for Outpatients (OP Surgery) across different departments/specialities.

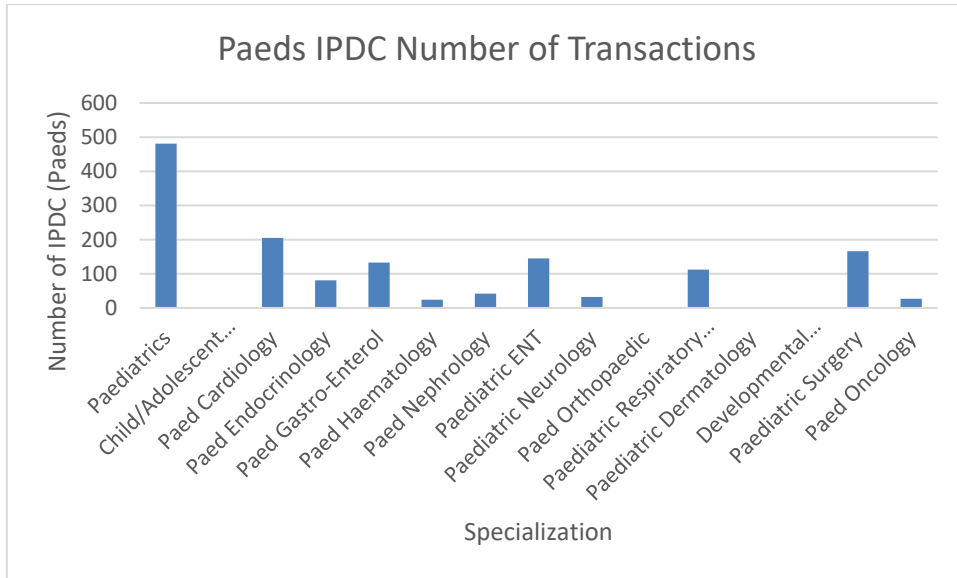


Figure. 4.25 Smart contract deployment cost for Inpatients and Day cases (IPDC Paeds) and their transaction detail across different departments/specialities.

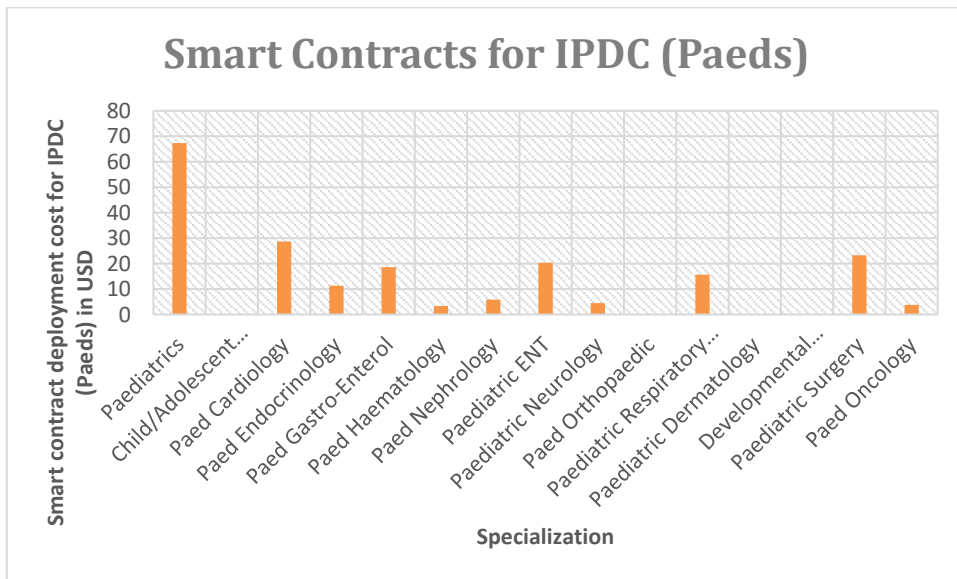


Figure. 4.26 Smart contract deployment cost for Inpatients and Day cases (IPDC Paeds) across different departments/specialities.

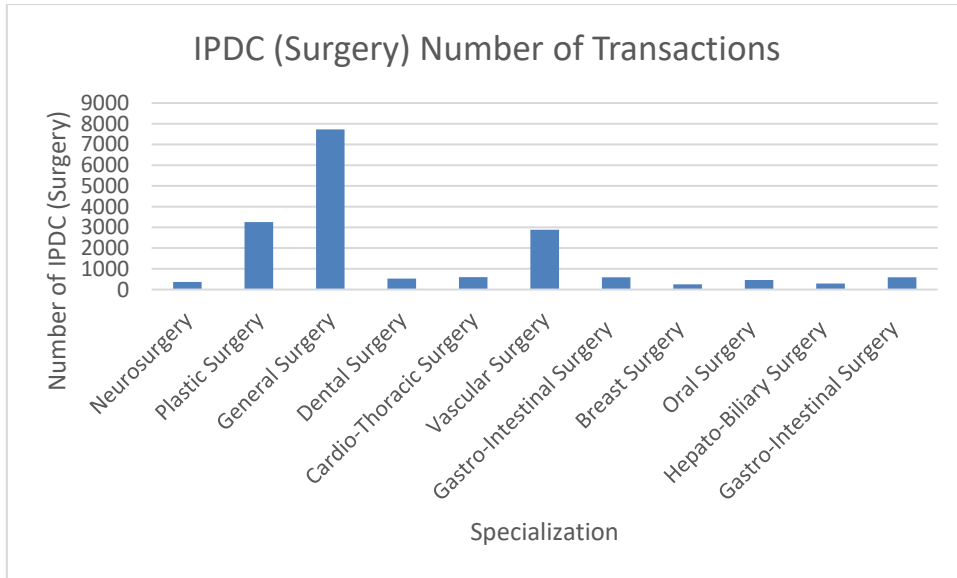


Figure. 4.27 Smart contract deployment cost for Inpatients and Day cases (IPDC Surgery) and their transaction detail across different departments/specialities.

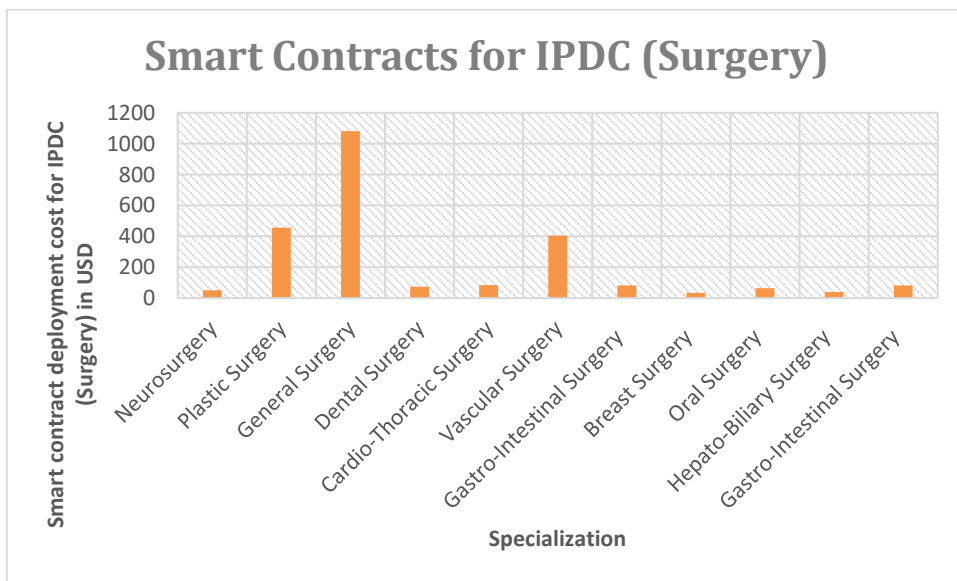


Figure. 4.28 Smart contract deployment cost for Inpatients and Day cases (IPDC Surgery) across different departments/specialities.

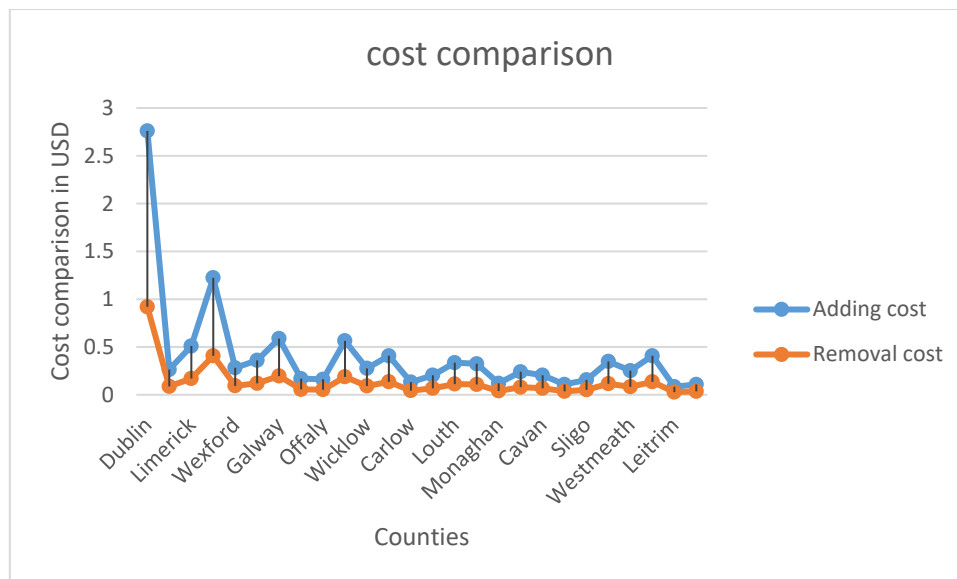


Figure. 4.29 Smart contract deployment cost for adding and removing of an entity across different counties.

4.6 Discussion

It is very well known that all patient records in conventional healthcare delivery models and systems, suppliers, labs, payers (i.e., insurance firms) and drug companies are held in various formats, so there is not at all standardization of the record keeping. This has contributed a lot to data breaches and the disarray we see in health information sharing today. Impoverished data-sharing infrastructure has also impeded advances in the drug discovery and public health research investigations and findings. Efforts to tackle this problem have primarily been focused on pushing a new universal standard around the ecosystem. These such attempts were unsuccessful, as they were quickly rejected by regulation, lobbying, and patient apathy. Owing to the lack of efficient collection and sharing of health data, the widespread acceptance of the concept of adjusting medical care to a patient's characteristics, desires and aspirations has been prevented. Personalized medicine and adequate treatment – or precision – has long been recognized as the future of healthcare, and industry operators have dedicated substantial resources to developing personalized healthcare opportunities, only to be stymied by the present system.

In this chapter, we have discussed the current needs, trends and requirements of the healthcare industry, the shortcomings of the present system, and given Ethereum-based

solutions for efficient healthcare management. Giving an overall overview of the state of the art personalized medicine, explaining the underlining issues with the existing healthcare system that hinder the introduction of personalized medicine and demonstrating how our built program provides solutions to these problems. We have also analyzed and calculated the practical cost of deploying smart contracts system for different health care scenarios and workflows, and found that with outpatient numbers the cost increases linearly. Health care departments such as paediatrics and general surgery costs are higher than others for these reasons.

4.7 Conclusion

Using the blockchain distributed technology, our blockchain based smart contract for healthcare management framework has shown how the concepts of decentralization can be applied to a large-scale data processing in medical environments and to expedite complex medical procedures. We demonstrated a revolutionary approach to the handling of medical records, offering traceability, connectivity and openness of the system through smart contracts. This program is structured to document consistency and granularity and allows for the exchange of patient data and opportunities to help the medical research program. We've suggested and designed possible applications of blockchain technology in health data management. From a medical perspective we have implemented a healthcare data management and sharing system based on the specified requirements in the medical eco-system. It is possible to ensure the utilization of blockchain technology, anonymity, protection, availability and fine-grained control of access to EHR data. The main aim of using blockchain as explained in this chapter is to improve the medical processes, and thus also improve the patient outcomes. Blockchain can help in many ways; reduce transaction costs by using smart contracts incorporating protocols for general purposes to simplify procedures, reduce administrative burdens and eliminate intermediaries. Many projects on blockchain are aimed at improving data collection, usage and exchange of health data from patients, researchers and sub-processors. Our proposed framework uses blockchain technology to build a system based on automated, distributed, stable, open and to provide a decentralized health-care ecosystem. This will encourage patients to freely and securely exchanging their medical records with physicians, hospitals, research organizations and other stakeholders involved in the system while maintaining absolute authority over the confidentiality of their medical healthcare data.

5 Blockchain Implementation of Ethereum Smart Contracts

In the blockchain research there are very few implementations of Blockchain-based smart contract systems. This practical aspect is considered in this chapter, while giving detailed description of the implementation of smart contracts that we introduced in chapter 4 of this thesis. The exchange of electronic medical data among different stakeholders in the healthcare eco-system, such as patients, physicians and researchers, will encourage greater and efficient integrated healthcare infrastructure. In order to make this possible we implemented a system for exchanging medical information based on permissions control mechanism over Ethereum blockchain based smart contract and different bits of information is being shared among various stakeholder of the system. All the healthcare information resides in the local database, and permission-related information has been stored on the Ethereum blockchain smart-contracts. In this chapter, implementations of smart contracts using Ethereum and Solidity are presented along with explanation of the code structure which are designed to automate the medical regulations. Also different workflows involving multiple stakeholders have been discussed. Structures of smart contracts are discussed in detail which shows the potential within a clinical data research network for managing data queries involving different workflows. Our proposed blockchain solution for health care extends the collection of clinical data to include data from groups of persons currently under-served by the health care system. The open data architecture of Blockchain makes the participation of "tricky-to-reach" users simpler, and more accessible for the general public.

5.1 Medical Smart Contract System

Here, we are taking the issuance of medical prescriptions as a first step to go into the implementation details of the system. A process diagram for issuing medical prescription has been shown in Figure 5.1, showing a medical prescription imitated by smart contracts. It is meant to be designed as so that the programmable components can be added a system, allowing for issuing and collection of a medicine, with expiry dates and patient ids.

Also very helpful in investigating the adverse effects of the drugs. There are three main parties involved in the system as doctors, patient and pharmacy, each of them having different permission access rights on the ethereum blockchain network.

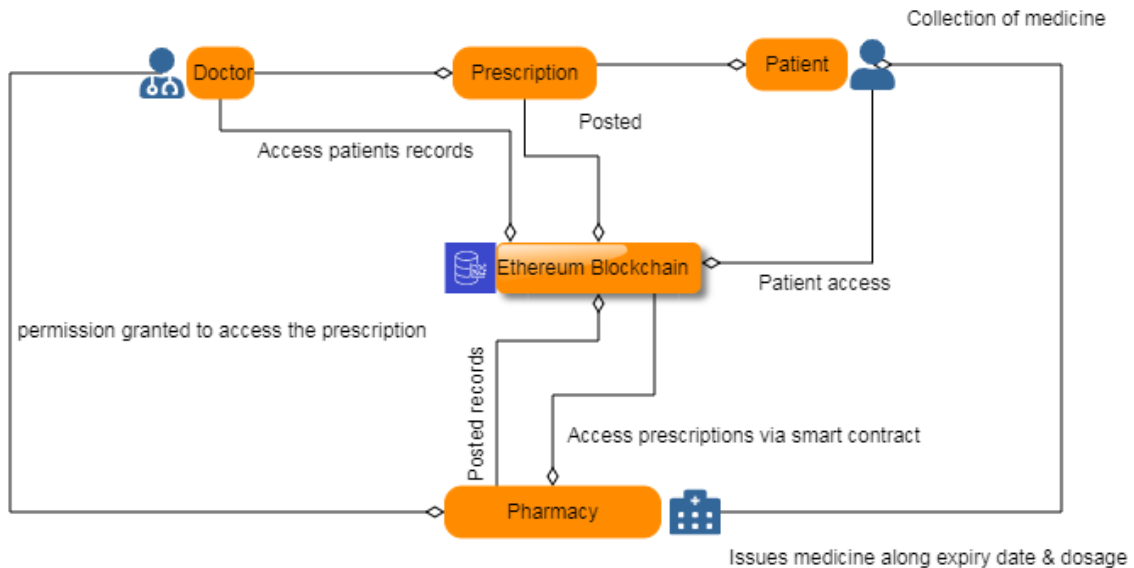


Figure. 5.1 Process flow diagram for issuing a medical prescription via smart contract.

We are using Ethereum platform and wrote the smart contracts using solidity programming language. After compiling the code, we deployed and executed the smart contract code on the ethereum blockchain platform. Figure 5.2 shows a smart contract pseudo code for the issuance of medical prescriptions written in Solidity and executed on Ethereum which corresponds to the particular instance represented in figure 5.1.

```

1 Medical Prescriptions
2 pragma solidity ^0.4.15; //Version of a solidity, we are using
3
4 contract Prescriptions { // initialization of a smart contract
5 //Mapping referred to hash tables (initialized virtually)
6 // addresses referred to Ethereum address
7     mapping(address => bool) patients; // Mapping for the address to the patients
8     mapping(address => bool) GP; //Mapping for the address to the doctors
9     mapping(address => bool) Pharmacy; //Mapping for the address to the producers(pharmacy)
10 // structure for the Medicinebox; it holds expiry date, medicine id, dosage variables
11     struct MedicineBoxDef {
12         uint medicineboxId;
13         uint usedBeforeDate;
14         bool isUsed;
  
```

Figure 5.1 Pseudo code showing different stakeholder and their mapping addresses

```
[vm] from:0xca3...a733c to:Prescriptions.(constructor) value:0 wei data:0x608...b0029 logs:0
hash:0x86a...24e3f
```

Figure 5.2 Function executed with no error and the transaction has been successfully completed and the event happened

status	0x1 Transaction mined and execution succeed
transaction hash	0x63350ad3c42c6bb1f5c07e50b29c64363c85f610486868fe0448d46dcf4475f8f
contract address	0xdc04977a2078c8ffdf086d618d1f961b6c546222
from	0xca35b7d915458ef540ade6068dfe2f44e8fa733c
to	Prescriptions.(constructor)

Figure 5.4 Transaction mined and execution succeed as the testing modifiers where a function has been executed with no error as the required stakeholder was the assigned actor

gas	3000000 gas
transaction cost	882658 gas
execution cost	626794 gas
hash	0x63350ad3c42c6bb1f5c07e50b29c64363c85f610486868fe0448d46dcf4475f8f

Figure 5.5 Contract Execution cost shown in the figure upon the successful completion of the transaction

Testing modifiers: In Figure (5.6) function executed with no error as the required admin was the assigned actor while in figure (5.7) error appears when an intended actor has an invalid address

```
transact to Prescriptions.removeAdmin errored: Error encoding arguments: Error: invalid address (arg="", type="string", value="")
```

Figure 5.6 Function executed with no error

```
[vm] from:0xca3...a733c to:Prescriptions.removeAdmin(address) 0xc2...739ef value:0 wei  
data:0x178...7c074 logs:0 hash:0xe5b...a2e3b
```

Figure 5.7 Error appears when an intended actor has an invalid address

5.2 Clinical Trials

A process flow diagram for conducting clinical trials have been shown in figure 5.8. Primary investigator initiate the study. FDA approves the application and gives approval of clinical trial. Sponsor create the contract and initiate the process. A more detailed description has been given in the previous chapter for the whole process. Algorithm 5.1 shows the clinical trial initiation process which involves number of steps as given below.

Algorithm 5.1: Clinical Trial process initiation

Input: Ethereum address of the patient and all the other stakeholders involved in the system

Process start, number of patients required, procedure protocols

If the application has been approve by the Investigational New Drug Authority

Then Allow the Input details to be included as valid transactions on the network

Initialization of the process = Access approved

End

else

Don't allow/accept unauthorized transactions

End

If Patient drop outs

Then Stop processing that further

Update the records

Notify/update the other peers in the network about the progress

End

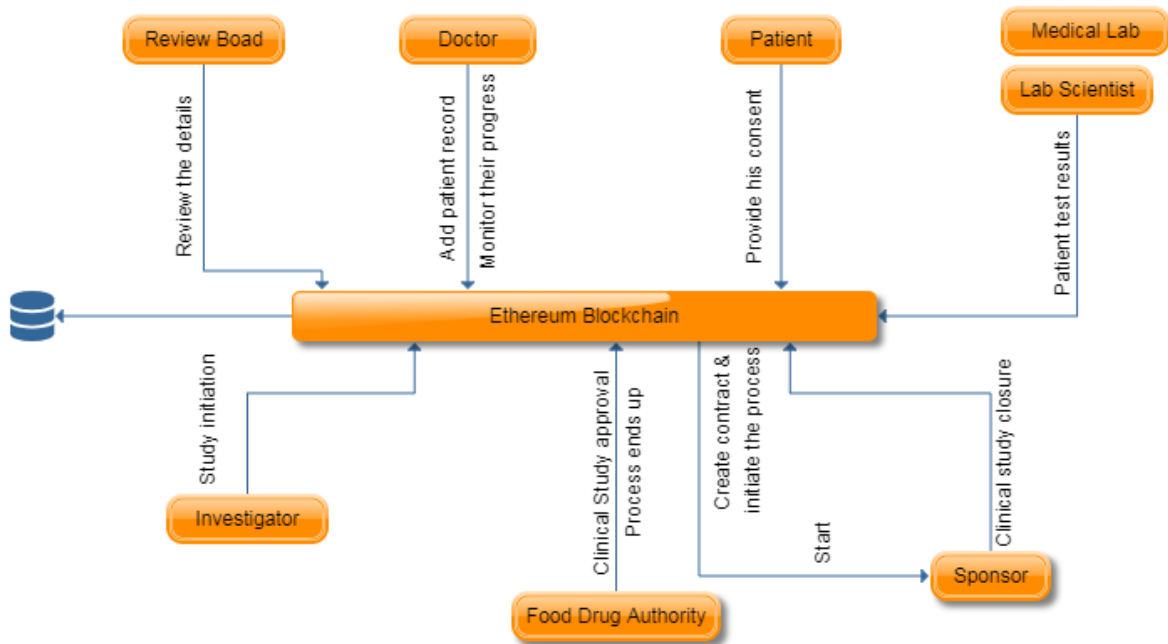


Figure 5.8 Process flow diagram for Clinical Trials

```

1 pragma solidity ^ 0.4.15; // Version of solidity, we are using
2
3 contract ClinicalTrials{ //Smart contract initialization
4
5     //mapping addresses of different participant involved in the process of Clinical Trials on Ethereum
6     mapping(address => bool) foodDrugsAuthority; // Mapping for the address to the food Drugs Authority;
7     mapping(address => bool) patients; // Mapping for the address to the patients
8     mapping(address => bool) RB; // Mapping for the address to the Review Board
9     mapping(address => bool) labScientist; // Mapping for the address to the lab scientist
10    mapping(address => bool) PrincipalInvestigator; // Mapping for the address to the Principal Investigator
11    mapping(address => bool) Sponsor; // Mapping for the address to the sponsor
12    mapping(address => bool) Doctor; // Mapping for the address to the doctor
13    address [] patientID;

```

Figure 5.9 Pseudo code showing different stakeholder and their mapping addresses for CTs

```

[vm] from:0xca3...a733c to:0xca35b7d915458ef540ade6068dfe2f44e8fa733c 0xca3...a733c
value:0 wei data:0x5da...0000 logs:0 hash:0x386...c26b8

```

Figure 5.10 Function executed with no error as the required admin was the assigned actor and the transaction has been successfully completed

5.3 Lab Test Results

A use case started when the patient visits a laboratory for the blood test. After all the processing, laboratory will put the patient results to his records via smart contracts access right given to them, the patient receives these notifications via Ethereum blockchain. A process diagram can be shown in the figure 5.11 explaining the whole process.

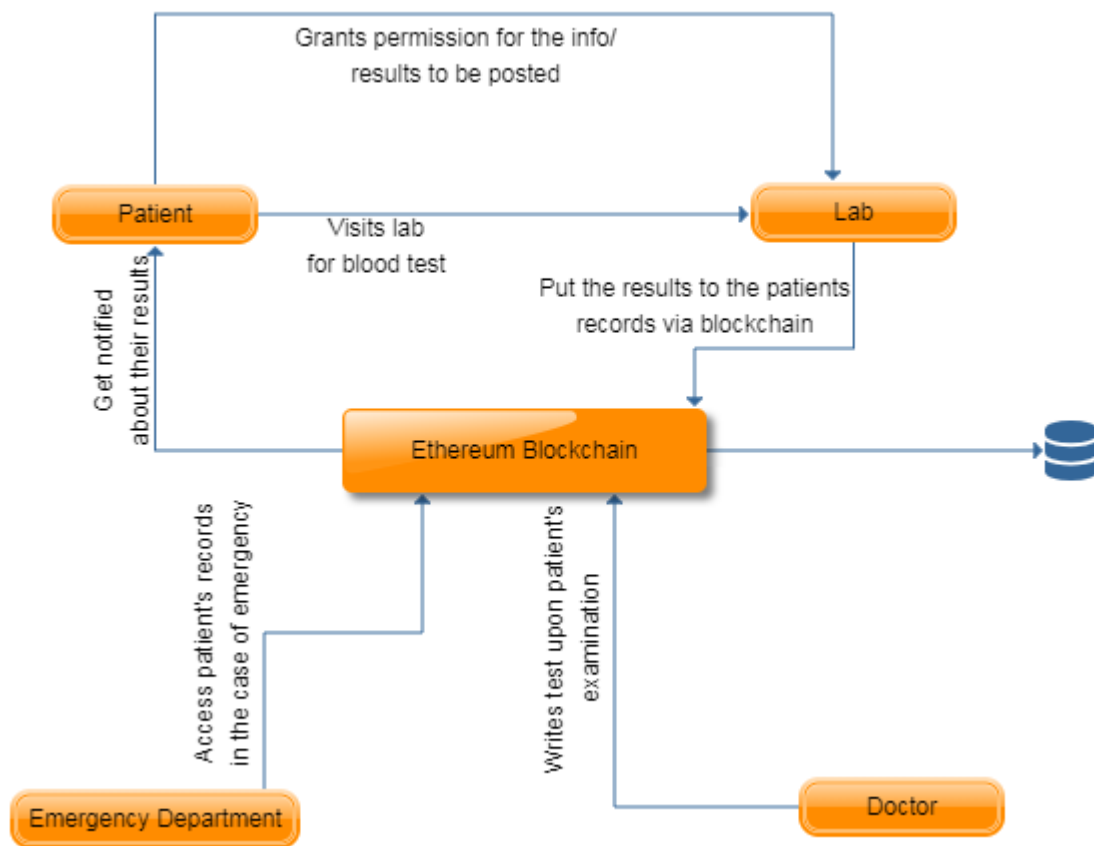


Figure 5.13 Process flow diagram for Lab Test Results

```

1 pragma solidity ^0.4.15;
2
3 contract LabResults{
4
5     mapping(address => uint[13]) Blood Test;
6
7     function setBloodResult (uint[13] memory bloodResults) public {
8         Blood[msg.sender] = bloodResults;
9     }
10
11     function getBloodResult () public view returns (uint[13] memory){
12         return Blood[msg.sender];
13     }
14
15 }
16
17 /*
18
19 Smart contract for storing test results data inside
20 the contract.

```

Figure 5.12 Pseudo code: Storing lab test results on the smart contracts

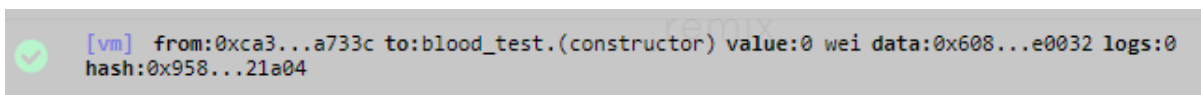


Figure 5.13 The event happened and the Function executed with no error hence the transaction has been successfully completed

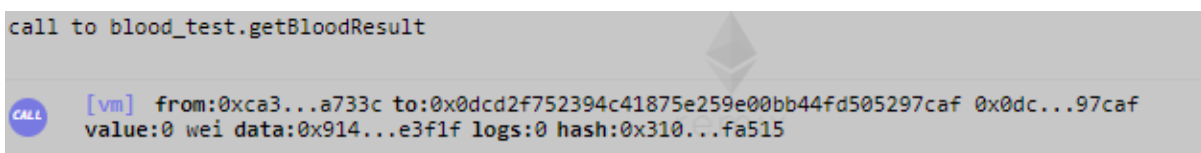


Figure 5.14 Call to the blood test for getting results, event happened and transaction successfully completed

5.4 Patient Consultant communication

To enable patient consultant communication and submitting a request for a medical condition. A process flow diagram has been shown in the figure 5.15. It starts with the submission request from patient for a specific medical treatment via Ethereum blockchain network. Primary doctor receives the request from the patient via smart contract on the network. After receiving the request, a primary doctor writes his recommendations and refer the patient to a specialist for further treatment via a blockchain. A consultant read those recommendation written by a

primary doctor and he proceed further with the further medication and treatment. Patient receives those recommendation via Etherem blockchain. We have discussed this process flow in more detail in the chapter 4 of this thesis. Here we are very specific towards the logical flow of the smart contract system

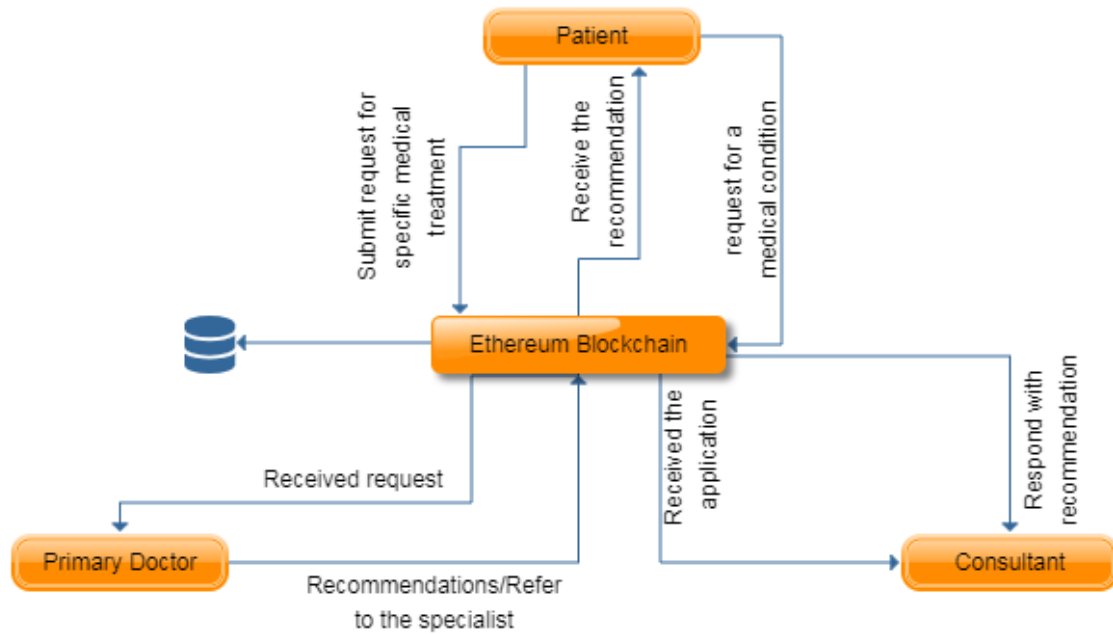


Figure 5.15 Process flow diagram for patient consultant and a physician communication and recommendations

```

1  pragma solidity ^0.4.15;
2
3  //Represents both a Patient and a consultant,
4  //Represents Primary Doctor,
5  //Represents Hospitals,
6  contract PatientConsultant {
7      address public agent;
8      bool public agentEnabled;
9      address[] public consultant;
10     bool[] public consultantEnabled;
11     address[] public relationships;
12
13     modifier isOwner() {
14         bool enable;
15         if(agentEnabled && msg.sender == agent) enable = true;
16         for(uint i = 0; i < consultant.length; i++) {
17             if(consultantEnabled[i] && msg.sender == consultant[i]) {
18                 enable = true;
19                 break;
20             }
21         }
22         if(!enable) revert();

```

Figure 5.16 Pseudo code showing different stakeholders

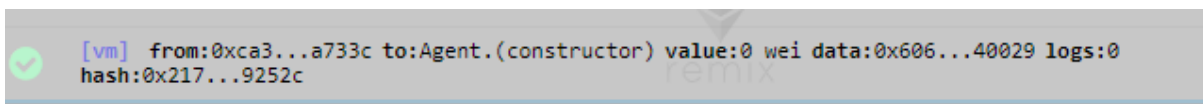


Figure 5.17 The event happened and the Function executed with no error hence the transaction has been successfully completed

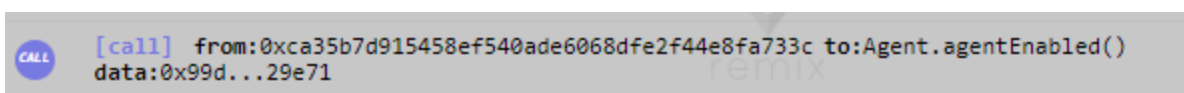


Figure 5.18 Call to the participant, event happened and transaction successfully completed

5.5 Health Insurance

Multiple stakeholders including physician, patient, pharmacy, lab and health insurance company involves in the system as seen by the process flow diagram. Each party connected via smart contract and putting every information on the Ethereum network. A diagram and a pseudo code have been given below in figure 5.19 and 5.20 respectively.

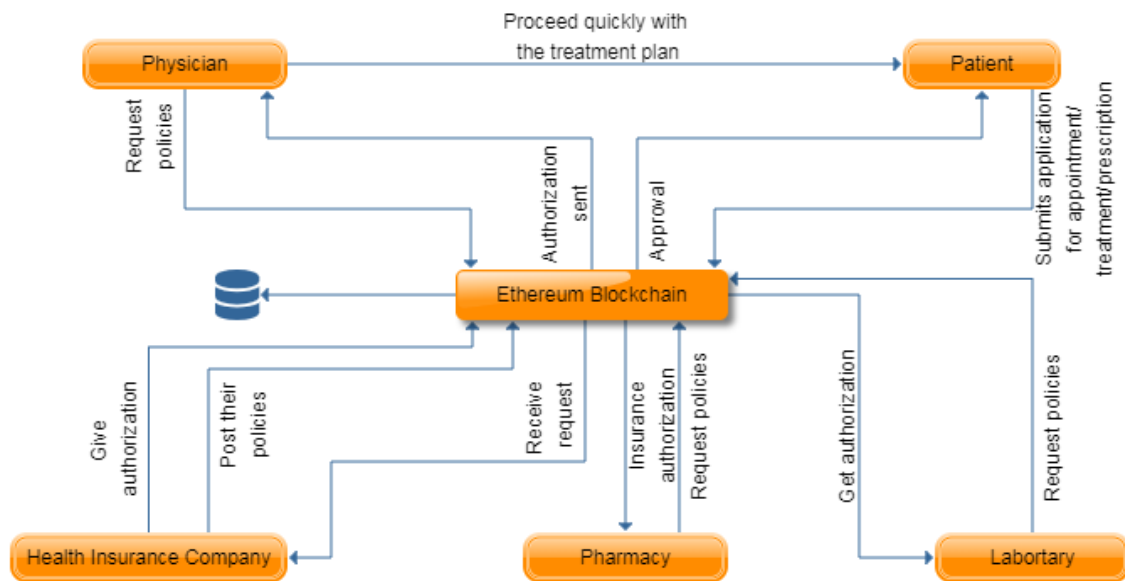


Figure 5.19 Process flow diagram for Health Insurance

```

1 pragma solidity ^0.4.15;
2
3 contract HealthInsurance{
4 //Mapping address to ids.
5 mapping(address=>uint) mapProposals;
6 //Mapping addresses
7 mapping(address=>uint) mapReimbursements;
8 //Mapping for the address to the hospital
9 mapping(address=>Hospital) mapHospitals;
10 //Default deposit amount that the hospital gives.
11 mapping(address=>Customer) mapCustomers;
12
13 uint public deposit;
14 //Default premium amount in Ethers.
15 uint public premium;
16 //Proposal ids counter.
17 uint public numberOfProposal;
18 uint public customerThreshold;
19 uint public votePercentLimit;
20 uint public votePercentAccept;
21 uint public customerCount;
22 bool public isActive;
23 uint public hospitalCount;
24 uint public treatmentCount;
25 uint public fundingPeriod;
26 uint public requiredHospital;
27 uint public requiredCustomer;
28 /*
29 Structure, It holds duration, validity, total votes and eligibility Of the premium
30 for voting.
31 */
32 struct Customer{
33     uint endPremium;
34     mapping(uint=>bool) mapHospitalVotes;
35     uint weight;

```

Figure 5.20 Pseudo code for Health Insurance

```
[vm] from:0xca3...a733c to:HealthInsurance.(constructor) value:0 wei data:0x606...70029
logs:0 hash:0x9f0...a5f47
```

Figure 5.21 The event happened and the Function executed with no error hence the transaction has been successfully completed

```
[call] from:0xca35b7d915458ef540ade6068dfe2f44e8fa733c to:HealthInsurance.fundingPeriod()
data:0x74d...7c62b
```

Figure 5.22 Call to the participant, event happened and transaction successfully completed

5.6 Surgery

Algorithm 5.2 shows the patient enrolment during surgical procedures. Getting consent for the patient to thoroughly monitoring and the initial assessment of the patients have been recorded on the blockchain as it can be seen from the figure 5.23. An algorithmic flow has been also discussed in the previous chapter.

Algorithm 5.2: Patient Enrolment

Input: Ethereum address of the patient and other information including consent forms

If All the information has been recorded and get approved

Then Allow the valid transactions to be added

Mapping of Patient’s address

Update the network members about the progress

End

else

Don’t allow/accept unauthorized transactions

End

If there is no consent

Then Stop processing that further

Notify/update the other peers in the network about the progress

End

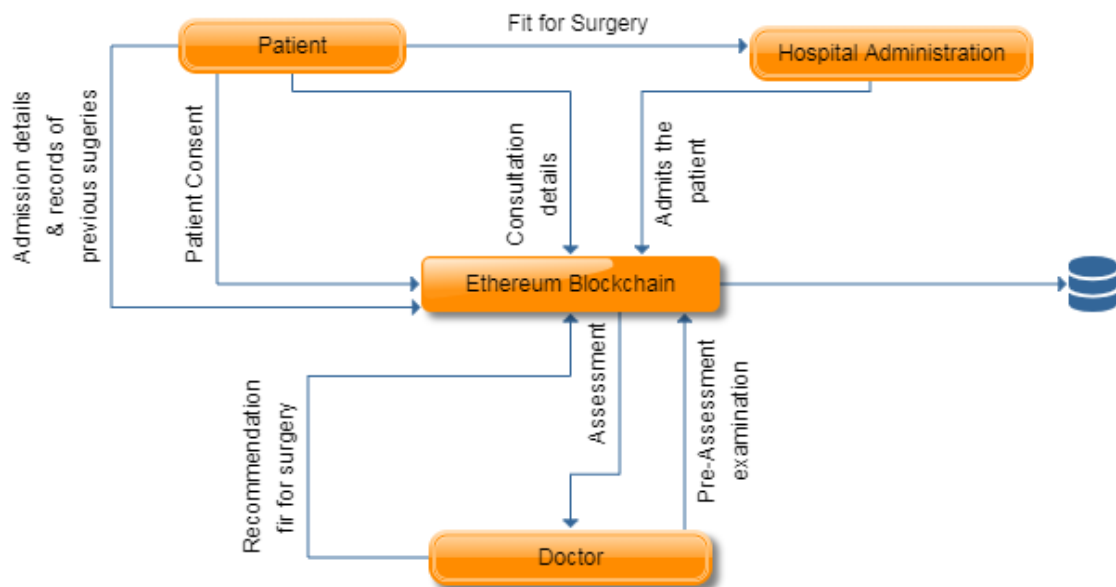


Figure 5.23 Process flow diagram for Surgery

```

1  pragma solidity ^0.4.15;
2
3  //Surgery
4  contract Surgery {
5      address public consultant;
6      bool public consultantEnabledEnabled;
7      address[] public relationships;
8      address [] public surgicalteam;
9      bool[] public surgicalteamEnabled;
10     address[] public patient;
11     bool[] public patientEnabled;
12     address anaesthesiologist;
13     bool[] public anaesthesiologistEnabled;
14
15
16     modifier isOwner() {
17         bool enable;
18         if(agentEnabled && msg.sender == agent) enable = true;
19         for(uint i = 0; i < consultant.length; i++) {
20             if(consultantEnabled[i] && msg.sender == consultant[i]) {
21                 enable = true;
22                 break;
23             }
24         }
25         if(!enable) revert();
26         _;
27     }
28
29     function Agent() public {
30         agent = msg.sender;
31         agentEnabled = true;

```

Figure 5.24 Pseudo code for the deployment of Surgery Smart Contract

```

[vm] from:0xca3...a733c to:Surgery.(constructor) value:0 wei data:0x606...50029 logs:0
hash:0x72f...98187

```

Figure 5.25 The event happened and the Function executed with no error hence the transaction has been successfully completed

```

[call] from:0xca35b7d915458ef540ade6068dfe2f44e8fa733c to:Surgery.getNumViewers()
data:0x046...f3ab7

```

Figure 5.26 Call to the participant, event happened and transaction successfully completed

5.7 Conclusion

In this chapter, we have discussed different medical procedures and their implementation detail comprehensively. The aim of this chapter was to thoroughly discuss the structures, function and the components of the smart contract system designed and implemented for the healthcare applications. Different process flow diagram have been shown to explain the medical procedures and the treatment protocols and different interaction among different stakeholders involved in the system via Ethereum smart contract system in this thesis. This implementation of the Ethereum smart contracts would show the great potential in developing distributed applications (Dapps) for medical eco-system.

6 Blockchain smart contract system for Energy Efficiency applications

In this chapter, we have investigated the Blockchain trends in the energy sector and implemented Blockchain based smart contract for trading of energy saving certificates to enhance trust, privacy and transparency among energy efficiency market stakeholders. Blockchain technology is ready to disrupt almost every business strategic model and the energy industry is no exception. Energy companies around the world have already started to explore the use of blockchain technology among other applications in large-scale energy trading platforms, peer-to - peer energy trading markets, project financing, supply chain monitoring and asset management. Information and communications technology (ICTs) have recently begun to revolutionize the energy environment and now blockchain technology provides an additional opportunity to make the energy system faster, more efficient, more reliable and safer in the long run.

This work was done in a collaboration with IERC and Tyndall National Institute on introducing a new energy policy regulatory scheme where my main focus was to design and implement a smart contract system for the energy saving certificates. As I was looking into the blockchain based smart contract applications, we extended our work for the energy systems applications. This work is an additional contribution for the scope of this thesis. We looked more closely at the use of blockchain technology for its potential use in the energy efficiency industry and decided how it could make energy efficiency markets safer and more open in the longer term. This work explores in depth the key advantages of using blockchain in the energy efficiency market by introducing and analyzing two main case studies as appropriate for blockchain applications — I the UK Energy Company Obligation Scheme (ECO) and ii) the Italian White Certificate Scheme (IWCH). We discussed how the key issues surrounding energy efficiency savings trading — correct estimate of savings, stakeholder data transparency, and inefficient administrative processes — can be resolved by applying a smart contract framework centered on blockchain. This chapter presents the implementation of an intelligent contract framework for exchanging energy-saving certificates obtained via smart contract transactions on the Ethereum blockchain platform.

The energy sector is in transformation and the integration of distributed renewable energy sources into the existing centralized energy system is facing several challenges. Digital technologies like the Internet of Things (IoTs) [142] and blockchain system as enablers for the creation of a decentralized and democratized network of resources. Blockchain is being evaluated for various applications and systems in the energy sector as a means of solving protection and accountability issues and improving process efficiency by providing a decentralized authority framework, thereby creating a win-win scenario for all the stakeholders involved in the system. This research examines the application of blockchain technology to address the current challenges of the energy efficiency market and proposes a smart contract framework for exchanging energy-saving certificates on a transparent and stable digital transaction platform without any third party having to infer in the system.

Figure 6.1 shows main applications of blockchain based systems. For peer-to - peer energy trading [143] [144] [145], blockchain can provide a secure trading verification mechanism without requiring third party authentication. Having a centralized global blockchain network can also provide cross-border, seamless energy trading. Blockchain will enable prosumers to participate in the local energy market where they can rely on digital technology that can make transactions faster, easier, and cheaper than a conventional centralized energy system. It has also been tested in the charging facilities for electric vehicles (EVs) where it will allow access to all charging points for EV drivers through the creation of a network of EVs and charging stations and the development of such an simple payment and efficient settlement mechanism for all parties involved. Several energy firms are also pursuing blockchain technologies in supply and value chains with the aim of enhancing visibility and reducing the loss of assets from output to consumption. Project financing is also studied where blockchain is used to increase transparency and liquidity of pay-outs.

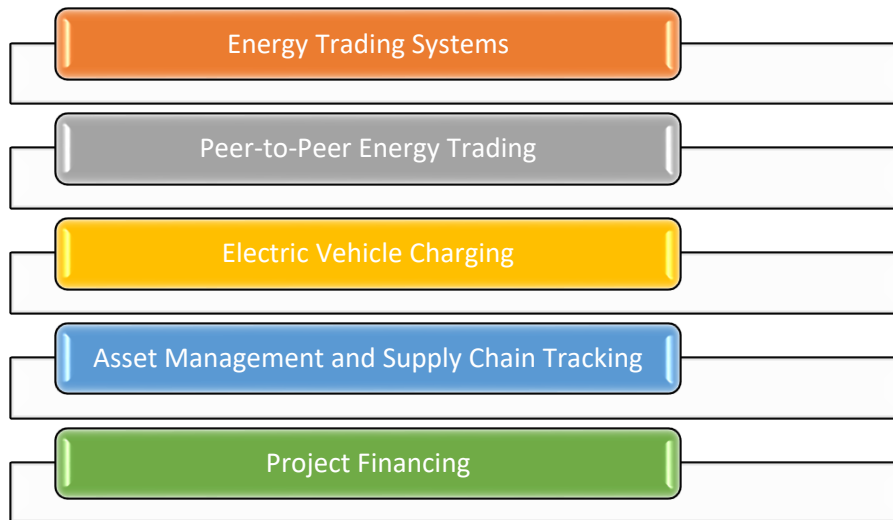


Figure. 6.1 Schematic of the Blockchain-based key energy applications. Reprinted with permission from Khatoun et al., *Energies* 2019; 12(17), 3317.

6.1 Smart Contract implementation for Energy Saving Certificates

In the previous sections of this chapter, we have briefly introduced smart contract features in the energy saving certificate management systems as a way to overcome issues such as third party reliance, improved data security, data audits and logs, and easy buying and selling of energy saving certificates. The smart contract system enabled by blockchain will help end users to securely trade their energy-saving certificates, offering to help one user achieve acknowledgement for their additional energy savings while at the same time allowing another user to fulfil their obligations. These will also help to monitor the energy saving certificates with their unique identification number from their origin to the end of the process. All permissions to access data are stored in the smart contracts by allowing authenticated users to access and control the data. Within this chapter the design of an energy saving certificate smart contract management system (Figure 6.2 and 6.3) has been prototyped using the Ethereum Blockchain framework.

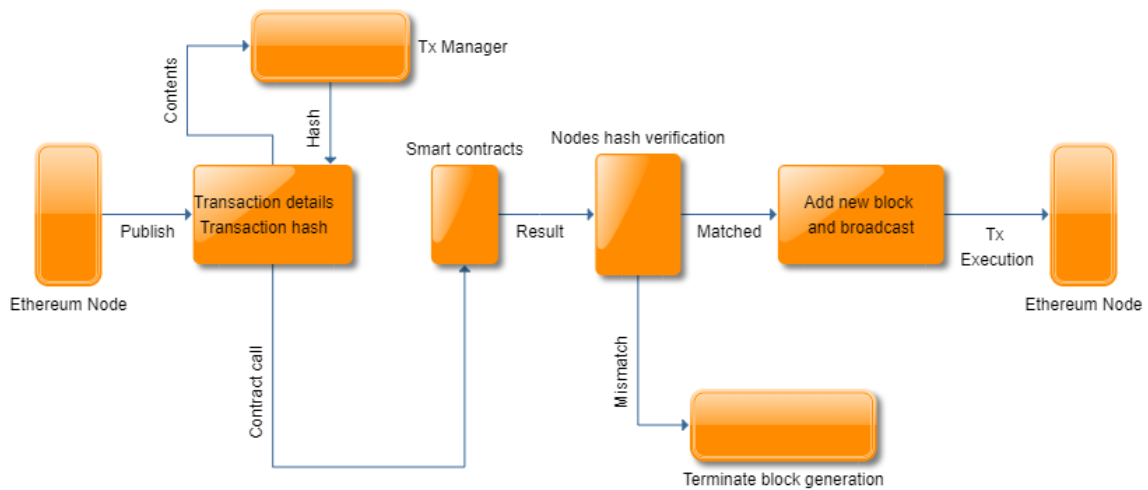


Figure. 6.2 Smart contract based peer-to-peer energy saving certificate trading system:
Consensus protocol

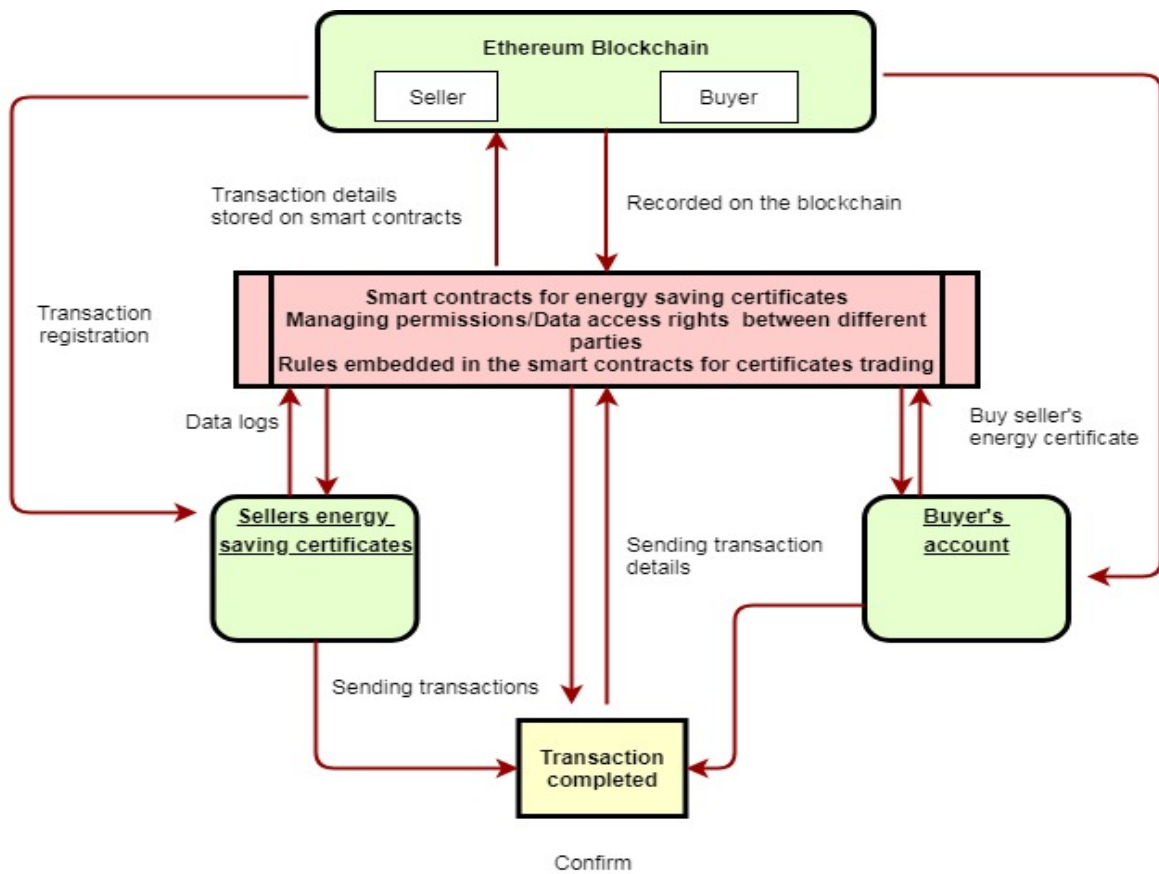


Figure. 6.3 Blockchain-based smart contract system for energy saving certificates.
Reprinted with permission from Khatoun et al., Energies 2019; 12(17), 3317.

The Kovan test network was used as an Ethereum wallet alongside Metamask. The Kovan test chain is basically a PoF blockchain for the Ethereum platform which uses the same technology as the Ethereum Mainnet blockchain. The aim of designing this smart contract system is to introduce such a platform where energy-saving certificates can be traded efficiently, eliminating the necessity of third parties. The smart contracts' key elements are represented in tasks, events, state variables, and modifiers. In Figure 6.4 which shows the main function of energy saving certificates, it maps the buyer, seller and governing body to the transaction. If the provider approves the request, the trading of energy certificates will go on further otherwise not. An Authorization algorithm has been given below which shows how the process initiated on the Ethereum network.

Algorithm: Authorization

Input: Ethereum address of stakeholders involved in the system

Initialization of the process = Access approved

If Initiation request approved

Add the record into the chain

Address Mapping for the stakeholders

Notify the other members in the network for enrolment of new members/peers

end

else

Don't accept transaction from unauthorized persons

End

Through the function Sell), (we initialize the contract, declare variables, functions and assign the owner as msg.sender. A modifier function, only Owner, has been used with the Sell) (function whenever the owner of the smart contract executes it and verifies the owner to sell the amount of energy overachieved). Solidity smart contract elements are well established in Figure 6.4 which shows how a smart contract was developed, and it is possible to see different interactions between various functions to run the transactions within the system. The very first line in the source code reveals that for solidity version 0.4.15, this program is written for. Pragma sets out the instructions provided to the compiler about how to handle the source code elements. The whole smart contract system presents a collection of functions and data (its

states), which resides on the Ethereum blockchain specific address. The owner is the administrator in charge of selling energy-saving certificates.

```
pragma solidity ^0.4.15;

contract energysaving certificates {

mapping (address => mapping (address => bool)) regulatory authority;

mapping (address => mapping (address => bool)) seller;

mapping (address => mapping (address => bool)) buyer;

event Overachieved (address tokenGet, uint amountGet, address tokenGive, uint amountGive,
uint expires, uint nonce, address user);

event Calculatesavings (address tokenGet, uint amountGet, address tokenGive, uint
amountGive, uint expires, uint nonce);

event Issuecertificates (address tokenGet, uint amountGet, address tokenGive, uint
amountGive, address get, address give);
```

Figure. 6.4 Components of a solidity smart contract. Reprinted with permission from Khatoon et al., *Energies* 2019; 12(17), 3317.

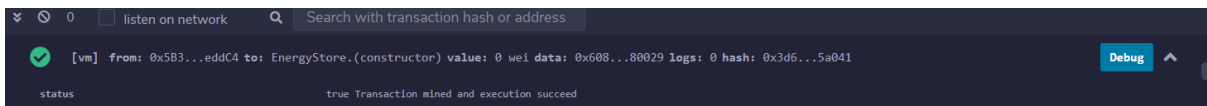


Figure 6.5 The event happened and the Function executed with no error hence the transaction has been successfully completed

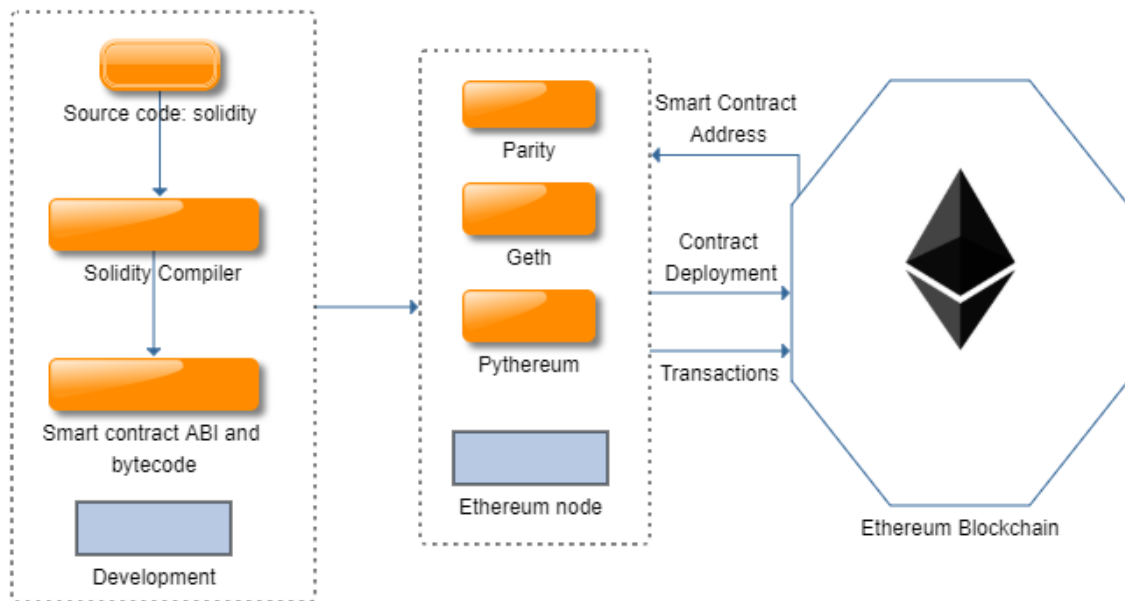


Figure. 6.6 Smart contract deployment on the Ethereum Blockchain.

The event happened and the function executed with no error hence the transaction has been successfully completed in figure 6.5. Smart contract deployment and the development process can be seen in figure 6.6. A smart contract is running on the Ethereum network as shown in figure 6.7, it also shows the transaction flow and how Metamask uses the owner's private key to sign the transactions. To verify the transaction and that all of the relevant information is stored for each transaction, we are using Etherscan. Etherscan is Ethereum's leading blockchain blockexplorer. A BlockExplorer is practically a search engine that helps the users to search, confirm, and validate Ethereum blockchain transactions. Figure 6.8 is an image taken for the blockchain transactions on the Etherscan. This data contains the level of complexity whilst also mining the block, the hash function of the transaction, the gas limit, and the gas used for the transactions to run on the Ethereum network; the nonce which is basically an arbitrary number ("used only once" — during the mined result) makes sure that all the data has been permanently stored on the blockchain. Whilst also giving the account details, one could see the specific details of the transaction on the Etherscan. The proposed approach has been implemented in the form of a smart contract on the Ethereum blockchain, as a distributed execution code. The trade algorithm has been written in solidity programming language and has been tested on the Ethereum blockchain network.

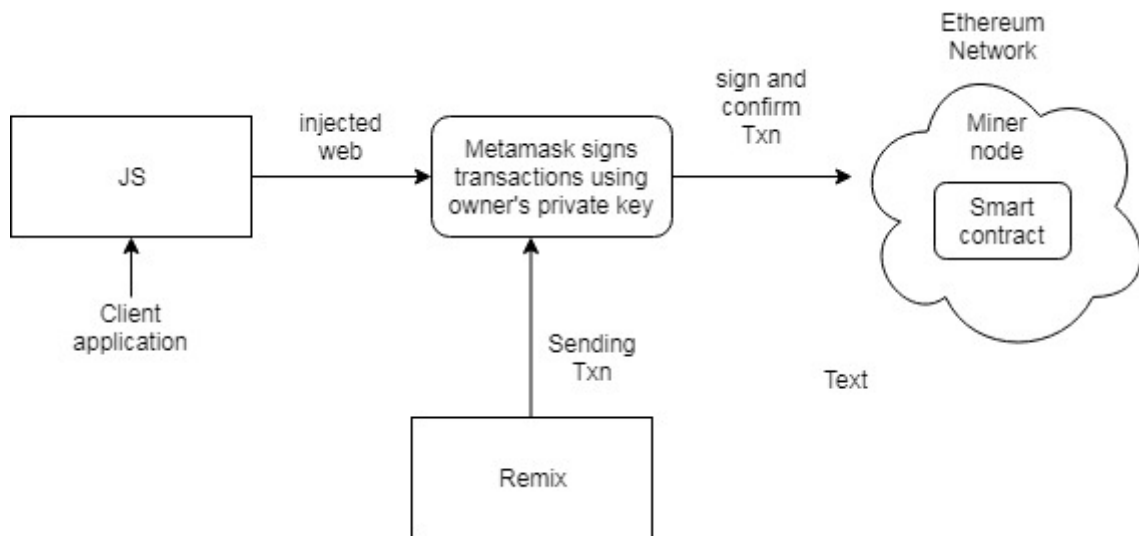


Figure. 6.7 Ethereum transactions workflow. Reprinted with permission from Khatoun et al., *Energies* 2019; 12(17), 3317.

⑦ Mined by:	0x0010f94b296a852aaac52ea6c5ac72e03afd032d (POA-Paritytech) in 16 secs
⑦ Block Reward:	5.00354826 Ether (5 + 0.00354826)
⑦ Uncles Reward:	0
⑦ Difficulty:	340,282,366,920,938,000,000,000,000,000,000,000
⑦ Total Difficulty:	3,677,308,016,815,390,000,000,000,000,000,000,000,000,000
⑦ Size:	9,904 bytes
⑦ Gas Used:	3,548,260 (44.35%)
⑦ Gas Limit:	8,000,000
⑦ Extra Data:	020405/Parity-Ethereum/1.33.0/li (Hex:0xde830204058f5061726974792d457468657265756d86312e33332e30826c69)
⑦ Hash:	0xd543f54899cbd148cd4a4bc9d378ba9477d9282a87791c90d657a63270c72d37
⑦ Parent Hash:	0xf200cd7079530eb180a4c5e4d78184d26b790991bd636abb515c579282bfb258
⑦ Sha3Uncles:	0x1dcc4de8dec75d7aab85b567b6cc41ad312451b948a7413f0a142fd40d49347
⑦ Nonce:	0xb841edf85da56605a8c262f9e586472411a7f0bc02cbea642496d035b0e923eac05046c558e6fca0a3e70a0640005ba970da68030a97209fc02e812de7eb360879d401

Figure. 6.8 Blockchain smart contract transactions on Ethereum. Reprinted with permission from Khatoun et al., *Energies* 2019; 12(17), 3317.

6.2 Blockchain applications in the previous energy efficiency schemes

Blockchain technology has the potential to boost transparency and consumer trust and could be used to transform many initiatives for energy efficiency. It can provide consumers with an additional incentive to participate in energy efficiency and energy-saving campaigns by

enabling them to trade those savings and start generating additional funds through an automated process based on smart contracts.

The United Kingdom is enforcing its targets under Article 7 of the Energy Efficiency Directive through the implementation and administration of the (ECO) [150]. This imposes a burden on energy suppliers by introducing energy conservation programs to reduce energy sales by 1.5 per cent annually. Member States (EU directive) have adopted a range of approaches to achieving this objective, including the introduction of a White Certificate Scheme (WCS). To date, WCSs have been in some form implemented in the UK, France, Italy and (recently) Poland respectively. Specific deployment methods vary in each country but generally WCSs require that:

- White certificates are issued by the regulatory authority (normally issued by the energy regulators in the Member State) to verify that the energy consumption reduction has been accomplished.
- Obligatory entities (usually energy suppliers and/or distributors) must show that they may have accomplished their energy-saving obligations by submitting to the regulator sum of white certificates that suits their energy-saving goal at the end of every year.
- White certificates may be obtained by the agreed party either by the implementation of approved energy efficiency programs and the issuance of certificates directly by the regulator or by the acquisition of white certificates from a third party directly or through the spot market. Obligated parties who cannot return appropriate quantity of white certificates at the end of the year must pay a fine.
- The White Certificates spot market must be regulated by an independent entity and must register and verify all transactions that take place.

6.2.1 The Case Study 1: The Italian White Certificate Scheme (WCS)

Italian White Certificate Scheme (WCS) has been one of the most popular examples of a trading system designed to boost end-user energy efficiency. The White Certificate Scheme WCS is also stated to have the maximum potential to promote energy efficiency in Italian industries and is expected to achieve at least 60 per cent of the EU Directive 2012/27 / EU 2020 target [151]. The scheme imposes an obligation on electricity and gas distribution system operators (DSOs) with more than 50,000 customers in order to achieve an annual energy

saving target either by enforcing energy-efficient solutions among end users, or by purchasing white certificates from other DSOs equal to their obligation, or a combination of the two. Every white certificate is equal to one ton of oil equivalent (toe) and is provided by the regulator when additional energy savings compared to the aim are made. A basic block diagram of the Italian White Certificates scheme (WCS) can be seen in Figure 6.8 and it can be noticed that this scheme involves a range of stakeholders for different activities [152]. Dario Di Santo et al. have explained the detailed workings of this scheme in [153]. There are two significant mechanisms — measurement and verification (M&V), and white certificate issuance and trading. These are the complex processes in nature which are not entirely transparent. Blockchain technology will significantly boost the trust between the various stakeholders and making these processes more efficient and reliable [154].

A smart contract which would be stored on the blockchain network, could be built that may have all the terms from M&V to certificate trading as shown in Figure 6.9. The blockchain technology would allow end-users to exchange their white certificates easily and safely, helping one user gain appreciation for their additional energy savings while the other user can fulfill their obligation. It can also help monitor the white certificates from their origin to their surrender with its unique Id. There would be no need for a centralized entity to maintain and authorise trading as it can be managed directly through the smart contract that will significantly reduce trading management administration costs and can also motivate other smaller consumers who were previously unable to take part in the scheme due to high transaction costs. Blockchain will also improve the transaction speed, since trading approval by third parties will no longer be required.

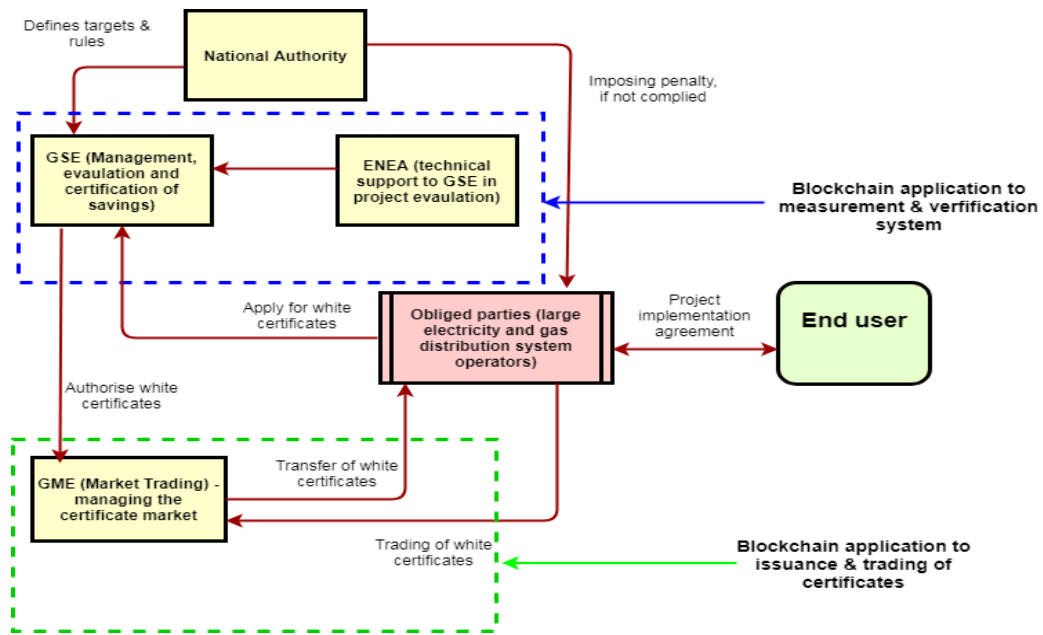


Figure. 6.9 Key stakeholder and processes in Italian White Certificate Scheme. .
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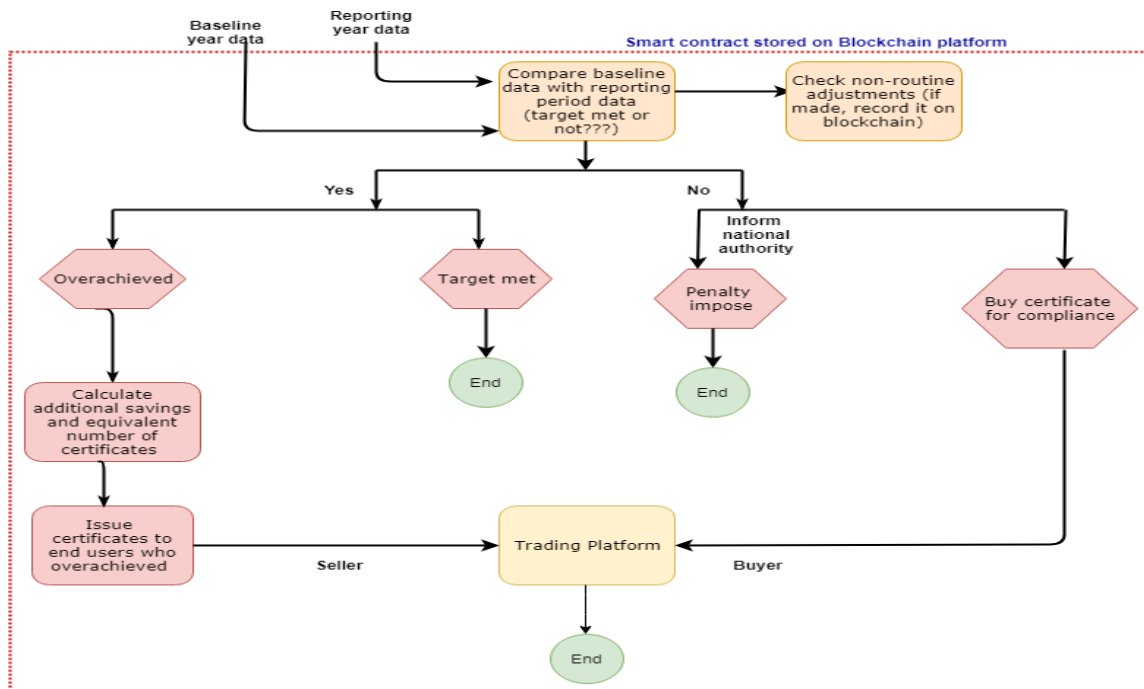


Figure. 6.10 Process flow under smart contract on the blockchain platform. Reprinted
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6.2.2 The Case Study 2: The UK Energy Company Obligation Scheme (ECO)

Under Article 7 of the Energy Efficiency Directive, the UK is delivering its targets through the implementation and management of the Energy Company Obligation (ECO) scheme. This program places a specifications on energy suppliers with more than 250,000 domestic consumers who deliver more than 500 GWh of electricity or 1400 GWh of gas to promote and deploy energy efficiency measures at household [155]. The aim is to reduce energy consumption required to heat homes by implementing energy efficiency measures (such as insulation, more effective boilers and intelligent heating control systems) [156], Ultimately targeting energy deprivation elimination in disadvantaged households. The benchmarks for each compulsory energy supplier are set by the governing body, Ofgem, who is also responsible for deciding whether each supplier fulfills its obligations, audits the scheme, prevents deceitful compliance claims and reports advancement to the UK Government [157]. Energy suppliers have recently been allowed to exchange their obligations with other contracted suppliers and Ofgem is also responsible for managing the trade arrangements.

In order for this system to work properly and efficiently all the stakeholders in the value chain system including energy efficiency initiatives installers, energy suppliers and the UK government must support and trust Ofgem to implement the scheme safely, effectively and with honesty. While using this type of centrally controlled third-party system is the widely accepted method of ensuring transparency in the recent times through any supply chain, its weakness is that the system relies on the integrity and ability of those system operators to keep the data they manage secure. Therefore the system is open to failures because of organizational bias, external hackers or potential fraud. Blockchain may be used to tackle this issue.

Blockchain could be used to build a digital public decentralized ledger to record all the transactions relating to ECO delivery. A smart contract may indeed be built using the blockchain technology that records a qualified installer based on a set of verifiable requirements for any installation of an ECO measure at a home property. It can even be linked to energy consumption before and after deployment in order to demonstrate compliance with actual, rather than deemed, energy savings. By their design, the blocks on the ledger are connected, meaning that the new entry relies on the content of the previous block that prevents retroactive modification of any block because that would change all the subsequent entries. As each participant in the production chain can attach blocks to the blockchain and use their own digital signature to verify the validity of the transaction, peer-to - peer trading can take place

immediately between the installer and the energy supplier or even between the energy suppliers that enable them to transact their obligations directly with no need for a market operator to validate transactions. It will theoretically reduce the operating costs for the ECO system while also rising the degree of trust in the system at the same time.

6.3 Benefits of utilizing blockchain technology in the energy efficiency market

Energy efficiency already has great potential to bring the most positive effects. Energy Efficiency 2018 study by the International Energy Agency notes that enhancing energy quality will reduce energy bills to customers by more than \$500 billion per year [146]. As the technology such as blockchain progresses, it will give consumers the ability to exchange their excess electricity. Consumers will be driven further towards energy savings and improving their homes' energy efficiency as they will be given an extra additional benefit to monetize their excess energy. As the market for energy efficiency is projected to grow over time, blockchain technology could considerably improve the overall administrative procedures, openness of the system, cost and trust between various stakeholders. Some of the key advantages are shown and explained below in Figure 6.10.

6.3.1 Encryptions of the energy savings

Encryption is a method of converting digital data or other information to a code in order to avoid unauthorized access. Encrypting and exchanging of the energy savings over the blockchain has the potential to safeguard the market. Energy baseline and savings data are one of the energy efficiency market's most important assets as well as several transactions, from bank payments to amounts paid to energy service providers and technology companies, depend solely on this. Data security has become a significant problem in this digitized world and blockchain can provide opportunities to secure customer data on energy savings for a more safe energy efficiency markets. When gathering and checking energy savings, it is difficult to gain the confidence of customers. It involves high costs for energy control, estimation and verification, and this, combined with a lack of clarity in energy measurements, acts as an obstacle to energy efficiency contracting. By providing safe, independent verification of energy transaction data and savings, blockchain provides accountability and establishes trust with customers.

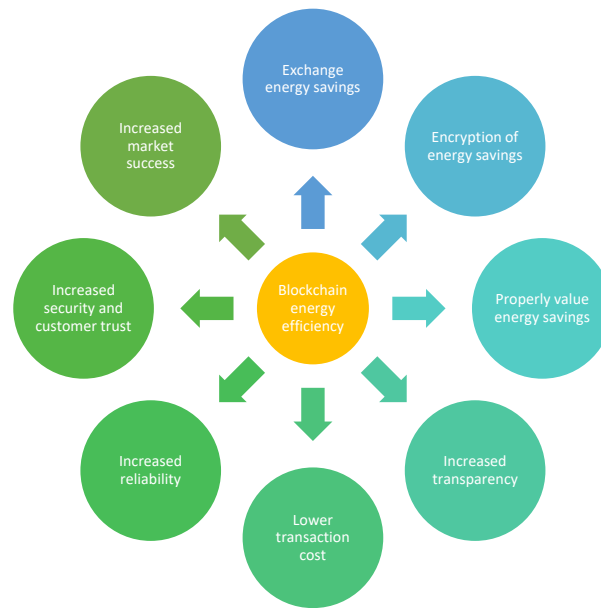


Figure. 6.11 Benefits of blockchain in the energy efficiency sector. Reprinted with permission from Khatoon et al., *Energies* 2019; 12(17), 3317.

6.3.2 Exchange of the energy savings

So far we have spoken about exchanging excess power production for peer-to-peer energy trading. But what if people in their locality want to trade energy savings? Can energy savings be built up and traded for a new energy-efficiency product that one would want to buy? Blockchain technology seems to have some opportunities here because energy savings data can be encrypted and stored on the blockchain platform to balance the energy bill or buy additional energy services.

6.3.3 Valuation of energy savings

Energy efficiency valuation has been very difficult, since the benefits of energy efficiency cannot be measured or evaluated technically in many cases. Blockchain, together with ICTs and process automation, may help to some degree in determining energy savings and their related benefits [147].

6.3.4 Increasing transparency

Since blockchain is a distributed ledger technology, digital data can be shared on a secure and tamperproof platform in a transparent manner. Interfering with the shared data on

the blockchain platform is a highly costly and technically impossible process. Blockchain is a trustless system so each data shared with the other blocks is verified by all the blocks in the chain, meaning that all the blocks will have data on energy savings [148] [149].

6.3.5 Lowering the transaction costs

Blockchain does not need intermediaries and the transaction may occur peer-to - peer directly which reduces process complexity and associated costs. In this way, the transaction cost of managing energy related contracts can be reduced considerably. In the case of the energy efficiency market, particularly in energy performance contracting, streamlining the transaction costs for ESCOs, banks, utilities and customers through a blockchain process can be reduced.

6.3.6 Increasing reliability

Trust is very important term in this new world , especially when it comes to storing of information when it can be stored either at a single point or in multiple account books belonging to different stakeholders without any automated processes. If information is stored at a single point, the time taken to gather the required information would make it very difficult to track and audit. Since blockchain is a trustless distributed ledger technology where information is recorded in different blocks, the overall system reliability can be significantly improved.

6.3.7 Increasing customer trust and security

Blockchain is made safe through its cryptography methods, which ensures that the energy saving data of consumers, information from financial institutions or data related to any stakeholder in the energy efficiency industry would be encrypted. Blockchain can also make the process automated rather than manual via smart contract features which can help increase consumer trust in the system.

6.3.8 Increasing the market success

Once the blockchain technology, such as energy performance contracting, is applied to the energy efficiency market, this can bring security , transparency, confidence, lower

operational costs , energy savings authorisation, and payments in an automated way. This will carry the energy efficiency market the next stage of growth. ICTs and blockchain can significantly reduce market obstacles and set a new energy efficiency trajectory for success.

6.4 Conclusions

Moving to a smart, integrated prosumers grid would require the implementation of new technology, as well as the opportunity to value energy conservation steps, so that the resulting savings can be shared equally and transparently. Blockchain technology offers an optimism for the energy sector that it will be possible to provide a safe and secure digital transaction system in which consumers can participate directly in the energy market. In this chapter we have addressed the use of blockchain for the energy efficiency market and some of the benefits that implementation of blockchain technology could bring to the stakeholders if appropriate structures could be introduced. The issues surrounding energy efficiency savings and trading markets, such as proper savings valuation, stakeholder data transparency, inefficient administrative procedures, and high energy-efficiency market complexities are very well known. Blockchain's potential application to address some of these major issues was explored by examining two case studies — the Italian White Certificate Scheme (WCS) and the UK Energy Company Obligation Scheme. This chapter also presents an algorithm designed for the trading of energy-saving certificates, which is implemented via a smart contract system based on the Ethereum blockchain. Unlike the other conventional energy saving certificate trading systems, our approach offers a decentralized, safe, automated, time-stamped and transparent trading platform among multiple users using blockchain technology.

There will still be challenges around the technology on its own that are currently being acknowledged such as scalability, performance, standardization, complexity, cost and skills. Given that a number of pilot projects are already underway to assess the usage of blockchain in a variety of energy-related applications, now is the best time to explore how the technology might be useful to the energy efficiency sector and to thoroughly examine the obstacles that exist before its commercialisation. This research work clearly suggests the technology's potential in the energy trading systems. While this technology has the ability to impact the energy efficiency market positively, we must also consider how future policy and regulatory models will look like and also what would be the position of the various stakeholders in the future energy efficiency market will shift.

In this work we have collaborated with International Energy Research Centre Cork and Tyndall National Institute on implementing new energy policy regulatory scheme. We were involved in the technical part of this work and our collaborators provided data on the energy policy side. We were looking into the Smart contract applications for medical healthcare management systems, we extended our work for the energy system applications. This chapter is an additional contribution to this thesis.

7 Conclusions and future directions

The work described in this thesis details the design and development of smart contract system for blockchain based applications. We have designed and implemented smart contract system for blockchain based applications across healthcare (Healthcare Management to Facilitate Medical Ecosystems) and Energy efficiency (increasing energy efficiency by designing smart contract system for energy-saving certificates). We have also identified key themes, developments and emerging areas of healthcare and energy research in this thesis.

7.1 Smart contracts for Healthcare Management to facilitate Medical Eco-system

In this work, the feasibility of Blockchain based smart contracts for healthcare management has been investigated. This research work also proposes multiple workflows that are involved in the landscape of health care using blockchain technology for better data management. This will includes accessing and managing a considerable amount of medical information. In implementing the workflows of the medical smart contract management system, the related costs for this system were calculated in terms of a detailed feasibility study. A transaction group in blockchain networks is combined into blocks of transactions connected in the chain using the hash of the previous block's record. Therefore, as a property of immutability, the basic security feature of blockchain networks is enforced. The further the block is along the chain (the older it is), the more the data included in it is protected from changes. If an attacker tries to change any of the keys, the local register will immediately cease to be valid because the hash values inside the next blocks headers will be completely different depending on the hash function mechanism. Moreover, this network is usually referred to as a distributed registry, as data is stored on each node operating in each of the individual networks. Each block plays a key role in connecting with the previous block, and with the following block, as soon as it comes into the system to be a part of the chain. The main role of each block is to record, validate and distribute the transactions among other blocks. This means that a block in the chain cannot be removed or altered as this would change every subsequent block. It would serve research as well as personalized medicine to create a single storage location for all health data, track personalized data in real-time and set data access permissions at a granular level.

Healthcare researchers need extensive data sets to accelerate disease understanding, speed up clinical research discovery, quickly track drug development and design specific treatment plans determined by genetics, lifespan and environment. While having patients from different racial and socio-economic backgrounds and from various geographic regions, our Ethereum-based blockchain shared data network will have a broad variety of data collection. In longitudinal research it offers great knowledge as blockchain gathers health data over a person's lifetime. It will expand health data collection to include data from groups of people who are currently under-served by the medical system or who are not traditionally interested in research. Blockchain's open data ecosystem makes it easier for "hard-to-reach" markets to be involved, and more positive results for the general public. This program would likely promote the development of a new breed of "smart" health care provider apps that would circumvent the latest medical studies and create tailor-made treatment pathways. The health care provider and patient would also have access to this information and they could thoroughly engage in a cooperative, educated discussion of research-based treatment options rather than the best case based on intuition.

In this thesis using blockchain technology, our smart contract-based healthcare management system has demonstrated how decentralization concepts can be applied to large-scale data processing in medical environments, and how complex medical procedures can be streamlined. We show an innovative approach to medical record management, providing auditability, interoperability and accountability through intelligent contracts. Developed to monitor consistency and variability, this system allows patient data to be exchanged and medical researchers have the opportunity to adopt the programme. We have presented possible applications of blockchain technology in the management of health data. From a medical point of view we have developed a demand-focused model of data management and sharing. Blockchain technology, transparency, security, availability and fine control of access to EHR data can be assured. The main aim of using blockchain, as stated in this thesis, is to improve healthcare processes and hence patient outcomes. Blockchain can help in many ways; reduce transaction costs by using smart contracts embedded in protocols for general purposes to simplify processes, reduce unnecessary costs and remove intermediaries; our proposed approach uses blockchain technologies to design an iterative, scalable, stable, open and decentralized healthcare ecosystem. It will motivate patients to share their medical records openly and securely with doctors, hospitals, research organizations and other stakeholders —

all while maintaining complete control over the confidentiality of their health records. This would resolve many of the current healthcare system's problems, including data siloing, inconsistency with the legacy network, unstructured data processing problems, prohibitively expensive operating costs, lack of information security and unanswered privacy issues.

7.2 Blockchain based smart contract system for energy efficiency

Throughout this work, we discussed how the key issues surrounding energy efficiency savings trading – accurate estimate of savings, stakeholder data transparency, and inefficient administrative processes can be solved by implementing a smart contract framework based on blockchain. An implementation of the Ethereum based smart contract system for trading energy saving certificates obtained through execution of smart contract transactions on Ethereum blockchain was presented. We discussed in detail the key advantages and implications of using blockchain in the energy efficiency sector by presenting and discussing some case studies as potential blockchain applications – (i) The UK Energy Company Obligation Scheme and (ii) The Italian White Certificate Scheme (WCS).

. In either sellers or local energy trading applications, such as peer-to - peer energy trading, blockchain will provide a reliable trading verification process without needing third party authentication. Having a standardized global blockchain infrastructure can also provide cross-border, frictionless energy trade. Blockchain will enable prosumers to take part in the local energy market where they would rely on technology that can make transactions faster, cheaper and easier than a traditional centralized energy system. Blockchain has also been tested in charging facilities for electric vehicles (EVs) where this will allow access to all charging points for EV drivers through the creation of a network of EVs and charging facilities and the development of an simple payment and efficient settlement mechanism for all parties involved. Several energy firms are also pursuing blockchain technologies in supply and value chains with the aim of enhancing visibility and reducing the loss of assets from output to consumption. Project financing is also studied where blockchain is used to improve the efficiency and effectiveness of the system and liquidity of payments.

Shifting towards a smart, integrated prosumers grid would require the implementation of new technology, as well as the capacity to value energy conservation steps, so that the resulting savings can be shared equally and transparently. For the energy market, blockchain technology offers an optimism that a safe and trustworthy digital transaction platform can be

built where customers can participate directly in the energy sector. We addressed the use of blockchain for the energy efficiency market in this report, and some of the benefits that applying this technology could bring to stakeholders if the correct frameworks could be implemented. The issues surrounding trading savings in energy efficiency, such as proper savings valuation, stakeholder data transparency, inefficient management procedures, and the high energy efficiency market complexities are well known. Two case studies – the Italian White Certificate Scheme and the UK Energy Company Duty Scheme – explored the possible use of blockchain to resolve some of these key issues. In addition, we presented an algorithm designed to trading energy saving certificates, implemented through a smart contract framework based on blockchain. Unlike the traditional energy saving certificate trading system system , this system offers a distributed, stable, automated, time-stamped and transparent trading system between different users using distributed ledger technology.

7.3 Reflection and Impact Assessment

The smart contract based framework demonstrates how design concepts of decentralization and blockchain can lead to stable, interoperable systems. Using Ethereum smart contracts to facilitate a content-control network through various storage and provider sites, authentication log controls access rights while offering full record monitoring, auditability and data sharing to the parties involved. We demonstrated a revolutionary approach for accessibility of open APIs and network structure.

7.4 Future Work

In our current system, we used (PoW) mechanism and maintained the data off-chain due to cost constraint and the computation power. As it is always expensive to store the data on-chain. As in the scope of future work, our intention is to use (PoS) protocol and keep the data on the chain instead of maintaining it in a separate local database. However, doing (PoS) right away is a significant technological issue, and it's not as trivial as using (PoW) to gain network consensus. This allows the Ethereum network's nodes to agree on the current status of all data stored on the Ethereum blockchain, preventing specific types of economic threats.

Ethash, the proof-of-work protocol, requires miners to compete in a game of trial and error to obtain the nonce for a block. Only valid nonce blocks can be added to the network. A miner will continually run a dataset, which can only be obtained by downloading and running

the entire chain (as such a miner does), through some kind of mathematical function while racing to build a block.

At its most basic level, proof-of-stake and proof-of-work have the same ultimate goal: to assist the decentralized network in reaching safe consensus. However, there are some distinctions in terms of procedure and personnel: For staked ETH, PoS reduces the importance of computational resources. Validators substitute miners in PoS. Validators put their ETH on the line to enable the creation of new blocks. The Validators do not strive to build blocks; rather, an algorithm selects them randomly. At certain stages, the status of the block is declared final if two-thirds of the validators agree. Validators must stake their entire stake on this, so if they try to conspire later, they will lose everything.

Validators, unlike proof-of-work, shouldn't have to utilize a lot of computing power as they're chosen at random and aren't competing. They don't have to mine blocks; all they have to do is produce them when they're needed and validate suggested blocks when they're not. Attesting is the term for this type of validation. Attesting might be thought of as stating, "This block looks alright to us." Validators are rewarded for suggesting new blocks and attesting to existing ones. One can lose their stake if they try to attest the illegitimate blocks. The fundamental mechanism that activates validators when enough stake is received is known as proof-of-stake. To become a validator on Ethereum, users must invest 32 ETH. Validators are assigned to produce blocks at random and are accountable for double-checking and confirming any blocks they do not make. The stake of the user is also used to incentivize positive validator activity. For example, a user may lose a portion of their share if they go offline, fail to validate or lose their entire investment if they engage in wilful collusion. PoS is better when it comes to utilize lot of computational power. The future scope of this work lies in migration to the (PoS) protocol completely.

References

- [1] “Cardano - Home of the Ada cryptocurrency and technological platform.” [Online]. Available: <https://www.cardano.org/en/home/>. [Accessed: 25-Mar-2020].
- [2] “Bitcoin: A Peer-to-Peer Electronic Cash System.” [Online]. Available: <https://bitcoin.org/en/bitcoin-paper>. [Accessed: 24-Mar-2020].
- [3] “Home | Ethereum.org.” [Online]. Available: <https://ethereum.org/>. [Accessed: 25-Mar-2020].
- [4] P. Deepak, M. Nisha, and S. P. Mohanty, “Everything You Wanted to Know About the Blockchain,” *IEEE Consum. Electron. Mag.*, vol. 7, no. 4, pp. 6–14, 2018.
- [5] “What are Trustless Environments & How Cryptocurrencies Create Them ?” [Online]. Available: <https://blockonomi.com/trustless-environments/>. [Accessed: 25-Mar-2020].
- [6] “What is Blockchain?” [Online]. Available: <https://lisk.io/what-is-blockchain>. [Accessed: 25-Mar-2020].
- [7] M. Jakobsson and A. Juels, “Proofs of Work and Bread Pudding Protocols(Extended Abstract).” Springer US, pp. 258–272, 1999.
- [8] Z. Wan, D. Lo, X. Xia, and L. Cai, “Bug Characteristics in Blockchain Systems: A Large-Scale Empirical Study,” in *IEEE International Working Conference on Mining Software Repositories*, 2017, pp. 413–424.
- [9] P. Zheng, Z. Zheng, X. Luo, X. Chen, and X. Liu, “A detailed and real-time performance monitoring framework for blockchain systems,” in *Proceedings - International Conference on Software Engineering*, 2018, pp. 134–143.
- [10] “Blockchain: Everything You Need to Know.” [Online]. Available: <https://www.investopedia.com/terms/b/blockchain.asp>. [Accessed: 25-Mar-2020].
- [11] “Block hashing algorithm - Bitcoin Wiki.” [Online]. Available: https://en.bitcoin.it/wiki/Block_hashing_algorithm. [Accessed: 25-Mar-2020].
- [12] “Bitcoin Cash - Peer-to-Peer Electronic Cash.” [Online]. Available: <https://www.bitcoincash.org/>. [Accessed: 25-Mar-2020].
- [13] “Bitcoin Puzzle Worth 2.1 BTC STILL Unsolved, Find New Clues Here.” [Online]. Available: <https://bitcoinist.com/bitcoin-puzzle-worth-2-1-btc-still-unsolved-find-new-clues-here/>. [Accessed: 25-Mar-2020].
- [14] “Proof-of-Work vs. Proof-of-Stake - HydroMiner - Medium.” [Online]. Available:

- <https://medium.com/@hydrominer/proof-of-work-vs-proof-of-stake-7b3afe24f0cc>.
[Accessed: 25-Mar-2020].
- [15] “Peercoin — The Pioneer of Proof of Stake.” [Online]. Available: <https://www.peercoin.net/>. [Accessed: 25-Mar-2020].
- [16] “Home | Monero - secure, private, untraceable.” [Online]. Available: <https://www.getmonero.org/>. [Accessed: 25-Mar-2020].
- [17] “XRP | Ripple.” [Online]. Available: <https://ripple.com/xrp/>. [Accessed: 25-Mar-2020].
- [18] “Buy Binance Coin | Buy BNB | Buy Binance Coin with Credit Card | Binance.com.” [Online]. Available: <https://www.binance.com/en/buy-Binance-Coin>. [Accessed: 25-Mar-2020].
- [19] “EOSIO - Blockchain software architecture.” [Online]. Available: <https://eos.io/>. [Accessed: 25-Mar-2020].
- [20] “Tether – Stable digital cash on the Blockchain.” [Online]. Available: https://tether.to/?__cf_chl_jschl_tk__=b1913042d380bf14ca2b13c04df5c8f1af13b7ae-1585175857-0-AU9TLe7_54PS7gaaC-15mCwIasWUzTe33Dfq_Tz1ARJmBJHRO5zHo2crYG5_D4zlSTr0dq4rWZDZB3FTBXMHV8rtOHzuSz3FbGGxWfAxB8fyXSvcWnXZ0awtoGsMPRxgUGG8xL_DE9ubKTYbdmORbBJvyCE14U-seAbHWJZRAi8XSUEngK7Zlw14khM6ta-1WDewukzYo_fodpek264Z47j0JFPuzL5WOi65sUwWb8ztIjE-Ux10DkoKI3eFYpGU8mzIos7m3rCbW5v1hCNkOrI. [Accessed: 25-Mar-2020].
- [21] “Stellar - an open network for money.” [Online]. Available: <https://www.stellar.org/>. [Accessed: 25-Mar-2020].
- [22] “Dash - Dash is Digital Cash You Can Spend Anywhere.” [Online]. Available: https://www.dash.org/?__cf_chl_jschl_tk__=3074aa005757ec111f908f14b3d1e51a6094671e-1585175637-0-ASWYPw59Zwz-8hi9rf_gTzNMvH8QmJWt2YcSWJoL-OfAb88hLxFf-PjQ2d0XFRKskk0gyZhNCwwEiPzJPMLdat9CMLgkaYtiZA4VtAxf6kBQ-o8FMhPQHNYKY_XwYCazCOfqYwDk0z74DryMUGg2d8k8xTyqQEv1bDUORZw0l5KZ_0MnflBW9L4xrjfPPEXTDVnFklK_Z2TF0PkxoIk2cgU_4bITKJX6zDnhhDV-O7vtDALkgoy_ydoCJ0YxLmf6VkTwgN-qQOW_bbksqhlTxdw. [Accessed: 25-Mar-2020].
- [23] “Litecoin - Open source P2P digital currency.” [Online]. Available: <https://litecoin.org/>. [Accessed: 25-Mar-2020].

- [24] “(6) The difference between a Private, Public & Consortium Blockchain. | LinkedIn.” [Online]. Available: <https://www.linkedin.com/pulse/difference-between-private-public-consortium-collin-thompson/>. [Accessed: 24-Mar-2020].
- [25] G. A. Oliva, A. E. Hassan, and Z. M. Jiang, “An exploratory study of smart contracts in the Ethereum blockchain platform,” *Empir. Softw. Eng.*, pp. 1–41, Mar. 2020.
- [26] N. Grech, L. Brent, B. Scholz, and Y. Smaragdakis, “Gigahorse: Thorough, Declarative Decompilation of Smart Contracts,” in *Proceedings - International Conference on Software Engineering*, 2019, vol. 2019-May, pp. 1176–1186.
- [27] R. Tonelli, G. Destefanis, M. Marchesi, and M. Ortu, “Smart Contracts Software Metrics: a First Study,” Feb. 2018.
- [28] L. Luu, D. H. Chu, H. Olickel, P. Saxena, and A. Hobor, “Making smart contracts smarter,” in *Proceedings of the ACM Conference on Computer and Communications Security*, 2016, vol. 24-28-October-2016, pp. 254–269.
- [29] N. Szabo, “Formalizing and securing relationships on public networks,” *First Monday*, vol. 2, no. 9, Sep. 1997.
- [30] M. Bartoletti, S. Carta, T. Cimoli, and R. Saia, “Dissecting Ponzi schemes on Ethereum: Identification, analysis, and impact,” *Futur. Gener. Comput. Syst.*, vol. 102, pp. 259–277, Jan. 2020.
- [31] I. Grishchenko, M. Maffei, and C. Schneidewind, “Foundations and Tools for the Static Analysis of Ethereum Smart Contracts.” Springer International Publishing, pp. 51–78, 2018.
- [32] “The Ethereum Virtual Machine — How does it work? - MyCrypto - Medium.” [Online]. Available: <https://medium.com/mycrypto/the-ethereum-virtual-machine-how-does-it-work-9abac2b7c9e>. [Accessed: 25-Mar-2020].
- [33] “1. What Is Ethereum? - Mastering Ethereum [Book].” [Online]. Available: <https://www.oreilly.com/library/view/mastering-ethereum/9781491971932/ch01.html>. [Accessed: 25-Mar-2020].
- [34] “Elliptic Curve Cryptography - KeyCDN Support.” [Online]. Available: <https://www.keycdn.com/support/elliptic-curve-cryptography>. [Accessed: 25-Mar-2020].
- [35] “Elliptic Curve Cryptography: a gentle introduction - Andrea Corbellini.” [Online]. Available: <https://andrea.corbellini.name/2015/05/17/elliptic-curve-cryptography-a-gentle-introduction/>. [Accessed: 25-Mar-2020].
- [36] S. Tikhomirov, E. Voskresenskaya, I. Ivanitskiy, R. Takhaviev, E. Marchenko, and Y.

- Alexandrov, “SmartCheck: Static analysis of ethereum smart contracts,” in *Proceedings - International Conference on Software Engineering*, 2018, pp. 9–16.
- [37] “Smart Contracts: The Future of Blockchain? Mason Hayes Curran.” [Online]. Available: <https://www.mhc.ie/latest/blog/smart-contracts-the-future-of-blockchain>. [Accessed: 25-Mar-2020].
- [38] “JavaScript | MDN.” [Online]. Available: <https://developer.mozilla.org/en-US/docs/Web/JavaScript>. [Accessed: 25-Mar-2020].
- [39] “Solidity — Solidity 0.6.4 documentation.” [Online]. Available: <https://solidity.readthedocs.io/en/v0.6.4/>. [Accessed: 25-Mar-2020].
- [40] “Solidity: Why You May Want to Learn This Ethereum Smart Contract Language - Bitcoin EU.” [Online]. Available: <https://bitcoin.eu/solidity-why-you-may-want-to-learn-this-ethereum-smart-contract-language/>. [Accessed: 25-Mar-2020].
- [41] “Ethereum for Developers | Ethereum.org.” [Online]. Available: <https://ethereum.org/developers/>. [Accessed: 25-Mar-2020].
- [42] “Introduction to Smart Contracts — Solidity 0.6.4 documentation.” [Online]. Available: <https://solidity.readthedocs.io/en/v0.6.4/introduction-to-smart-contracts.html>. [Accessed: 25-Mar-2020].
- [43] “A 101 Noob Intro to Programming Smart Contracts on Ethereum.” [Online]. Available: <https://medium.com/@ConsenSys/a-101-noob-intro-to-programming-smart-contracts-on-ethereum-695d15c1dab4>. [Accessed: 25-Mar-2020].
- [44] “Introducing Web3 Plugins - MetaMask - Medium.” [Online]. Available: <https://medium.com/metamask/introducing-the-next-evolution-of-the-web3-wallet-4abdf801a4ee>. [Accessed: 25-Mar-2020].
- [45] “Ethereum (ETH) Blockchain Explorer.” [Online]. Available: <https://etherscan.io/>. [Accessed: 25-Mar-2020].
- [46] Y. Hu, M. Liyanage, A. Mansoor, K. Thilakarathna, G. Jourjon, and A. Seneviratne, “Blockchain-based Smart Contracts - Applications and Challenges,” pp. 1–26, 2018.
- [47] X. Yue, H. Wang, D. Jin, M. Li, and W. Jiang, “Healthcare Data Gateways: Found Healthcare Intelligence on Blockchain with Novel Privacy Risk Control,” *J. Med. Syst.*, vol. 40, no. 10, pp. 1–8, Oct. 2016.
- [48] “Intelligent Computing, Information and Control Systems: ICICCS 2019 - Google Books.” [Online]. Available: <https://books.google.ie/books?id=EMO3DwAAQBAJ&pg=PA528&lpg=PA528&dq=Lemieux,+V.L.+Trusting+records:+Is+Blockchain+technology+the+answer?+Rec.+M>

- anag.+J.+2016,+26,+110–139&source=bl&ots=sdEanEVLlm&sig=ACfU3U28vZ1ImmLC8WpjphVYPb9P9UQH1w&hl=en&sa=X&ved=2ahUKEwie2Zzz4rLoAhUaXRUIHYgXDJIQ6AEwAHoECAYQAQ#v=onepage&q=Lemieux%2C V.L. Trusting records%3A Is Blockchain technology the answer%3F Rec. Manag. J. 2016%2C 26%2C 110–139&f=false. [Accessed: 24-Mar-2020].
- [49] M. N. Kamel Boulos, J. T. Wilson, and K. A. Clauson, “Geospatial blockchain: Promises, challenges, and scenarios in health and healthcare,” *International Journal of Health Geographics*, vol. 17, no. 1. BioMed Central Ltd., 05-Jul-2018.
- [50] I. Weber, X. Xu, R. Riveret, G. Governatori, A. Ponomarev, and J. Mendling, “Using Blockchain to Enable Untrusted Business Process Monitoring and Execution,” *Int. Conf. Bus. Process Manag.*, pp. 329–347, 2016.
- [51] W. J. Gordon and C. Catalini, “Blockchain Technology for Healthcare: Facilitating the Transition to Patient-Driven Interoperability,” *Comput. Struct. Biotechnol. J.*, vol. 16, pp. 224–230, 2018.
- [52] D. Ichikawa, M. Kashiyama, and T. Ueno, “Tamper-resistant mobile health using blockchain technology,” *JMIR mHealth uHealth*, vol. 5, no. 7, pp. 1–10, 2017.
- [53] A. A. Vazirani, O. O’Donoghue, D. Brindley, and E. Meinert, “Implementing blockchains for efficient health care: Systematic review,” *J. Med. Internet Res.*, vol. 21, no. 2, pp. 1–12, 2019.
- [54] S. Rouhani and L. Butterworth, “MediChain TM : A Secure Decentralized Medical Data Asset Management System,” no. Section II.
- [55] H. Wu and C. Tsai, “Toward Blockchains for Health-Care Systems,” *IEEE Consum. Electron. Mag.*, vol. 7, no. july, pp. 65–71, 2018.
- [56] B. Shen, J. Guo, and Y. Yang, “MedChain: Efficient healthcare data sharing via blockchain,” *Appl. Sci.*, vol. 9, no. 6, 2019.
- [57] S. Khezr, M. Moniruzzaman, A. Yassine, and R. Benlamri, “Blockchain technology in healthcare: A comprehensive review and directions for future research,” *Appl. Sci.*, vol. 9, no. 9, pp. 1–28, 2019.
- [58] A. T. Litchfield, A. Khan, " A And Khan, and A. Khan, “CONF-IRM) 5-2019 Review of Issues in Healthcare Information Management Systems and Blockchain Solutions,” vol. 1, 2019.
- [59] J. Vora *et al.*, “BHEEM: A Blockchain-Based Framework for Securing Electronic Health Records,” *2018 IEEE Globecom Work. GC Wkshps 2018 - Proc.*, pp. 1–6,

- 2019.
- [60] A. Petre, “Blockchain use cases in healthcare,” *LinkedIn Pulse*, vol. 111, pp. 1–41, 2017.
- [61] A. A. Siyal, A. Z. Junejo, M. Zawish, K. Ahmed, A. Khalil, and G. Soursou, “Applications of Blockchain Technology in Medicine and Healthcare: Challenges and Future Perspectives,” *Cryptography*, vol. 3, no. 1, p. 3, 2019.
- [62] F. Jamil, L. Hang, K. H. Kim, and D. H. Kim, “A novel medical blockchain model for drug supply chain integrity management in a smart hospital,” *Electron.*, vol. 8, no. 5, pp. 1–32, 2019.
- [63] S. H. Lee and C. S. Yang, “Fingernail analysis management system using microscopy sensor and blockchain technology,” *Int. J. Distrib. Sens. Networks*, vol. 14, no. 3, 2018.
- [64] C. Agbo, Q. Mahmoud, and J. Eklund, “Blockchain Technology in Healthcare: A Systematic Review,” *Healthcare*, vol. 7, no. 2, p. 56, 2019.
- [65] A. Azaria, A. Ekblaw, T. Vieira, and A. Lippman, “MedRec: Using blockchain for medical data access and permission management,” *Proc. - 2016 2nd Int. Conf. Open Big Data, OBD 2016*, pp. 25–30, 2016.
- [66] P. Zhang, J. White, D. C. Schmidt, and G. Lenz, “Design of blockchain-based apps using familiar software patterns with a healthcare focus,” *Proc. 24th Conf. Pattern Lang. Programs*, p. 19, 2017.
- [67] T. Kumar, V. Ramani, I. Ahmad, A. Braeken, E. Harjula, and M. Ylianttila, “Blockchain utilization in healthcare: Key requirements and challenges,” *2018 IEEE 20th Int. Conf. e-Health Networking, Appl. Serv. Heal. 2018*, pp. 1–7, 2018.
- [68] Jp. Genestier *et al.*, “Blockchain for Consent Management in the eHealth Environment: A Nugget for Privacy and Security Challenges,” *J Int Soc Telemed eHealth*, vol. 5, pp. 24–25, 2017.
- [69] M. Nofer, P. Gomber, O. Hinz, and D. Schiereck, “Blockchain,” *Bus. Inf. Syst. Eng.*, vol. 59, no. 3, pp. 183–187, 2017.
- [70] D. Shrier, W. Wu, and A. Pentland, “Blockchain & Infrastructure,” *MIT Connect. Sci. Eng.*, pp. 1–18, 2016.
- [71] R. Stephen and A. Alex, “A Review on BlockChain Security,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 396, no. 1, 2018.
- [72] X. Liang, S. Shetty, D. Tosh, C. Kamhoua, K. Kwiat, and L. Njilla, “ProvChain: A Blockchain-Based Data Provenance Architecture in Cloud Environment with

- Enhanced Privacy and Availability,” *Proc. - 2017 17th IEEE/ACM Int. Symp. Clust. Cloud Grid Comput. CCGRID 2017*, pp. 468–477, 2017.
- [73] T. K. Mackey *et al.*, ““Fit-for-purpose?” - Challenges and opportunities for applications of blockchain technology in the future of healthcare,” *BMC Med.*, vol. 17, no. 1, pp. 1–17, 2019.
- [74] M. Greenberger, “Block what? The unrealized potential of blockchain in healthcare,” *Nurs. Manage.*, vol. 50, no. 5, pp. 9–12, May 2019.
- [75] K. V. O. Rabah, “Challenges & Opportunities for Blockchain Powered Healthcare Systems: A Review.” 2017.
- [76] I. Radanović and R. Likić, “Opportunities for Use of Blockchain Technology in Medicine,” *Appl. Health Econ. Health Policy*, vol. 16, no. 5, pp. 583–590, Oct. 2018.
- [77] A. Khatoon, “A Blockchain-Based Smart Contract System for Healthcare Management,” *Electronics*, vol. 9, no. 1, p. 94, Jan. 2020.
- [78] “The strategic business value of the blockchain market | McKinsey.” [Online]. Available: <https://www.mckinsey.com/business-functions/mckinsey-digital/our-insights/blockchain-beyond-the-hype-what-is-the-strategic-business-value>. [Accessed: 24-Mar-2020].
- [79] A. Khatoon, P. Verma, J. Southernwood, B. Massey, and P. Corcoran, “Blockchain in Energy Efficiency: Potential Applications and Benefits,” *Energies*, vol. 12, no. 17, p. 3317, Aug. 2019.
- [80] “Implementation of Blockchain on Peer-to-Peer Energy Trading.” [Online]. Available: <https://www.blockchain-council.org/blockchain/what-is-blockchain-how-does-it-relate-to-p2p/>. [Accessed: 24-Mar-2020].
- [81] “Blockchain and the Rise of Peer-to-Peer Power Markets - Microgrid Media.” [Online]. Available: <http://microgridmedia.com/blockchain-distributed-peer-peer-energy-markets/>. [Accessed: 24-Mar-2020].
- [82] M. R. Alam, M. St-Hilaire, and T. Kunz, “Peer-to-peer energy trading among smart homes,” *Appl. Energy*, vol. 238, no. October 2018, pp. 1434–1443, 2019.
- [83] M. Andoni *et al.*, “Blockchain technology in the energy sector: A systematic review of challenges and opportunities,” *Renew. Sustain. Energy Rev.*, vol. 100, no. February 2018, pp. 143–174, 2019.
- [84] F. P. (Fereidoon P. Sioshansi, *Consumer, prosumer, prosumer : how service innovations will disrupt the utility business model.* .
- [85] “First European energy trade over the blockchain.” [Online]. Available:

- <https://enerchain.ponton.de/index.php/11-first-european-energy-trade-over-the-blockchain>. [Accessed: 24-Mar-2020].
- [86] “Scaling up blockchain for peer-to-peer energy trading | Engerati,” <https://www.engerati.com/>.
- [87] “New York neighbours power up blockchain-based Brooklyn Microgrid.” [Online]. Available: <https://www.siliconrepublic.com/machines/brooklyn-microgrid-blockchain-energy-networks>. [Accessed: 24-Mar-2020].
- [88] C. Zhang, J. Wu, C. Long, and M. Cheng, “Review of Existing Peer-to-Peer Energy Trading Projects,” *Energy Procedia*, vol. 105, pp. 2563–2568, 2017.
- [89] “How can blockchain save energy? Here are three possible ways. | ACEEE.” [Online]. Available: <https://www.aceee.org/blog/2018/10/how-can-blockchain-save-energy-here>. [Accessed: 24-Mar-2020].
- [90] “ESCO contracts – Energy Service Companies (ESCOs) – Analysis - IEA.” [Online]. Available: <https://www.iea.org/reports/energy-service-companies-escos-2/esco-contracts>. [Accessed: 24-Mar-2020].
- [91] O. Gurcan, M. Agenis-Nevers, Y. M. Batany, M. Elmtiri, F. Le Fevre, and S. Tucci-Piergiovanni, “An Industrial Prototype of Trusted Energy Performance Contracts Using Blockchain Technologies,” *Proc. - 20th Int. Conf. High Perform. Comput. Commun. 16th Int. Conf. Smart City 4th Int. Conf. Data Sci. Syst. HPCC/SmartCity/DSS 2018*, no. July, pp. 1336–1343, 2019.
- [92] “Blockchain and energy efficiency: a match made in heaven? | ACEEE.” [Online]. Available: <https://www.aceee.org/blog/2018/04/blockchain-and-energy-efficiency>. [Accessed: 24-Mar-2020].
- [93] “IPEEC - Blockchain technology brings innovative ways to achieve energy efficiency.” [Online]. Available: <https://ipeec.org/bulletin/82-blockchain-technology-brings-innovative-ways-to-achieve-energy-efficiency-.html>. [Accessed: 24-Mar-2020].
- [94] J. A. F. Castellanos, D. Coll-Mayor, and J. A. Notholt, “Cryptocurrency as guarantees of origin: Simulating a green certificate market with the Ethereum Blockchain,” *2017 5th IEEE Int. Conf. Smart Energy Grid Eng. SEGE 2017*, pp. 367–372, 2017.
- [95] J. Lee and H. Kim, “in the Internet of Things,” no. july 2017, pp. 134–136, 2020.
- [96] W. Ejaz and A. Anpalagan, *Internet of Things for Smart Cities: Overview and Key Challenges BT - Internet of Things for Smart Cities: Technologies, Big Data and Security*. 2019.
- [97] C. Li and L. Zhang, “A Blockchain Based New Secure Multi-Layer Network Model

- for Internet of Things,” pp. 33–41, 2017.
- [98] M. Conoscenti, A. Vetro, and J. C. De Martin, “Blockchain for the Internet of Things: A systematic literature review,” *Proc. IEEE/ACS Int. Conf. Comput. Syst. Appl. AICCSA*, vol. 0, pp. 1–6, 2016.
- [99] S. Huckle, R. Bhattacharya, M. White, and N. Beloff, “Internet of Things, Blockchain and Shared Economy Applications,” *Procedia Comput. Sci.*, vol. 58, pp. 461–466, 2016.
- [100] A. Gervais, G. O. Karame, K. Wüst, and H. Ritzdorf, “On the Security and Performance of Proof of Work Blockchains Vasileios Glykantzis Srdjañ Capkun,” *Bitcoin.org*, 2017.
- [101] D. Mendez Mena, I. Papapanagiotou, and B. Yang, “Internet of things: Survey on security,” *Inf. Secur. J.*, vol. 27, no. 3, pp. 162–182, 2018.
- [102] “USING BLOCKCHAIN TO SUPPORT PROVENANCE IN THE INTERNET OF THINGS,” 2017.
- [103] M. Banerjee, J. Lee, and K. K. R. Choo, “A blockchain future for internet of things security: a position paper,” *Digit. Commun. Networks*, vol. 4, no. 3, pp. 149–160, 2018.
- [104] M. Ammar, G. Russello, and B. Crispo, “Internet of Things: A survey on the security of IoT frameworks,” *J. Inf. Secur. Appl.*, vol. 38, no. February, pp. 8–27, 2018.
- [105] N. Fabiano, “Internet of Things and the Legal Issues related to the Data Protection Law according to the new European General Data Protection Regulation,” *Athens J. Law*, vol. 3, no. 3, pp. 201–214, 2017.
- [106] O. Ala-Peijari, “Bitcoin The Virtual Currency: Energy Efficient Mining of Bitcoins. Master’s Thesis,” pp. 12–16, 2015.
- [107] X. Zhu, “Autonomic Identity Framework for the Internet of Things,” 2017.
- [108] S. Kornmesser, “Theoretizität im logischen empirismus und im strukturalismus - Erläutert am fallbeispiel des neurobiologischen konstruktivismus,” *J. Gen. Philos. Sci.*, vol. 39, no. 1, pp. 53–67, 2008.
- [109] N. Fabiano, “The Internet of Things ecosystem : the blockchain and privacy issues . The challenge for a global privacy standard,” vol. 2060, 2017.
- [110] C. Decker, C. Decker, and R. Wattenhofer, “Information propagation in the Bitcoin network Information Propagation in the Bitcoin Network,” *13-th IEEE Int. Conf. Peer-to-Peer Comput.*, no. August, pp. 1–10, 2016.
- [111] A. Dorri, S. S. Kanhere, and R. Jurdak, “Blockchain in Internet of Things : Challenges

- and Solutions.”
- [112] D. W. Kravitz and J. Cooper, “Securing User Identity and Transactions Symbiotically : IoT Meets Blockchain,” 2017.
- [113] G. Zyskind, O. Nathan, and A. Pentland, “bok%3A978-1-4899-7537-9,” *Ieee*, pp. 180–184, 2015.
- [114] J. A. Dev, “Bitcoin mining acceleration and performance quantification,” *Can. Conf. Electr. Comput. Eng.*, pp. 1–6, 2014.
- [115] F. Kaup, P. Gottschling, and D. Hausheer, “PowerPi: Measuring and modeling the power consumption of the Raspberry Pi,” *Proc. - Conf. Local Comput. Networks, LCN*, pp. 236–243, 2014.
- [116] A. Khatoon and P. Corcoran, “Privacy concerns on Android devices,” in *2017 IEEE International Conference on Consumer Electronics, ICCE 2017*, 2017.
- [117] A. Khatoon and P. Corcoran, “Android permission system and user privacy-A review of concept and approaches,” in *IEEE International Conference on Consumer Electronics - Berlin, ICCE-Berlin*, 2017, vol. 2017-Sept.
- [118] K. Christidis and M. Devetsikiotis, “Blockchains and Smart Contracts for the Internet of Things,” in *IEEE Access*, vol. 4, no. , pp. 2292-2303, 2016.,” *IEEE Access*, vol. 4, pp. 2292–2303, 2016.
- [119] M. Ruta, F. Scioscia, S. Ieva, G. Capurso, and E. Di Sciascio, “Semantic Blockchain to Improve Scalability in the Internet of Things,” 2017.
- [120] J. Kishigami, S. Fujimura, H. Watanabe, A. Nakadaira, and A. Akutsu, “The Blockchain-Based Digital Content Distribution System,” *Proc. - 2015 IEEE 5th Int. Conf. Big Data Cloud Comput. BDCloud 2015*, pp. 187–190, 2015.
- [121] S. Sicari, A. Rizzardi, L. A. Grieco, and A. Coen-Porisini, “Security, privacy and trust in Internet of things: The road ahead,” *Comput. Networks*, vol. 76, pp. 146–164, 2015.
- [122] A. Bahga and V. K. Madiseti, “Blockchain Platform for Industrial Internet of Things,” pp. 533–546, 2016.
- [123] L. C. Ankit Songara, “Blockchain : A Decentralized Technique for Securing Internet of Things,” *Int. Conf. Emerg. Trends Eng. Innov. Technol. Manag. (ICET EITM-2017)*, no. October, pp. 2–5, 2017.
- [124] M. Pustišek and A. Kos, “Approaches to Front-End IoT Application Development for the Ethereum Blockchain,” *Procedia Comput. Sci.*, vol. 129, pp. 410–419, 2018.
- [125] A. Ouaddah, A. Abou Elkalam, and A. Ait Ouahman, “FairAccess: a new Blockchain-based access control framework for the Internet of Things,” *Secur. Commun.*

- Networks*, vol. 9, no. 18, pp. 5943–5964, 2016.
- [126] J. Kreku, V. Vallivaara, K. Halunen, and J. Suomalainen, “Evaluating the efficiency of blockchains in IoT with simulations,” *IoTBDS 2017 - Proc. 2nd Int. Conf. Internet Things, Big Data Secur.*, no. April, pp. 216–223, 2017.
- [127] A. Beikverdi and J. Song, “Trend of centralization in Bitcoin’s distributed network,” *2015 IEEE/ACIS 16th Int. Conf. Softw. Eng. Artif. Intell. Netw. Parallel/Distributed Comput. SNPD 2015 - Proc.*, pp. 1–6, 2015.
- [128] G. Di Battista, V. Di Donato, M. Patrignani, M. Pizzonia, V. Roselli, and R. Tamassia, “Bitconeview: Visualization of flows in the bitcoin transaction graph,” *2015 IEEE Symp. Vis. Cyber Secur. VizSec 2015*, pp. 1–8, 2015.
- [129] Q. Xia, E. B. Sifah, A. Smahi, S. Amofa, and X. Zhang, “BBDS: Blockchain-based data sharing for electronic medical records in cloud environments,” *Inf.*, vol. 8, no. 2, 2017.
- [130] R. Dennis and G. Owen, “Rep on the block: A next generation reputation system based on the blockchain,” *2015 10th Int. Conf. Internet Technol. Secur. Trans. ICITST 2015*, pp. 131–138, 2016.
- [131] T. Bocek, B. B. Rodrigues, T. Strasser, and B. Stiller, “Blockchains everywhere - A use-case of blockchains in the pharma supply-chain,” *Proc. IM 2017 - 2017 IFIP/IEEE Int. Symp. Integr. Netw. Serv. Manag.*, pp. 772–777, 2017.
- [132] S. R. Bryatov and A. A. Borodinov, “Blockchain technology in the pharmaceutical supply chain: Researching a business model based on Hyperledger Fabric,” *CEUR Workshop Proc.*, vol. 2416, pp. 134–140, 2019.
- [133] L. A. Linn and M. B. Koo, “Blockchain For Health Data and Its Potential Use in Health IT and Health Care Related Research,” *ONC/NIST Use Blockchain Healthc. Res. Work.*, pp. 1–10, 2016.
- [134] R. Dennis and G. Owen, “Rep on the block: A next generation reputation system based on the blockchain,” *2015 10th Int. Conf. Internet Technol. Secur. Trans. ICITST 2015*, pp. 131–138, 2016.
- [135] X. Liang, J. Zhao, S. Shetty, J. Liu, and D. Li, “Integrating blockchain for data sharing and collaboration in mobile healthcare applications,” *IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. PIMRC*, vol. 2017-Octob, pp. 1–5, 2018.
- [136] P. Zhang, M. A. Walker, J. White, D. C. Schmidt, and G. Lenz, “Metrics for assessing blockchain-based healthcare decentralized apps,” *2017 IEEE 19th Int. Conf. e-Health Networking, Appl. Serv. Heal. 2017*, vol. 2017-Decem, pp. 1–4, 2017.

- [137] “US20150332283A1 - Healthcare transaction validation via blockchain proof-of-work, systems and methods - Google Patents.” [Online]. Available: <https://patents.google.com/patent/US20150332283A1/en>. [Accessed: 25-Mar-2020].
- [138] “Welcome - HSE Open Data.” [Online]. Available: <https://data.ehealthireland.ie/>. [Accessed: 24-Mar-2020].
- [139] C. Burger, A. Kuhlmann, P. Richard, and J. Weinmann, “Blockchain in the energy transition. A survey among decision-makers in the German energy industry,” *Ger. Energy Agency*, p. 41, 2016.
- [140] World Energy Council and PwC, “The Developing Role of Blockchain,” p. 22, 2017.
- [141] I. Renewable Energy Agency, “Aggregators: Innovation landscape brief,” 2019.
- [142] and E. K. Saraju P. Mohanty, Uma Choppali, “Everything you wanted to know about smart cities,” *IEEE Consum. Electron. Mag. Electron.*, vol. 10, pp. 409–410, 2016.
- [143] “First European energy trade over the blockchain.” [Online]. Available: <https://enerchain.ponton.de/index.php/11-first-european-energy-trade-over-the-blockchain>. [Accessed: 25-Mar-2020].
- [144] T. Sousa, T. Soares, P. Pinson, F. Moret, T. Baroche, and E. Sorin, “Peer-to-peer and community-based markets: A comprehensive review,” *Renew. Sustain. Energy Rev.*, vol. 104, no. June 2018, pp. 367–378, 2019.
- [145] P. Verma, B. O’Regan, B. Hayes, S. Thakur, and J. G. Breslin, “EnerPort: Irish Blockchain project for peer- to-peer energy trading,” *Energy Informatics*, vol. 1, no. 1, 2018.
- [146] “Market Report Series energy efficiency 2018 Market Report Series energy efficiency 2018.”
- [147] “How Blockchain Improves the Energy Management Systems Sector | INN.” [Online]. Available: <https://investingnews.com/innspired/using-blockchain-to-improve-the-energy-management-systems-sector/>. [Accessed: 25-Mar-2020].
- [148] “How blockchain can make the world more energy efficient | World Economic Forum.” [Online]. Available: <https://www.weforum.org/agenda/2017/09/blockchain-energy-efficiency-finance>. [Accessed: 25-Mar-2020].
- [149] “Blockchain to increase efficiency and transparency in the energy sector | Commodity Inside.” [Online]. Available: <https://commodityinside.com/blockchain-can-increase-efficiency-transparency-energy-sector/>. [Accessed: 25-Mar-2020].
- [150] “Energy efficiency directive | Energy.” [Online]. Available: <https://ec.europa.eu/energy/topics/energy-efficiency/targets-directive-and->

- rules/energy-efficiency-directive_en. [Accessed: 25-Mar-2020].
- [151] “The Italian White Certificates Scheme - D.Rotiroti, GSE.” [Online]. Available: <https://www.slideshare.net/gserinnovabili/the-italian-white-certificates-scheme-drotiroti-gse>. [Accessed: 25-Mar-2020].
- [152] F. Testa, “Italian Energy Efficiency White Certificate Scheme ” “Thanks to the Energy Efficiency Certificates (TEE), an innovative and pioneering system, we have achieved from 2005 to 2013 annual energy savings of 5Mtoe/year and incentivised more than €22 billion investments in energy efficiency.”
- [153] D. Di Santo, V. Venturini, D. Forni, and E. Biele, “The white certificate scheme : the Italian experience and proposals for improvement,” pp. 249–260, 2011.
- [154] “Best Blockchain Cryptocurrency Trading Platform in Singapore.” [Online]. Available: <https://newconomy.media/news/singapore-builds-solar-energy-trading-platform-on-blockchain>. [Accessed: 25-Mar-2020].
- [155] “Energy suppliers | Ofgem.” [Online]. Available: <https://www.ofgem.gov.uk/environmental-programmes/eco/energy-suppliers>. [Accessed: 25-Mar-2020].
- [156] P. R. S. A-e, “Energy Company Obligation (ECO3): Measures table,” no. January, p. 2020, 2020.
- [157] “About the ECO scheme | Ofgem.” [Online]. Available: <https://www.ofgem.gov.uk/environmental-programmes/eco/about-eco-scheme>. [Accessed: 25-Mar-2020].
- [158] A. Outchakoucht and J. P. Leroy, “Dynamic Access Control Policy based on Blockchain and Machine Learning for the Internet of Things,” vol. 8, no. 7, pp. 417–424, 2017.
- [159] “CONNECTING MULTIPLE DEVICES WITH BLOCKCHAIN,” 2017.