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Engineering valuation of blockchain technology in the context of petroleum supply chain: A real options approach

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by

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DEDICATION

I would like to dedicate this thesis to my fiancé, Melinda, without whose support and encouragement I would not have been able to complete this work. I would also like to thank my parents, Farideh and Mehrdad, and my sister, Bita whom I have felt their presence by my side constantly even though they have been far away from me.

TABLE OF CONTENTS

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ABSTRACT

In this paper, we mathematically model and analyze occurrence of trade disputes in the context of a petroleum supply chain network which includes a seller, a buyer and an arbitrator. We study how switching from conventional trading system to a blockchain-based system could help decrease the number of disputes while maintaining the profitability of trading. Specifically, we determine what is the optimal timing to switch to blockchain technology through arbitrator's perspective under petroleum price uncertainty. The way blockchain technology aids trade irrefutability is to provide a secure and immutable distributed ledger which ensures each trade is recorded and timestamped with no participant being able to alter the transactions history. Consequently, participants trading in a safe network, can trust the system and conduct transactions more securely. Currently, around nine percent of crude oil transactions are disputed, which equates to around USD 150 billion each year. In a petroleum trading network, the disputes filed by either seller or buyer are consequences of fraud and/or error. Studies have shown, integrating Blockchain technology into trading network significantly reduces the probability of transactions disputes and trades recorded on a blockchain distributed ledger has higher finality rates.

Although there has been much interest in blockchain technology applicable to petroleum industry supply chain, there has been little analytical investigation of irrefutability, one of the critical attributes of the blockchain technology. Irrefutability corresponds to a network characteristic which prevents any participant to question the integrity of transactions recorded on ledger and any future disputes. Throughout this work, we aim to show how irrefutability can be valued, in the context of petroleum industry supply chain, from a perspective of stochastic optimal control. We will show how petroleum strike prices for switching to blockchain technology can be found via real options approach through modeling fraud uncertainty. In other words, we are going

to demonstrate under what conditions it is economically feasible from arbitrator's perspective to implement a blockchain technology by modeling number of disputes as a function of system's reliability. Even though at a first glance arbitrator may have no reason to favor blockchain over traditional system because of decrease in dispute resolution payments due to increased trade finality, on the other hand we conclude a profit for arbitrator which is sourced in higher transaction verification fees as number of transactions increases due to improved reliability of the system.

CHAPTER 1. GENERAL INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Oil and gas are sold in large volumes and as such entail significant value, not unlike the size and scale of transaction between banks (Tordo, et al., 2011). The frequency of transactions is also high; for example, according to (Siddiqui, et al., 2013) a 300,000 barrel per day oil refinery will need to source a large crude carrier every week to maintain adequate volumes and cargos can cost as much as USD 100 million (two million barrels at USD 50 per barrel). Oil companies also need to be aware of where the crude oil is sourced. Some exporting nations such as IRAN are subject to sanctions to prevent trade for this commodity. These sanctions often impel such nations to make transactions through private entities which frequently result in fraud. Non-transparent transactions are often exposed to lack of intractability (Torbat, 2005).

In petroleum industry, companies often incur significant costs to ensure that every participant in a trading network behaves in accordance to the pre-defined contract. Most overhead costs belong to reduction in misunderstandings, disputes and fraud. Writing and tracking all the contracts, compliance forms, reporting and monitoring, audit trails are examples of efforts to ensure the system integrity in presence of a third party as an arbitrator. According to (Ghandi & Lin, 2014) by recording the information of the participants, locations, commodity type and real-time measured value on the blockchain, dispute resolution can be done in a consolidate manner instead of reconciling disparate databases. Disputes are direct outcomes of violation of some clauses of an agreements between parties involved in a trade if the accused party fails to recognize the fault (Aniello, et al., 2016). Utilizing a third party as the dispute resolution method is associated with fees involved for each transaction and trust issues. In the context of petroleum industry, oil and gas companies have had issues with supply and demand due to price volatility in recent years which ultimately resulted in reduction in exploration, production and supply efforts (Pirog, 2012). Due to these factors, oil and gas companies have been forced to re-design their supply chain management and how they incorporate technology in their transaction processing system (Papageorgiou. 2009)

Petroleum trading system is a complex network where higher degree of trust is essential due to the sensitivity of transactions. Large volume transactions and high value shipments require the trading system to be secure. Trust is crucial in petroleum supply chain and any effort to default on agreements will result in the transaction to be terminated. This delicacy leads any trading system to include a third party to oversee the transactions and intervene on every occasion that system is alarmed. The third party could be assigned as a government or private entity. According to Melese (2010) "The objective of firms doing business with the government is to maximize profits. The intent of a protest system is to provide a decentralized governance mechanism to oversee the integrity, equity, and efficiency of the procurement process. Although, government's intent is for protesters to act as a type of third-party oversight of government buyers (procurement officials, etc.), the reality is that because protesters themselves are in competition as sellers, they have conflicting objectives."

In recent years, Blockchain technology has been introduced as a decentralized governance mechanism with features such as immutability, irrefutability and integrity (Hyvärinen, et al., 2017) However, conditions under which blockchain technology would be feasible and possess value to be implemented to reduce the number of protests in bidding processes, have not been studied.

According to Melese (2010), there is only one way a bidder (seller) can win a protest: the protest must have merit and be sustained given that it has merit. P_S Is the probability that a protest is sustained given it has merit and P_M Is the probability that a process has merit. As describe in

Melese (2010) P_M Is positively correlated with errors, E, and fraud, F. So, any efforts to reduce fraud and/or errors will reduce the probability a protest has merit and, reduce the expected benefits of a protest. Likewise, P_S Is positively correlated with fraud and error whereas it is negatively correlated with the price, P, offered by the bidder.

Blockchain technology primarily targets industries and government processes where there is an abundancy of human and traditional databases errors and fraudulent attempts to alter the records (Mohammed, et al., 2012) and (Hilborn, 2013).Hence, this technology is an optimal candidate to prevent such behaviors, which will result in reducing the expected benefit of protests and increasing the associated cost with protests. To achieve this goal, blockchain technology aims at ensuring the transparency and accountability of the evaluation and selection process and substituting an immutable record of transactions where probability of fraud is insignificant (Angraal, et al., 2017).

In a petroleum trading network, the participants will protest about 10% of trades which results in trade disputes (Wang, et al., 2011). The disputes are direct outcome of fraud and/or error. Any effort to reduce the probability of fraud and/or error will result in increasing trade finality, lowering the number of protests.

In the traditional settings and absence of blockchain technology, employ a trusted-third party (TTP) which is responsible of checking if every participant complies with pre-determined agreements. Disputes are usually resolved by this entity as well. In these setting, third party is considered as the single point of failure and needs to be trusted at all stages over the trading period. If this entity behaves maliciously or colludes with other parties, there is no chance of proving the wrong.

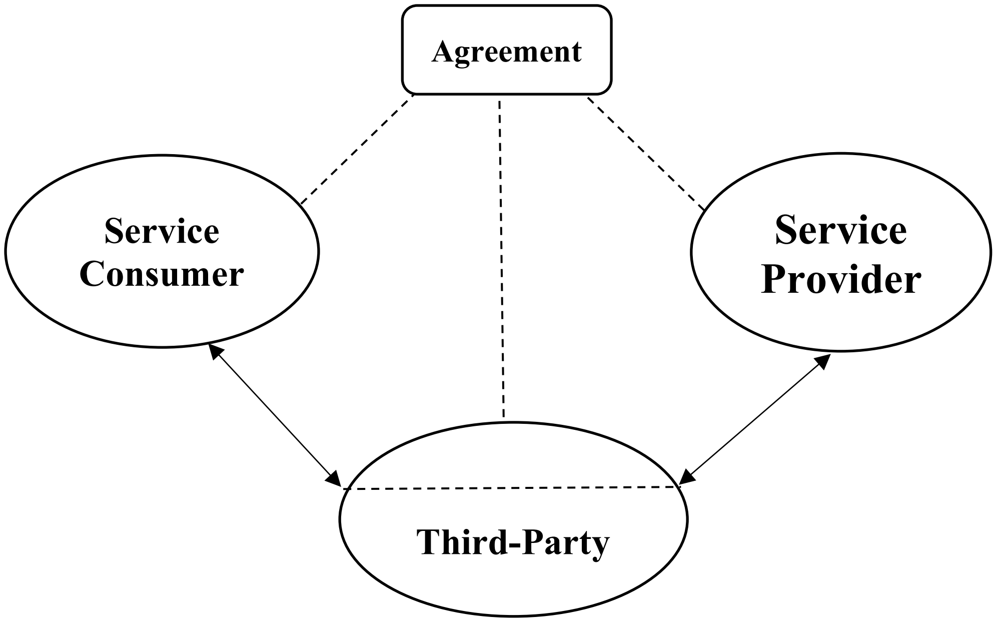

Figure 1 – Traditional Setting

Oil and gas contracting can be complex, with lengthy contracts and agreements (Capper, 2010). Smart contracts are self-executing contracts based on agreed criteria and written in code, removing the ambiguity of terms and reducing the requirement for lawyers to draft and interpret. When the criteria of the contract are fulfilled, ownership or payment, for example, will be

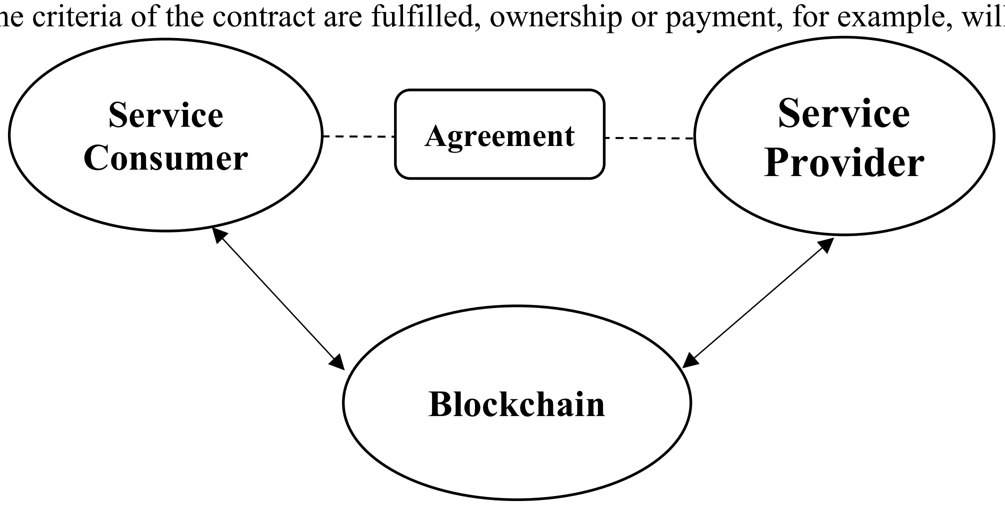

Figure 2 – Blockchain-based Setting

Automatically transferred (Sklaroff, 2017).

Trading commodities such as petroleum based on a blockchain technology results in technology, inventories, contracts, payments and other data being shared directly between parties with encrypted connections (Rahmadika, et al., 2018). Commodity exchanges on blockchain, for example, can support oil and gas trading directly between parties anywhere in the world, while removing the role banks, brokerage firms or other intermediaries have traditionally played. The oil and gas industry present a particularly compelling opportunity to leverage blockchain technologies due to the high transactional values (and therefore risks) and economic pressures to reduce costs (Idachaba, 2012).

The reason for the interest in Blockchain is its central attributes that provide security, anonymity and data integrity without any third-party organization in control of the transactions. Blockchains allow us to have a distributed peer-to-peer network where non-trusting members can interact with each other without a trusted intermediary, in a verifiable manner. Blockchain technology is a distributed ledger to share information equally among all the participants. The information shared included is but not limited to financial transaction data, legal contracts, deeds of ownership and identity documentation. The recorded information is stored on a ledger that is distributed across every node (i.e. Participant's computer) in a network. The blockchain technology provides the data encryption that many entities seek to ensure that the data is not prone to any malicious attacks or breach. Historical transactions in the Blockchain may not be deleted or altered without invalidating the chain of hashes since each block is "chained" back to the previous block by containing a hash representation of the previous block.

Furthermore, blockchain technology creates a clear audit trail of time-stamped data as documented blocks that could be accessed by authorities for taxation and audit purposes. Due to the immutability nature of distributed ledger, once the information is published, verified and broadcasted, it will become tamper proof and any future attempts to alter the history of the ledger would result in total change in the chain which is computationally exhaustive and impractical. Blockchain could provide a fully transparent and secure record of the entire supply chain. Oil and gas contracting can be complex, with lengthy contracts and agreements. Smart contracts are self-executing contracts based on agreed criteria and written in code, removing the ambiguity of terms and reducing the requirement for lawyers to draft and interpret. When the criteria of the contract are fulfilled, ownership or payment, for example, will be automatically transferred.

To mention several Blockchain based systems major characteristics, the following are the most important ones:

- **Data immutability** which depends on the consensus mechanism when the transaction is taken to be committed/confirmed
- **Traceability**
- **Irrefutability** (of transactions): provided by the immutable chain of cryptographically-signed historical transactions

Other major characteristics include but not limited to Integrity, Transparency, and equal rights. As previously discussed blockchain-based trading networks ensure integral traceability, fight fraud and minimize the system errors as it provides traceability of rice by recording all the events happening in the supply chain. As any other revolutionary technology, Blockchain has major technical drawbacks. In this section we mention a number of limitations that need further study and continuous improvement:

- **Privacy**: no privileged user, every participant can join the network to access all the information on Blockchain and validate new transactions

- **Scalability**: capability of the system to handle a growing amount of data (transactions):
    a. The size of the data on Blockchain
    b. The transaction processing rate
    c. The latency of data transmission

Blockchain technology is categorized into two main types: Permissioned and Permission-less. Permission-less technology such as cryptocurrencies (Bitcoin, Ethereum, etc.) Incorporates the benefit of the doubt among the participants. It is a trust-less system where anyone has the permission to enter, write and read on the network. On the other hand, permissioned blockchain such as IBM Hyperledger sets limited access for players in the network based on their participation purpose. For example, a seller might have full permission on read and write to the ledger but not given access to verify the transactions, which is instead done by a third party (arbitrator). Due to the high transaction value and security issues, the petroleum trading network studied in this work belongs to permissioned blockchain with limited number of participants.

First generation Blockchains like Bitcoin have limited capability to support programmable transactions while second generation blockchains such as Ethereum provide a general-purpose programmable infrastructure with a public ledger that records the computational results. In addition to programmable transactions, second generation blockchain support smart contracts which are programs

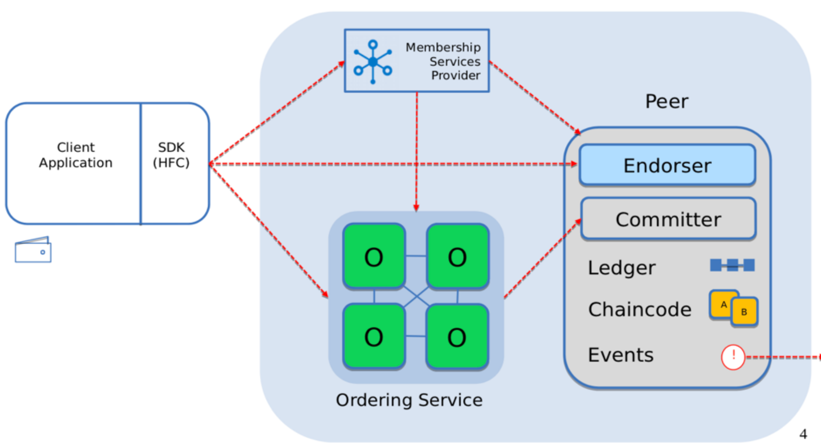

Figure 3 - Overall workflow of a Distributed Ledger

source: IBM Hyperledger Fabric

deployed and run on a distributed ledger network. Smart contracts can express triggers, conditions and business logic embedded in transactions. Now let us review transaction lifecycle in a blockchain technology. We will discuss how a transaction is published by one of the participants, verified by members and broadcasted through the network by all members. Ultimately, being recorded on the chain and included in the respective blocks.

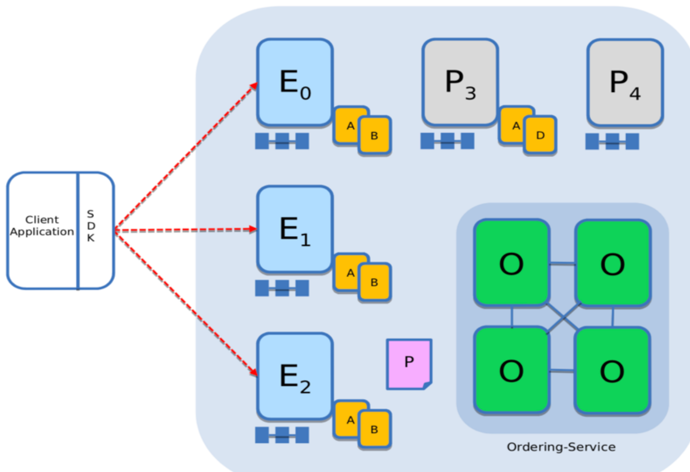

Figure 4 - Submission of buy request

source: IBM Hyperledger Fabric

Buyer submits a transaction proposal (10 barrels of oil @ $60/barrel) for Smart Contract. It must target the required peers {E_0, E_1, E_2} and not others {P_3, P_4}. Through endorsement policy, which describes the conditions by which a transaction can be endorsed. A transaction can only be considered valid if it has been endorsed according to its policy. Each chain-code is associated with an Endorsement Policy. In this case, it is stated that E_0, E_1 and E_2 must sign while P_3, P_4 are not part of the policy. Later on, E_0, E_1 and E_2 will each execute the proposed transaction. None of these executions will update the ledger. Each execution will capture the set of Read and Written data, called RW sets, which will now flow in the fabric. Transactions can be signed & encrypted. The

RW sets are signed by each endorser, and also includes each record version number. (This information will be checked much later in the consensus process also known as **verification.**)

Ordering service collects transactions into proposed blocks for distribution to committing peers. Peers can deliver to other peers in a hierarchy (not shown)

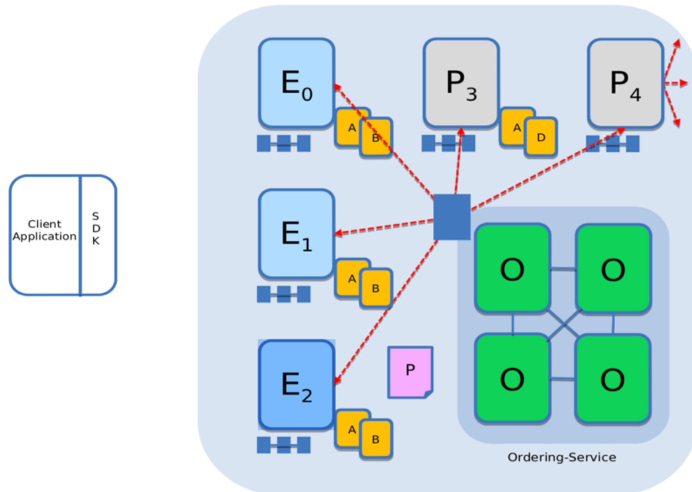

Figure 5 - Validation process initiation

Source: IBM Hyperledger Fabric

All participants verify transactions

Every committing peer verifies against the endorsement policy. Verified transactions are applied to world state and retained on the ledger. Not verified transactions are also retained on the ledger but do not update world state. After the buyer proposal has been posted on a block, the same workflow is applied to seller proposal. All the steps are identical in validation and verification.

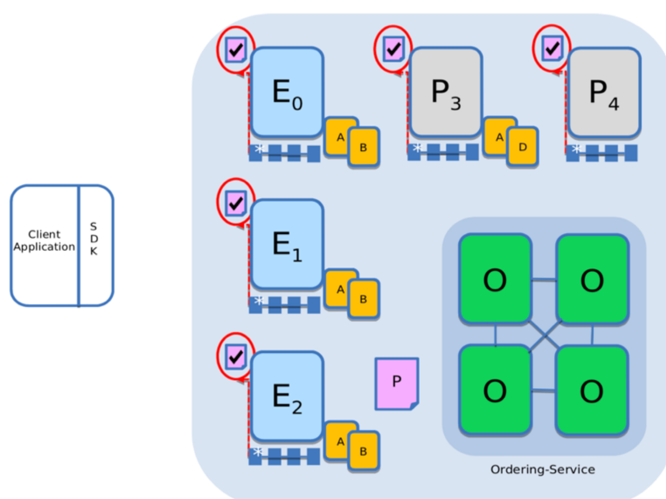

Figure 6 - Each verifier participates in verification process

Source: IBM Hyperledger Fabric

1.2 Organization of The Thesis

The organization of this thesis is as follows. In section 1.3 a comprehensive literature review on two pertaining topics is conducted. First blockchain technology as a disruptive innovation is studied through scholars' work. Next, Real Options theory through academic and industrial perspective is review. Later, on chapter 2, we will study the Seller, as one of the main decision makers in switching from traditional record keeping to the novel blockchain technology. A formal mathematical model along sensitivity analysis is presented. In chapter 3, we study the Buyer who shares the mirror utility function as the seller (buyer's cost contributes to the seller's revenue.) Chapter 4 is dedicated to the Arbitrator as the system operator and how to maximize their utilities while maintaining the system integrity without any cost included in our model. Chapter 5 presents an extensive numerical analysis to validate the analytical results. On chapter 6, we study the arbitrator with operational cost included. Finally, we conclude by discussion and conclusion sections, chapter 7 and chapter 8 on what are the implications of implementing blockchain technology between participants in a petroleum trading network and who benefits the most from this switch decision.

1.3 LITERATURE REVIEW

1.3.1 Literature on Blockchain

Blockchain technology is a distributed ledger to share information equally among all the participants (Wattenhofer, 2017). The information shared included is but not limited to financial transaction data, legal contracts, deeds of ownership and identity documentation. The recorded information is stored on a ledger that is distributed across every node (i.e. Participant's computer) in a network (Zhang, et al., 2018). The blockchain technology provides the data encryption that many entities seek to ensure that the data is not prone to any malicious attacks or breach (Boutelle, et al., 2017). Historical transactions in the Blockchain may not be deleted or altered without invalidating the chain of hashes since each block is "chained" back to the previous block by containing a hash representation of the previous block (Tan, 2017).

The reason for the interest in Blockchain is its central attributes that provide security, anonymity and data integrity without any third-party organization in control of the transactions (johansson & Nilsson, 2018). Blockchains allow us to have a distributed peer-to-peer network where non-trusting members can interact with each other without a trusted intermediary, in a verifiable manner (Sharma, et al., 2017) and (Neudecker & Hartenstein, 2018).

Furthermore, blockchain technology creates a clear audit trail of time-stamped data as documented blocks that could be accessed by authorities for taxation and audit purposes (Sutton & Samavi, 2017). Due to the immutability nature of distributed ledger, once the information is published, verified and broadcasted, it will become tamper proof and any future attempts to alter the history of the ledger would result in total change in the chain which is computationally exhaustive and impractical (Liao, 2017).

Finally, (Cong & He, 2019) studied the impact of blockchain and smart contracts on decentralized consensus in trades. They assessed how decentralization could impact consensus quality and how blockchain technology could affect competition. They argue that information distribution through smart contracts could encourage information symmetry by providing enhanced entry and competition. However, collusion and consequently, trade disputes are resulted of asymmetric information distribution. Later on, they introduce the concept of system operator as an arbitrator who may behave malignantly in times.

1.3.2 Literature on Real Options

Traditionally, the net present value (NPV) and discounted cash flow (DCF) are heavily used in evaluating projects investments under deterministic conditions as suggested by (El-Temtamy & Gendy, 2014) but investments projects have evolved and now they are faced with multiple uncertainties and risks and these traditional methods are insufficient to deal with uncertain conditions (Chen, et al., 2007). Irreversibility of projects cannot be characterized by traditional approaches since in these traditional techniques assumption of irreversibility is not present (Lambert, et al., 2015). Although, in some projects these assumptions are valid, in most of real-world projects we usually face an irreversible decision. In fact, (Habib & Hasan, 2017) pointed out the ability to delay an investment until more information is gathered and uncertainties could be reduced, provides the decision maker the opportunity to redesign the decision structure based on the information and not take immature action. Unlike traditional approaches, real option approach (ROA) gives the flexibility to evaluate different scenarios under high level of uncertainty (Damodaran, 2005).

The term "real options" was first used by a theoretical study of debt policies in (Myers, 1977). Real option analysis (ROA), refers to viewing the option-based of projects or financial assets and it deals with practically implementing option valuation tools and techniques. Option valuation was originally developed for the pricing of the financial options. The real options evaluation is classified into two categories: real options "on projects" and "in projects". The former is a means to exploit the flexibility inherent in sequential investments as proposed by Adner and Levinthal (2004) whereas the latter refer to the available managerial flexibility from "an industrial engineering/production management perspective" (Bengtsson, 2001).

Real Option Approach is one of the most well-known theories for valuation of projects under uncertainty. Real Options can be viewed "as the right, but the obligation, to take an action (e.g., differing, expanding, contracting or abandoning) at a predetermined cost, called exercise price, for a predetermined period of time – the life of the option" (Copeland and Antikarov, 2003). There are similarities to Financial call options which an option is defined "An option is a security giving the right to buy or sell an asset, subject to certain conditions, within a specific period of time" according to Black and Scholes (1973). There are two types of options: American or European. If the option is exercised only on a specified future date, it is called "European option" whereas if the option can be exercised an any time up to the expiration date it is called "American option". So, an investment opportunity can be viewed as a call option. When a decision maker faces an opportunity to invest, they have the option to act now in return for an asset (e.g. Project) or postpone the action to future until more information is gathered. Most common of real options are the defer, time-to-build, alter operating scale, abandon, switch and growth options according to Trigeorgis (1996).

Valuing of real options according to Copeland an Antikarov (2003) depends on six variables: the value of the underlying asset, the exercise price, the time to expiration of the option, the uncertainty about the present value, the risk-free rate of interest over the life of the option, the dividends that may be paid by the underlying asset.

According to Kulatilaka and Amram (1999), there are three groups which solution methods can be organized: the partial differential equation approach, the binomial lattice approach and the simulation approach. The PDE approach represents the value of an option and it's dynamic by a partial differential equation and its boundary conditions which can be solved by analytical solutions, analytical approximations and numerical solutions. Cortazar et al. (1998) presented a model that determine the optimal timing of investment in environmental technologies. They assumed that the price follows a geometric Brownian motion and then used Ito calculus to compute the total differential of a function stochastic variable and the result was a PDE for the value of the real or financial option. In an energy system setting, analytical solutions were first applied to the financing of large-scale energy projects and later petroleum engineering projects which were considered to be large scale engineering projects utilized this method. PDE were widely used to assess the flexibility of power generation and thermal power plants. Most recently, extension to pdes were also used to quantify the value of renewable research and development investment, or postponing investments in renewable power plants.

The second method is binomial lattice which is based on optimizing the decision that influence future payoffs. By using this method, intermediate values and decisions become visible and valuable information about the option and how to deal with complex decision structures are provided. Deng and Xia (2006) proposed a stochastic dynamic programming valuation model for pricing electricity tolling contracts.

Third method is Monte Carlo simulation, which is frequently used in literature. In this method the optimal investment strategy is calculated at the end of each path and the payoff is calculated. The advantage of this method is that it has the capability to handle many real-world situations. In Monte Carlo simulation method, different scenarios are randomly generated, and a profit distribution is computed (Lazo, et al., 2007) and (Cvetanoska & Stojanovski, 2012).

In the following, we mention some of the application areas of applying ROA to a broad categories of engineering valuation projects. (Xi-bin Xiao, 2017) studied the problem of airport capacity expansion and by applying real options theory through analytical approach. They showed whether a real option is required for an airport or not based on the demand uncertainty and reserve costs. (Md. Aminul Haque, 2016) showed that by applying a new real options valuation method, project values are overestimated if only the commodity price uncertainty is considered instead of the joint effect of commodity price and the exchange rate uncertainty.

(Wilko Rohlfs, 2011) developed a multi-factor real options framework by considering the price of electricity, the price of CO2, the cost of CO2 capture, the transporting and storage and CCC retrofit investment costs as stochastic variables. They showed that the retrofit design option of the power plant seems unattractive by numerical simulation and investments in conventional coal-fired power plants with later capture and storage investments at higher costs than in the case of a capture-ready pre-installation are found out to be more economical feasible.

(Ajak Duany Ajak, 2015) proposed the suitability of using real option approach at the mine operational level that the decisions are made regularly rather than strategies that are reviewed after years. Their result showed how real option can be used in designing multiple pits in multi-zone ore deposits to create a switching option between pits and fluctuating commodity prices. The results presented the fact that the project's value increased considerably when flexibility was included in the mine design. Their analysis is based on the binomial decision tree.

(Kuangyuan Zhang, 2016) presented a theoretical two-stage economic model to derive the value of metal stockpiling for future processing once the mine is depleted and how it effects the mining rate. The optimal condition shows that the stockpiling option can significantly boost a mine's profit.

(William R. Binder, 2017) studied the impact of incorporating flexibility in the design of Hybrid Energy Systems by considering the option to upgrade or reconfigure the HES configurations at some point in the future in response to economic and technological changes that are initially unknown and uncertain. (Lixin tian, 2016) set up nuclear energy investment evaluation model based on Monte Carlo simulation and real option theory to evaluate the value of a nuclear power plant under abandon option (Charles Cheah, 2005) used a discrete-time model to evaluate several options in power plants in India to identify and capture flexibilities and concluded that ROA can be identified as a superior approach compared to Net Present Value method.

(joao Marques. Maria Cunha, 2017) proposed a multi-objective RO framework that incorporates the flexible design which is capable of replacing the traditional design of Water Distribution Networks, that accounts for uncertainty by taking a broader view of possible future options. They used a simulated annealing algorithm to identify Pareto-optimal solutions.

(Kang, 2016) presented a ROA that uses a binomial lattice model to determine optimal design and price decisions for hybrid electric vehicles that maximize expanded net present value of profit under gas price uncertainty over time.

(Jose Guedes, 2016) proposed a clinical approach of an offshore oil development project which assumes exploration options, appraisal options, scaling options and abandonment options and considers reserve size and price of oil uncertainties and concluded that the available options add to the value of the project with abandonment being the most valuable option.

CHAPTER 2. SELLER AS THE DECISION MAKER

2.1 Methodology

There are three participants in the system, trading petroleum as the main commodity initially in a traditional setting and later, at an optimal time, T^*, seller as the decision maker, decides to implement, design and switch to a unique blockchain framework due to economic circumstances. As a result, all other participant, in order to be able to trade with the (super) seller, will follow the decision and become members of the blockchain system. From point T^*, all trades are done based on the unique blockchain framework. For simplicity, the upstream process of petroleum exploration, production and transportation is excluded in this model and only the downstream trade is studied. In addition, it is assumed that the buyer and other parties will follow the seller in their decision to integrate blockchain technology to trading network. For the sake of simplicity, we assume that there is only one major provider (seller) and one major consumer (buyer) and one arbitrator who is in charge of resolving the disputes. What distinguishes the traditional setting from blockchain framework is the availability of an immutable record of transactions. Every transaction is timestamped, and the underlying source is clearly expressed.

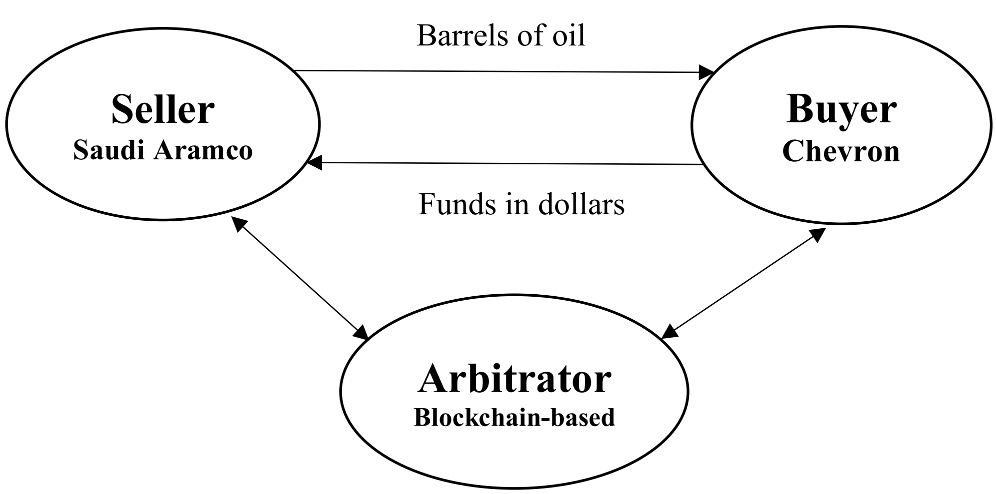

Figure 7 - Petroleum Trade Network in a Blockchain framework

What reduces the number of trade disputes is reduction in fraud and/or error. In a framework where maximum degree of accountability is reached, and all participants are vigilant and have access to the record of data, there is minimal chance of error and/or fraud, hence lowest probability of trade disputes.

In our framework, the fraud and/or error (whether from seller or buyer) happen at the rate of λ which results in the trade disputes. As previously discussed, trade disputes arise when the receiving party fails to acknowledge the violation of the agreement. In every dispute, there are fees associated with the filing the disputes. These fees correspond to our C_{P_t} In our model. Commodity price, petroleum price, follows a geometric Brownian Motion. The production cost is assumed to be constant over period of time and costs associated with filing the protest are functions of oil price. As oil price has positive growth rate, at some point in time, T^*, the seller (oil producer) decides to switch to blockchain technology with the hope of reduction in fraud and/or error which results in reducing the protest probability. Therefore, using blockchain will increase the settlement probability (which results in trade finality) by reducing fraud and/or error.

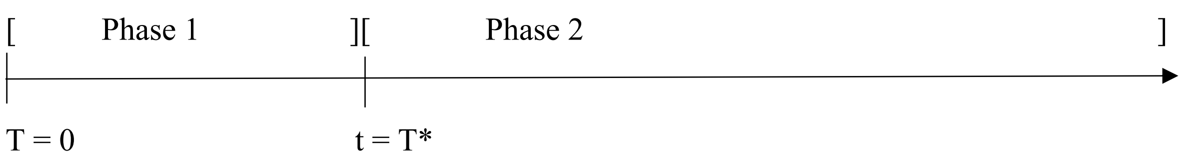

Figure 8 - The timeline before and after blockchain technology

As discussed earlier, the petroleum traded price is characterized by a geometric Brownian Motion with positive drift parameter (growth rate) α and volatility σ:

$$dP_t = \alpha P_t dt + \sigma P_t dz \tag{1}$$

Where P_t Is the petroleum price per unit barrel ($/barrel) at a time point t. α is the instantaneous growth rate of the petroleum price per unit (% per year; > 0) in, while σ is the instantaneous volatility of the petroleum per unit (% per square root of year). Finally, dt is the increment of time while dz is the increment of a standard Wiener process $z(t)$. That is, $dz = \varepsilon_t \sqrt{dt}$ Where $\varepsilon_t \sim N(0, 1)$.

Furthermore, we assume that for our trading network in question, the protest costs have the following relationship with oil price:

$$C_{pt} = \lambda \beta P_t \quad (2)$$

Where C_{p_t}The cost associated with the bid is protests which is proportional to petroleum price ($\frac{\$}{barrel*protest}$), λ is the protest rate (#protest/unit time), and β is the correlation coefficient $(unit\ time/protest^2)$. Moreover, it can be verified that the costs associated with protest follow a gbm.

The rest of the notations are given as follows:

I_1: Initial entry fee and installations costs to enter a blockchain trading

C_{prod}: Fixed production costs ($/barrels) which is assumed to be constant during the project

K: Number of barrels of oil traded (barrels)

ρ: the annual discount rate for money. Here we use the Weighted Average Cost of Capital (WACC)

2.2 Model Formulation

The utility function of seller is described as follows. The seller collects revenue from selling petroleum to the buyer at price P and bears production cost and protest cost. At an optimal time, due to the increasing nature of petroleum price, he/she decides to implement blockchain technology in order to reduce the cost associated with the protest. This decision results in reducing the number of protests which is a direct outcome of reduction in probability of fraud and/or error in trades. The seller decides to switch to blockchain technology by spending an initial investment cost I. Therfore the expected value function for production capacity of K:

$$V(P_t) = \text{Max}\, E\left[\int_0^{T^*} e^{-\rho t} K\left[P_t - C_{prod} - C_{p_t}\right]dt + \int_{T^*}^{\infty} e^{-\rho t} K\left[P_t - C_{prod} - C_{p_t}\right]dt - e^{-\rho T^*} I_1\right] \quad (3)$$

As discussed earlier, petroleum price is characterized by a geometric Brownian Motion (2). $V_2(P)$ can be characterized as the expected value gained if the company decides to adopt and invest in blockchain technology. After implementing the blockchain technology, the value of the trading project V_2 Obeys Bellman optimality principal:

$$\rho V_2(P)dt = \left[K\left(P - C_{prod} - C_{pt}\right)\right]dt + d\text{E}\left[V_2(P + dP)e^{-\rho t}\right] \quad (4)$$

Equation (4) states that the total return for this project through seller's perspective consists of the net revenue currently generated from oil production and selling plus the future expected appreciation in the value of the project.

After applying Ito's Lemma on dV_2, the Bellman optimality principle equation (4) yields a second order differential equation as follows.

$$\frac{1}{2}\sigma^2 P^2 V_2'' + \mu P V_2' - \rho V_2 + K\left(P - C_{prod} - C_{p_t}\right) = 0 \quad (5)$$

To solve the differential equation (5) we first note that a particular solution to equation (5) can be verified to be:

$$V_2(P) = \frac{KP}{\rho - \alpha} - \frac{KC_{prod}}{\rho} - \frac{KC_P}{\rho - \alpha} \tag{6}$$

Where a technical condition of $\rho - \alpha > 0$ is assumed as in Dixit and Pindyck (1994). Next, a homogeneous solution to Equation (5) can be verified to be:

$$V_2(P) = A_1 P^{\Pi_1} + A_2 P^{\pi_2} \tag{7}$$

Where $\pi_1, \pi_2 = \pm\left[\left(\frac{\sigma^2}{2} - \alpha\right) + \left(\left(\frac{\sigma^2}{2} - \alpha\right)^2 + 2\sigma^2\rho\right)^{0.5}\right]/\sigma^2$ While a technical condition of $\frac{\sigma^2}{2} - \alpha > 0$ is assumed in Dixit and Pindyck (1994) and the fundamental quadratic equation is as follows,

$$\frac{1}{2}\sigma^2\pi^2 + \left(\alpha - \frac{1}{2}\sigma^2\right)\pi - \rho = 0 \tag{9}$$

Which is an equation of π. Hence, general solution to the differential equation:

$$V_2(P) = A_1 P^{\Pi_1} + A_2 P^{\pi_2} + \frac{KP}{\rho - \alpha} - \frac{KC_{prod}}{\rho} - \frac{KC_P}{\rho - \alpha} \tag{10}$$

In the context of technology competition and innovation through real options theory, (Grenadier and Weiss, 1999) defined the boundary conditions for optimal technology upgrade at the optimal point as the expected payoff of the upgrade option at the moment the new technological innovation is implemented. This approach requires the understanding of the distribution of the payoff which may not be known a priori. They assumed that standard normal density and cumulative distribution function are necessary to utilize the boundary conditions.

Also, to best of the authors knowledge there has not been any scientific approach in correctly estimating the expected technological upgrading and improvement when the standard and prevailing technology becomes obsolete.

In another work, (Kauffman and Li, 2005) related the value of the project to value of the investment opportunity at the time of technology upgrade and derived the boundary conditions based on the relationship between the investment opportunity value and the project value. In our framework, we assume that once the firm adopts the new blockchain technology, it will continue using the technology forever, hence there is no future option values. The solution to the partial differential equation is as follows but since there is no future option the power terms in the value function are equal to zero.

According to Dixit and Pendyck (1994), if the price of oil approaches zero, the value of the trading project must approach zero, in other words, $V(0) = 0.$ Zero is an absorbing barrier for the geometric Brownian motion. However since $\pi_2 < 0$, the power of P goes to infinity as P goes to zero. To prevent the diverging, we set A_2 As zero. $A_2 = 0$

The other term, $A_1 P^{\Pi_1}$ Represents a component of V to reflect the speculative bubble as $\rightarrow \infty$. According to(Dixit and Pyndeck ,1994) after migrating to blockchain, the firm might make the decision to revalue the project above its fundamentals in the future if they expected to be able to gain a sufficient capital gain either by upgrading or abandoning the trading or other means. But that is not the case in our framework. We assumed as the firm makes the decision to switch to blockchain technology, it remains the principal trading framework through the seller perspective, hence there is no expected value of the trading above its fundamentals in the future, hence $B_1 = 0$

This simplifies our solution to the general solution as below:

$$V_2(P) = \frac{KP}{\rho - \alpha} - \frac{KC_{prod}}{\rho} - \frac{KC_P}{\rho - \alpha} \tag{11}$$

Now let us move on to the phase where the trade is being conducted in a traditional setting, without blockchain technology. Similar to phase 2, the petroleum price follows the same gbm as blockchain implementation does not change the nature of the commodity being traded. Also, the value of the trading network through seller's perspective obeys Bellman optimality principal:

$$\rho V_1(P)dt = \left[K\left(P - C_{prod} - C_{p_t}\right)\right]dt + d\mathrm{E}[V_1(P + dP)e^{-\rho t}] \tag{12}$$

Similarly, Equation (12) states that the total return for this project consists of the net revenue currently generated from the petroleum production and selling plus the expected future appreciation in the value of the project. We note that the main difference between equation (4) relative to equation (12) is the relationship shown in the following:

$$\begin{gathered} \lambda_2 = b\lambda_1 \\ b < 1 \end{gathered} \tag{13}$$

That is after implementation of blockchain technology at time point T^*, the protest rate decreases by a factor of *b*. This results in having larger protest cost before blockchain in comparison of after implementing blockchain technology. Therefore, the seller can count of cost savings due to the change of fraud/error probabilities.

After applying Ito's lemma for $dV_1(P)$, the bellman optimality principal yields a second order differential equation:

$$\frac{1}{2}\sigma^2 P^2 V_1'' + \mu P V_1' - \rho P V_1 + \left[K\left(P - C_{prod} - C_{P_t}\right)\right] = 0 \tag{14}$$

This differential equation is subject to the following boundary conditions:

$$V_1(P_1^*) = V_2(P_1^*) - I_1 \tag{15}$$

$$V_1'(P_1^*) = V_2'(P_1^*) \tag{16}$$

Where P_1^* Denotes the optimal threshold level of the petroleum price at which point the decision maker (seller) chooses to switch to a unique blockchain technology for trading. Value matching and smooth pasting conditions have the following interpretation. The first boundary condition ensures the value of the trading network before and after of the migration differs in only the investment cost. In other words, stating that the value of the project in Phase 1 at the time of change is equal to the value of the project in Phase 2 minus the cost of the technology implementation. The smooth pasting conditions ensures that the value function is continuous and smooth in the neighborhood of the optimality.

Employing a process analogous to the one used to derive the solution in the case of $V_2(P)$ in Phase 2, it can be verified that the solution to the differential equation (14) is given by

$$V_1(P) = A_3 P^{\Pi_1} + \frac{KP}{\rho - \alpha} - \frac{KC_{prod}}{\rho} - \frac{KC_P}{\rho} \tag{17}$$

Similarly, as $V_1(0) = 0$, we conclude that $A_4 = 0$. So, we only have the first term of the value of the option to migrate (switch) to blockchain technology with $\pi_1 > 1$. Using the boundary conditions (15) and (16), we can derive the coefficient A_3 And the optimal threshold for implementing blockchain in the trading network.

$$\boldsymbol{A_3 = \frac{K\lambda_1\beta(1-b)}{\rho\pi_1(P_1^*)^{\pi_1-1}}} \tag{18}$$

And

$$\boldsymbol{P_1^*} = \frac{\boldsymbol{\rho\pi_1 I_1}}{\boldsymbol{K\lambda_1\beta(1-b)(\pi_1-1)}} \tag{19}$$

2.3 Sensitivity Analysis

Now we conduct a sensitivity analysis based on the analytical solutions for economic parameters as follows. We examine the change of oil price threshold for implementing the blockchain technology with respect to investment cost for designing and implementing to the technology, I_1, the total number of barrels traded on the trading system, *K,* the protest rate before implementing the blockchain technology, λ_1 And the cost saving coefficient reflected in reduction in number of protests, *b*.

a) Taking a derivative of P_1^* With respect to I_1, we see the following:

$$\frac{\partial P_1^*}{\partial I_1} = \frac{\rho \pi_1}{K \lambda_1 \beta (1-b)(\pi_1 - 1)} > 0 \tag{20}$$

Since the right term of the above expression is always positive, we conclude that as the investment cost increases, the optimal threshold for switching to blockchain technology increases. In other words, higher implementation costs postpone the implementation project.

b) Next, we study the effect of *K:*

$$\frac{\partial P_1^*}{\partial K} = -\frac{\rho \pi_1 I_1}{K^2 \lambda_1 \beta (1-b)(\pi_1 - 1)} < 0 \tag{21}$$

This shows as larger number of barrels of oil is traded on the trading network, the probability of fraud and/or error increases, resulting in higher number of disputes. Hence, the decision maker is incentivized to implement the blockchain technology earlier. Meaning the optimal price threshold decreases and the trading quantity increases.

c) More importantly, we now see the effect of protest rate on implementation timing:

$$\frac{\partial P_1^*}{\partial \lambda_1} = -\frac{\rho \pi_1 I_1}{K\lambda_1^2 \beta (1-b)(\pi_1 - 1)} < 0 \tag{22}$$

This indicates as the protest rate increases, the optimal threshold for oil price decreases. This means that if the trading network's probability of fraud and error is high, resulting in larger number of protests, the seller decides to implement blockchain technology sooner rather than later.

d) Lastly,

$$\frac{\partial P_1^*}{\partial b} = \frac{\rho \pi_1 I_1}{K\lambda_1 \beta (1-b)^2 (\pi_1 - 1)} > 0 \tag{23}$$

This shows that the price threshold has a positive correlation with costs savings. Meaning that in the worst-case scenario, where the blockchain technology will not result in any difference for protest rate ($b = 1 \rightarrow \lambda_2 = \lambda_1$), the optimal threshold approaches ∞, meaning the decision maker will never choose to switch to blockchain technology.

CHAPTER 3. BUYER AS THE DECISION MAKER

In this section, we study the buyer as the decision maker. We argue that the buyer's utility function is a mirror of the seller's. Similar to the previous section, there are three participants in the system: the seller, the buyer, and the arbitrator. The buyer is acting as the main decision maker which all other participants will follow in the decision to switching to blockchain technology. The buyer decides to implement, design and switch to a unique blockchain framework due to economic circumstance. From point T^*, all trades are done based on the unique blockchain framework. For simplicity, the upstream process of petroleum exploration, production and transportation is excluded in this model and only the downstream trade is studied. Similarly, for the sake of simplicity, we assume that there is only one major provider (seller) and one major consumer (buyer) and one arbitrator who is in charge of resolving the disputes. What distinguishes the traditional setting from blockchain framework is the availability of an immutable record of transactions. The implemented blockchain system is identical and shares the same characteristics. At some point T^*, all participants enter blockchain technology and conduct transaction in the timestamped environment. In a framework where maximum degree of accountability is reached, and all participants are vigilant and have access to the record of data, there is minimal chance of error and/or fraud, hence lowest probability of trade disputes. The buyer's operational cost mostly comes from the oil purchase they make and some overhead costs which we assume are negligible. The revenue is generated through conducting business with downstream consumers (refineries, etc.).

As for the model characteristics, the same attributions follow. The petroleum price follows a geometric Brownian Motion. Similarly, trade disputes happen at a rate of λ which is the result of fraud and/or error. As oil price has positive growth rate, at some point in time, T^*, the seller (oil producer) decides to switch to blockchain technology with the hope of reduction in fraud and/or error which results in reducing the protest probability. Therefore, using blockchain will increase the settlement probability (which results in trade finality) by reducing fraud and/or error. As discussed earlier, the petroleum traded price is characterized by a geometric Brownian Motion with positive drift parameter (growth rate) α and volatility σ:

$$dP_t = \alpha P_t dt + \sigma P_t dz \tag{1}$$

Where P_t Is the petroleum price per unit barrel (\$/barrel) at a time point t. α is the instantaneous growth rate of the petroleum price per unit (% per year; > 0) in, while σ is the instantaneous volatility of the petroleum per unit (% per square root of year). Finally, dt is the increment of time while dz is the increment of a standard Wiener process $z(t)$. That is, $dz = \varepsilon_t \sqrt{dt}$ Where $\varepsilon_t \sim N(0,1)$.

As previously discussed, the dispute resolution costs follow the $C_{p_t} = \lambda\beta P_t$ Formula. Where C_{p_t}The cost associated with the bid is protests which is proportional to petroleum price ($\frac{\$}{barrel*protest}$), λ is the protest rate (#protest/unit time), and β is the correlation coefficient ($unit\ time/protest^2$) . Moreover, it can be verified that the costs associated with protest follow a gbm.

The rest of the notations are given as follows:

I_1: Initial entry fee and installations costs to enter a blockchain trading

P: Fixed revenue (\$/barrels) which is assumed to be constant during the project

K: Number of barrels of oil traded (barrels)

ρ: the annual discount rate for money. Here we use the Weighted Average Cost of Capital (WACC)

As can be seen above, the only difference between the model for the seller and for the buyer is the source of revenue and costs. They all share the dispute resolution cost, however the sources of revenue differ. To prevent repetition, we present the results in the form of discussion.

Similar to the previous section, there will be an optimal price threshold which the buyer makes the decision to switch from traditional record keeping to blockchain technology. We use stochastic calculus to apply Ito's lemma and solve Bellman optimality principal generated differentials equations. There are two phases in the model: before and after blockchain. The same assumption holds that once the decision maker (here, the buyer) switches to blockchain technology, they will remain with the tech upgrade for the foreseeable future.

CHAPTER 4. ARBITRATOR AS THE DECISION MAKER – COST FREE

4.1 Background

By implementing blockchain technology, the overall trust in the trading network evolves and participants are more willing to send and receive transactions. Meaning that as fraud and/or error decreases, participants are willing to issue transactions in higher frequency. On the other hand, as fraud and/or error increases before implementing blockchain, we can observe a reduction in the number of transactions. We can argue that number of transactions are negatively correlated with fraud and/error. In other words, if participants in the system observe that the probability of disputes which are direct results of fraud and/or error is minimal, they can entrust their assets in the system to higher extents, hence the number of transactions increases. Therefore $n \sim 1/\lambda$ where n is the number of transactions and λ is fraud and/or error rate.

To clarify, when we mention arbitrator in this paper, we intend to see this entity as a central entity with multiple roles. First, as mentioned in the previous section, arbitrator oversees the primary stage of dispute resolution. In case of a dispute, there are multiple stages until the dispute is completely resolved. However, for the sake of simplicity, we only study the primary level of dispute resolution which is conducted by the arbitrator. Next, the same entity is responsible for verification of transactions. For instance, when the buyer claims they can supply the funds for the specific transaction. In this case, the arbitrator verifies (with traditional or blockchain-based methods) that the claim is true. After the transaction has been verified, the other party is confident that the transaction is valid and ready to move forward. The application of blockchain technology is highlighted in this stage. Moreover, the arbitrator is contracted to design and implement blockchain technology in the future. This corresponds to this entity being paid the lump sum money of blockchain implementation, I_1. To summarize the arbitrator's responsibilities and roles in our model:

1. Dispute resolution through traditional and/or Blockchain settings
2. Transaction verification by overseeing the integrity of the system
3. Design, implement and maintain a unique Blockchain technology system

As discussed earlier, implementing blockchain technology results in additional trust between participants. In other words, participants can enter the system without fully trusting other players since the system is efficient to capture any fraudulent effort. This is the essence of Blockchain technology, a trustless system that encourages highest participation without worrying about fraud and/or error happening. As the probability of fraud and/or error decreases, seller and buyer mentioned in the previous section are more encouraged to entrust their assets and funds to the system for conducting transactions. We showed that after blockchain implementation the number of transaction increases. This results in more accumulation of transaction fees for arbitrator (verifier.) Therefore, the arbitrator can leverage the security and irrefutability of blockchain system to encourage other participants to switch to blockchain technology even though he/she is aware that by switching one of the main sources of revenue (dispute resolution costs paid by protester) will be diminished. We argue that by implementing blockchain technology, the arbitrator will receive:

1. The investment payment for designing, implementing and deploying Blockchain
2. The increased payment for surged number of transactions which corresponds to higher received accrued transaction fees

The gain profit due to these two sources, under certain conditions, will compensate the loss due to the reduction of dispute resolution costs by increased demand for transaction verification directed from either seller or buyer.

The arbitrator, in the trading system, may have incentive to act maliciously. In the trading framework, business arbitrators may favor a client and double spending attacks in traditional online trades are examples of abnormal behavior of arbitrators. In other scenarios, the arbitrator in our trading system, may act faithfully, but due to the fraud and/or error done by either seller or buyer, the verification process (report submission) does not reflect the ground truth. Nevertheless, the outcome of the trade is the same in both cases, whether the arbitrator conducts vicious behavior or seller and/or buyer act untruthfully.

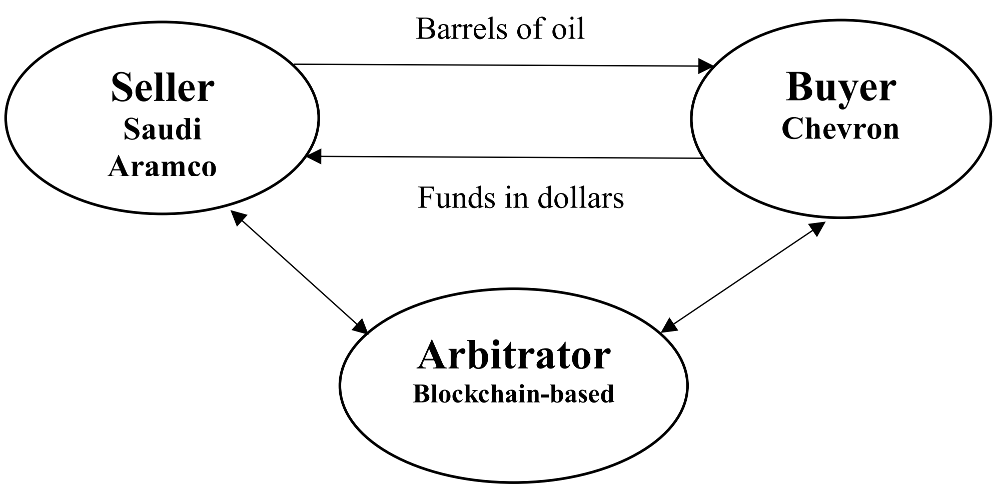

Figure 9 - Petroleum Trade Network in a Blockchain framework

In our framework, the fraud and/or error (whether from seller or buyer) happen at the rate of λ which results in the trade disputes. As previously discussed, trade disputes arise when the receiving party fails to acknowledge the violation of the agreement. In every dispute, there are fees associated with the filing the disputes. These fees correspond to our C_{P_t} In our model. Commodity price, petroleum price, follows a geometric Brownian Motion as suggested by (Postali & Picchetti, 2006). The production cost is assumed to be constant over time and costs associated with filing the protest are functions of oil price.

4.2 Methodology

There are three participants in the system, trading petroleum as the main commodity initially in a traditional setting and later, at an optimal time, T^*, the decision maker decides to switch a unique blockchain framework due to economic circumstances. As a result, all other participant, will follow the decision and become members of the blockchain system. From point T^*, all trades are done based on the unique blockchain framework. For simplicity, the upstream process of petroleum exploration, production and transportation is excluded in this model and only the downstream trade is studied. For the sake of simplicity, we assume that there is only one major provider (seller), one major consumer (buyer), and one arbitrator who oversees dispute resolution and transaction verification. What distinguishes the traditional setting from blockchain framework is the availability of an immutable record of transactions. Every transaction is timestamped, and the underlying source is clearly expressed. What reduces the number of bid protests is reduction in fraud and/or error. In a framework where maximum degree of accountability is reached, and all participants are vigilant and have access to the record of data, there is minimal chance of error and/or fraud, hence lowest probability of trade disputes.

Oil price with positive growth rate (Xu, 2006) at some point in time, T^*, the blockchain technology will be implemented with the hope of reduction in fraud and/or error which results in reducing the protest probability. Therefore, using blockchain will increase the settlement probability and trade finality by reducing fraud and/or error. Furthermore, there is a fixed transaction fee t for every instance of transaction verification done by the arbitrator. This fee as suggested is observed in both traditional and blockchain setting (Goodman, 1968) and (Koch &

Reitwießner, 2018). We hypothesis that as the probability of fraud and/or error decreases (by deploying the Blockchain technology) the overall trust in the trading network progresses and participants are more likely to trade with each other. Hence, the number of transactions which affects accumulated transaction fees increases. Although this is considered a charge for seller and buyer, increasing the total number of transactions will result in growing profit which surpasses the total transaction fees.

Now let us introduce some notations:

λ: fraud and/or error rate

I_1: Initial entry fee and installations costs to enter a blockchain trading

K: Number of barrels of oil traded (barrels)

ρ: the annual discount rate for money. Here we use the Weighted Average Cost of Capital (WACC)

$$dP_t = \alpha P_t dt + \sigma P_t dz \tag{1}$$

t: fixed transaction verification fee ($/transaction.barrel)

n: number of transactions (#transaction)

θ: equality coefficient

In our model the petroleum price is characterized by a geometric Brownian Motion with positive drift parameter (growth rate) α and volatility σ:

Where P_t Is the petroleum price per unit barrel ($/barrel) at a time point t. α is the instantaneous growth rate of the petroleum price per unit (% per year; > 0) in, while σ is the instantaneous volatility of the petroleum per unit (% per square root of year). Finally, dt is the increment of time while dz is the increment of a standard Wiener process $z(t)$. That is, $dz = \varepsilon_t\sqrt{dt}$ Where $\varepsilon_t \sim N(0,1)$.

Furthermore, we assume that for our trading network in question, the protest costs which correspond to one of the main sources of revenue for the arbitrator have the following relationship with oil price:

$$C_{pt} = \lambda\beta P_t \qquad (2)$$

Where C_{p_t} The cost associated with the bid is protests which is proportional to petroleum price ($\frac{\$}{barrel*protest}$), λ is the protest/fraud/error rate (#protest/unit time), and β is the correlation coefficient $(unit\ time/protest^2)$. Moreover, it can be verified that the costs associated with protest follow a gbm.

Furthermore, we argue that number of transactions is negatively correlated with the fraud and/or error rate. As before, as the trade finality and irrefutability increases meaning fraud and/or error rate decreases, participants are more likely to send transactions, hence the number of transactions increases. In other words:

$$n \sim \frac{1}{\lambda} \rightarrow n = \frac{\theta}{\lambda} \qquad (24)$$

Concretely:

$$n_2 = \frac{\theta}{\lambda_2} = \frac{\theta}{b\lambda_1} = \frac{1}{b}\, n_1 \qquad (25)$$

Where

$$0 < b < 1$$

$$\text{Hence, } n_2 > n_1$$

We are not studying the scenario where the arbitrator acts maliciously as it would break the trading framework since there is only one single verifier/arbitrator in our system. Studying the malicious behavior of arbitrator is outside the scope of my paper. In other words, whenever fraud and/or error occurs, it is conducted from either the buyer or the seller or both parties. Therefore, we are only going to study the scenario where the fraud and/or error is occurred because participants other than the arbitrator acted maliciously.

In our simplified trading model, we have:

$$U = C_{pt} + n \cdot C_{tv} \tag{26}$$

Where C_{pt} And C_{tv} Are arbitrator's revenue. Although in our model, the arbitrator's revenue from dispute resolution decreases as the system switches to blockchain technology, $\left(C_{pt}\right)_2 < \left(C_{pt}\right)_1$ (which is due to less disputes) the increase in number of transactions as a result of higher participation in the network (due to increase trust in a secure, immutable and irrefutable record) will result in accruing larger sum of transaction fees:

$$\left(C_{pt}\right)_2 < \left(C_{pt}\right)_1 \quad \text{And} \quad n_2 > n_1 \tag{27}$$

Moreover, as mentioned earlier, the number of transactions increases due to higher trust in the system by participants. Therefore, the arbitrator can collect increased amount of transaction verification fees by implementing the blockchain technology. The increase in transactions numbers and fees subsequently, compensate for the decrease in dispute resolution payments. We are going to study the conditions under which the arbitrator by switching to Blockchain technology not only does not lose profit, but also experiences increase in revenue. This incentivizes the incorporation of blockchain technology in trading systems through arbitrator's perspective.

4.3 Model Formulation

In this section we are going to present the mathematical formulation of investment valuation through the arbitrator's perspective. The arbitrator collects revenue from dispute resolution and transaction verification fees corresponding to a price P. At an optimal time, due to the increasing nature of petroleum price, blockchain technology is implemented in order to reduce the cost associated with the protest. This decision results in reducing the number of protests which is a direct outcome of reduction in probability of fraud and/or error in trades. Consequently, the expected value function for trading capacity of K through arbitrator's perspective is:

$$V(P_t) = \text{Max}\, E\,[\int_0^{T^*} e^{-\rho t} K[C_{pt} + n_1 \cdot C_{tv}]dt + \int_{T^*}^{\infty} e^{-\rho t} K[C_{pt} + n_2 \cdot C_{tv}]dt + e^{-\rho T^*} I_1] \tag{28}$$

Using notation for phase one and phase two (before and after blockchain implementation) and utilizing the Bellman principal of optimality, we formulate the value function of the trading network through arbitrator's perspective. As discussed earlier, petroleum price is characterized by a geometric Brownian Motion $dP_t = \alpha P_t dt + \sigma P_t dz$. $V_2(P)$ can be characterized as the expected value gained if the company decides to adopt and invest in blockchain technology.

$$\rho V_2(P)dt = [K(C_{pt} + n_2 \cdot C_{tv})]dt + d\text{E}[V_2(P + dP)e^{-\rho t}] \tag{29}$$

Equation (30) states that the total return for this project through arbitrator's perspective consists of the net revenue currently generated from dispute resolution payments and transaction verification fees plus the future expected appreciation in the value of the project.

After applying Ito's Lemma on dV_2, the Bellman optimality principle equation (30) yields a second order differential equation as follows.

$$\frac{1}{2}\sigma^2 P^2 V_2'' + \alpha P V_2' - \rho V_2 + K\left(C_{pt} + n_2 \cdot C_{tv}\right) = 0 \quad (30)$$

The optimality equation results in a second-order differential equation with homogenous and non-homogenous solutions. To solve the differential equation (31) we first note that a particular solution can be verified to be:

$$V_2(P) = \frac{KC_{pt}}{\rho - \alpha} + \frac{K(n_2 \cdot C_{tv})}{\rho} \quad (31)$$

Where a technical condition of $\rho - \alpha > 0$ is assumed as in Dixit and Pindyck (1994). Next, a homogeneous solution to Equation (10) can be verified to be:

$$V_2(P) = A_5 P^{\Pi_1} + A_6 P^{\pi_2} \quad (32)$$

Where $\pi_1, \pi_2 = \pm\left[\left(\frac{\sigma^2}{2} - \alpha\right) + \left(\left(\frac{\sigma^2}{2} - \alpha\right)^2 + 2\sigma^2\rho\right)^{0.5}\right]/\sigma^2$ While a technical condition of $\frac{\sigma^2}{2} - \alpha > 0$ is assumed in Dixit and Pindyck (1994) and the fundamental quadratic equation is similar to the previous section.

Which is an equation of π. Hence, general solution to the differential equation:

$$V_2(P) = A_5 P^{\Pi_1} + A_6 P^{\pi_2} + \frac{KC_{pt}}{\rho - \alpha} + \frac{K(n_2 \cdot C_{tv})}{\rho} \quad (33)$$

In the context of technology competition and innovation through real options theory, (Grenadier & Weiss, 1997) defined the boundary conditions for optimal technology upgrade at the optimal point as the expected payoff of the upgrade option at the moment the new technological innovation is implemented. This approach requires the understanding of the distribution of the payoff which may not be known a priori. They assumed that standard normal density and cumulative distribution function are necessary to utilize the boundary conditions.

Also, to best of the authors knowledge there has not been any scientific approach in correctly estimating the expected technological upgrading and improvement when the standard and prevailing technology becomes obsolete.

In another work, (Kauffman & Li, 2005) related the value of the project to value of the investment opportunity at the time of technology upgrade and derived the boundary conditions based on the relationship between the investment opportunity value and the project value. In our framework, we assume that once the firm adopts the new blockchain technology, it will continue using the technology forever, hence there is no future option values. The solution to the partial differential equation is as follows but since there is no future option the power terms in the value function are equal to zero.

According to (Pindyck & Dixit, 1994), if the price of oil approaches zero, the value of the trading project must approach zero, in other words, $V(0) = 0$. Zero is an absorbing barrier for the geometric Brownian motion. However since $\pi_2 < 0$, the power of P goes to infinity as P goes to zero. To prevent the diverging, we set A_6 As zero. $A_6 = 0$

The other term, $A_5 P^{\Pi_1}$ Represents a component of V to reflect the speculative bubble as $\rightarrow \infty$. According to (Pindyck & Dixit, 1994)after migrating to blockchain, the firm might make the decision to revalue the project above its fundamentals in the future if they expected to be able to gain enough capital gain either by upgrading or abandoning the trading or other means. But that is not the case in our framework. We assumed as the firm makes the decision to switch to blockchain technology, it remains the principal trading framework through the seller perspective, hence there is no expected value of the trading above its fundamentals in the future, hence $A_5 = 0$. This simplifies our solution to the general solution as below:

$$V_2(P) = \frac{KC_{pt}}{\rho - \alpha} + \frac{K(n_2 \cdot C_{tv})}{\rho} \tag{31}$$

To unify with our notations in the previous section, we have $\left(C_{pt}\right)_2 = \lambda_2 \beta P_t$. Hence,

$$V_2(P) = \frac{KC_{pt}}{\rho - \alpha} + \frac{K(n_2 \cdot C_{tv})}{\rho} = \frac{K\lambda_1 b\beta P}{\rho - \alpha} + \frac{K(\theta/b)(n_1 \cdot C_{tv})}{\rho} \tag{32}$$

By carefully examining the value function of the project, we can see, the value of the project is positively correlated with petroleum price and the number of transactions in the system. As price of petroleum increases, arbitrator's revenue increases. This highlights the importance of the price volatility, number of transactions, volume of the commodity being traded in the system (K, n & P.)

Now let us move on to the phase 1 where the trade is being conducted in a traditional setting, without blockchain technology. Similar to phase 2, the petroleum price follows the same gbm as blockchain implementation does not change the nature of the commodity being traded. Also, the value of the trading network through seller's perspective obeys Bellman optimality principal:

$$\rho V_1(P)dt = \left[K\left(C_{pt} + n_{\,1} \cdot C_{tv}\right)\right]dt + d\mathrm{E}[V_1(P + dP)e^{-\rho t}] \tag{33}$$

Where

$$\lambda_2 = b\lambda_1 \text{ And } n_2 = \frac{\theta}{b} n_1$$

$$\text{Where } \theta > 1 \text{ and } 0 < b < 1$$

The optimality principal states that the total value of the trading project through arbitrator's perspective is comprised the total revenue that arbitrator makes (by dispute resolution, verification fees, etc.) And the future appreciation of the project. Using Ito's lemma, a partial differential equation can be developed as follows subject to the subsequent boundary conditions:

$$\frac{1}{2}\sigma^2 P^2 V_1'' + \alpha P V_1' - \rho V_1 + \left[K\left(C_{pt} + n_{\ 1} \cdot C_{tv}\right)\right] = 0 \tag{34}$$

$$V_1(P_1^*) = \ V_2(P_1^*) - I_1 \tag{35}$$

$$V_1'(P_1^*) = \ V_2'(P_1^*) \tag{36}$$

Where P_1^* Denotes the optimal threshold level of the petroleum price at which point the decision maker chooses to switch to a unique blockchain technology for trading. Equation (35) is the value matching which ensures the value of the trading network before and after of the migration differs in only the investment cost. In other words, stating that the value of the project in Phase 1 at the time of change is equal to the value of the project in Phase 2 minus the cost of the technology implementation. Equation (36), smooth pasting conditions ensures that the value function is continuous and smooth in the neighborhood of the optimality.

One can verify that the general solution to the partial differential equation is as follows:

$$V_1(P) = A_7 P^{\Pi_1} + A_8 P^{\pi_2} + \frac{KC_{pt}}{\rho - \alpha} + \frac{K(n_1 \cdot C_{tv})}{\rho} \tag{37}$$

As $V_1(0) = 0$ we conclude that $A_8 = 0$ (corresponding to $\pi_2' < 0.$) Therefore, we only have the first term of the value of the option to migrate to blockchain technology with $\pi_1 > 1$. Hence the solution for the value of the trading project through arbitrator's perspective in the first phase is:

$$V_1(P) = A_7 P^{\Pi_1} + \frac{KC_{pt}}{\rho - \alpha} + \frac{K(n_1 \cdot C_{tv})}{\rho} \tag{38}$$

Utilizing the boundary conditions stated above, we can solve for the optimal price threshold, P^*, and the exponential coefficient, A_7.

$$V_1'(P_1^*) = \ V_2'(P_1^*) \tag{3}$$

Results in

$$A_7 = \frac{\left[-\frac{K\lambda_1\beta}{\rho-\alpha}(1-b)\right]}{\pi_1 P^{*\pi_1-1}} \tag{39}$$

And

$$V_1(P_1^*) = V_2(P_1^*) - I_1 \tag{21}$$

$$P^* = \frac{[-\rho I_1 + Kn_1 \cdot C_{tv}(\theta - b)]}{\frac{K\lambda_1\beta\rho(1-b)(\pi_1-1)}{\pi_1(\rho-\alpha)}} \tag{40}$$

With a condition $\theta > b$

4.4 Sensitivity Analysis

Now we conduct a sensitivity analysis based on the analytical solutions for economic parameters as follows. We examine the change in oil price threshold for implementing the blockchain technology with respect to investment cost for designing and implementing to the technology, I_1 And the fraud and/or error rate before implementing the blockchain technology, λ_1

a) Taking a derivative of P_1^* With respect to I_1, we see the following:

$$\frac{\partial P_1^*}{\partial I_1} = -\frac{\rho}{\frac{K\lambda_1\beta\rho(1-b)(\pi_1-1)}{\pi_1(\rho-\alpha)}} < 0 \tag{41}$$

Since the right term of the above expression is always negative, we conclude that as the investment payments to the system implementor increases, the optimal threshold for switching to blockchain technology decreases. In other words, higher implementation investment is an incentive for the arbitrator to participate in migrating to Blockchain.

b) More importantly, we now see the effect of fraud and/or rate on implementation timing:

$$\frac{\partial P_1^*}{\partial \lambda_1} = -\frac{[-\rho I_1 + K n_1 C_{tv}(\theta - b)]}{\frac{K\lambda_1^2 \beta\rho(1-b)(\pi_1 - 1)}{\pi_1(\rho - \alpha)}} < 0 \tag{42}$$

For reasonable investment costs and high transaction values, this indicates as the fraud and/or error increases, the optimal threshold for oil price to switch to blockchain decreases. This means that if the trading network's probability of fraud and error is high, resulting in larger number of protests, we need to implement blockchain technology sooner rather than later. Also, this refers to lower number of transactions as $n \sim 1/\lambda$ states that higher fraud and/or rate results in less participation in the system.

CHAPTER 5. NUMERICAL ANALYSIS FOR THE ARBITRATOR'S MODEL

In this section we numerically illustrate some of the key features of our arbitrator as the decision maker model. This numerical example is manly focused on validating the findings for the arbitrator mathematical model.

1. Parameter values: Let us first present the parameter values used in this section. Even though these values are hypothetical, to be realistic numbers, we have consulted the U.S. Energy Information Administration as well as others (e.g., Croghan, et al., 2017; (Fasanya & Onakoya, 2013)). These are summarized in Table 1.

Table 1 – Parameters and corresponding values

Parameters	Numerical values
Trading quantity *K*	5000 barrels
Investment cost *I*	$100,000
Annual discount rate ρ	0.05
Annualized growth rate of oil price α	0.03
Annualized volatility of oil price σ	0.25
Fraud and/or error rate λ_1	10
Fraud and/or error rate λ_2	2
Blockchain system efficiency coefficient *b*	0.2
Fixed transaction fee *t*	$0.3/transaction
Number of transactions n_1	40

2. The switching decision: By applying the parameter values to Equations (15), (21), (23), (25), the threshold value of P^* (\$/barrel) as well as the functions of $V_1(P)$ and $V_2(P)$ can be calculated. The numerical results are summarized in Table 2.

Table 2 - Numerical results for switching decision

Decision variables	Numerical values
$\boldsymbol{\pi'_1}$	1.28507
$\boldsymbol{P^*}$	\$97/barrel
$\boldsymbol{A_3}$	-422511
$\boldsymbol{V_1(P)}$	$-422511\boldsymbol{P}^{1.28507} + 2.5 \times 10^6\boldsymbol{P} + 1.2 \times 10^6$
$\boldsymbol{V_2(P)}$	$500000\boldsymbol{P} + 6 \times 10^6$

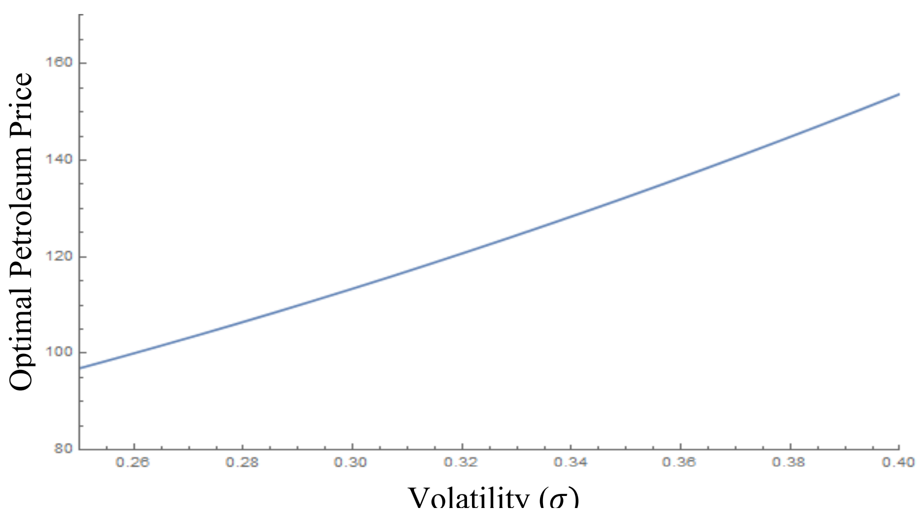

Figure 10 - Optimal price threshold movement versus volatility

3. In Figure 10, the threshold of P^* Is depicted with respect to the volatility of the petroleum price. This threshold increases as the price of petroleum becomes more volatile, which indicates that a higher degree of volatility will delay the switching decision.

4. In Figure 11, the threshold of P^* Is depicted with respect to the growth rate of the petroleum price. The threshold increases exponentially as the growth rate increases. This implies that higher growth rate implies postponing the switching to Blockchain technology.

5. In Figure 12, the threshold of P^* Is depicted with respect to the investment payment to implement and maintain blockchain technology. As seen above, higher investment payment to the arbitrator induces early switching to blockchain technology. This is

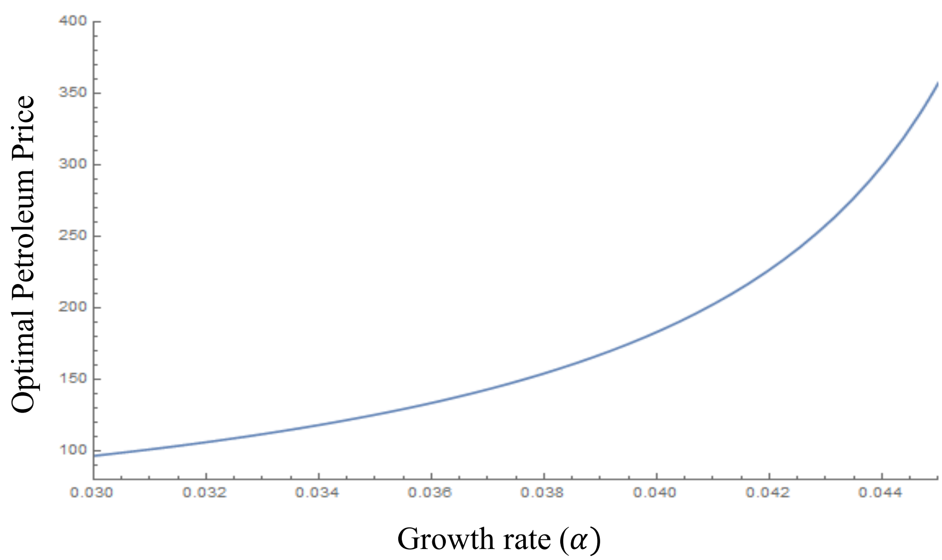

Figure 11 - Optimal price threshold versus growth rate

reasonable that the higher incentive to switch to the new technology would be, the earlier the arbitrator is opting to migrate to blockchain.

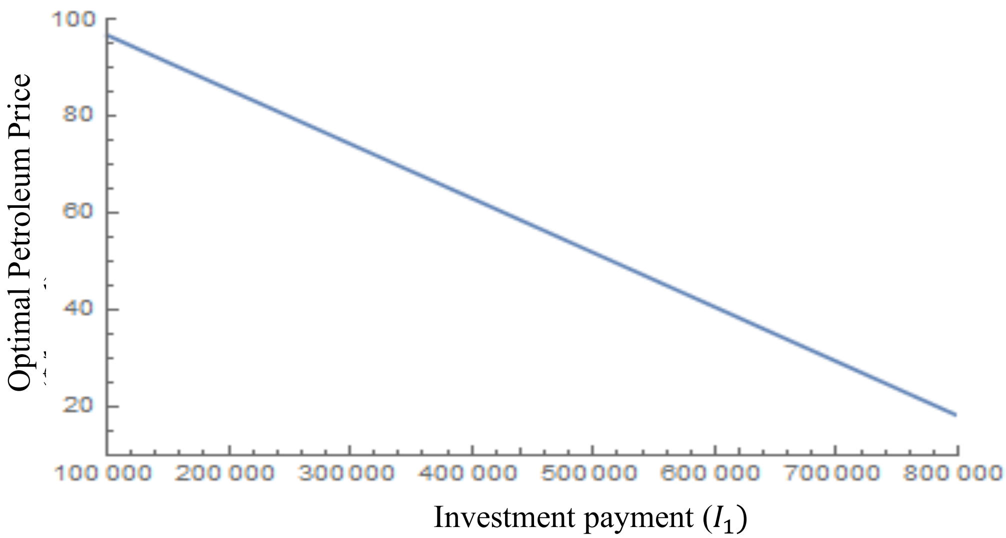

Figure 12 - Optimal price threshold versus investment payment

6. In Figure 13, the threshold of P^* Is illustrated with respect to the trading capacity. As shown above, we can observe that as the trading capacity increases, the threshold increases as well. This is due to higher transaction fee collected. However, after a marginal value,

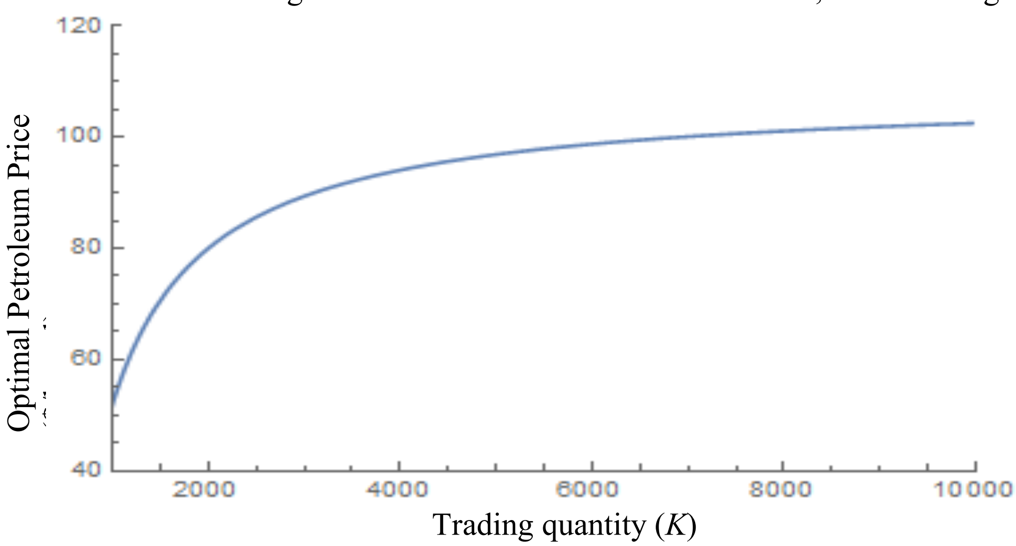

Figure 13 - Optimal price threshold movement versus trading quantity

increases in trading capacity will not affect the optimal threshold and the threshold will peter out.

7. In Figure 14, the threshold of P^* Is illustrated with respect to the fraud and/or error rate, λ. As we can see, as the fraud/error rate increases, the threshold decreases. It is interesting to note that as the fraud/error rate increases, meaning a smaller number of transactions will happen, the arbitrator favors switching to blockchain as early as possible. As we can see, the theoretical upper bound of fraud/error rate will result of not waiting at all and immediately make the migration to the new technology decision. On the other hand, if there

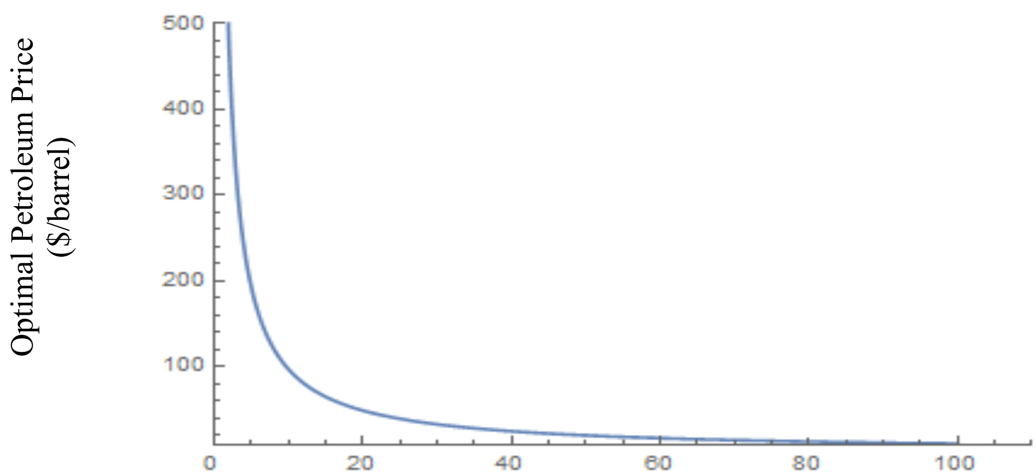

Figure 14 - Fraud and/or error rate λ

is no fraud/error happening on the trading system, corresponding to $\lambda \to 0$, the firm will never switch to blockchain technology as $P^* \to \infty$.

8. In Figure 15, we have illustrated the historical petroleum price movements to depict graphically how the price moves and how we identify an optimal threshold for switching to blockchain technology.

Figure 15 - Petroleum price from 2000 - 2010

Source: U.S. Energy Information Administration

CHAPTER 6. ARBITRATOR AS THE DECISION MAKER – COST INCLUDED

In this chapter we will study the arbitrator as the decision maker, similar to the previous chapter, however, costs associated with labor and overhead are included as a parameter on the value function. All the notations and assumptions are the same except that there is an associated cost with verification process which arbitrator needs to incur. The new utility function is as follows:

$$U = C_{pt} + n \cdot C_{tv} - C_A \tag{27}$$

We assume that there is an equilibrium for this cost. Before implementing blockchain, number of transactions are not as large as after implementing blockchain (due to reasoning mentioned in the previous sections) Hence, one might think that there is less labor cost for transaction verification from the arbitrator perspective. However, as mentioned before, number of disputes are higher before implementing blockchain, hence the costs associated with dispute resolution will compensate lower transaction verification costs. Therefore, we assume that operational and labor costs for the arbitrator is fixed throughout the project (i.e. Before and after implementing blockchain)

With that being said, the new value function is as follows:

$$\begin{aligned} V(P_t) = \text{Max}\, E\,[\int_0^{T^*} e^{-\rho t} K\big[C_{pt} + n_1 \cdot C_{tv} - C_A\big]dt \\ + \int_{T^*}^{\infty} e^{-\rho t} K\big[C_{pt} + n_2 \cdot C_{tv} - C_A\big]dt + e^{-\rho T^*} I_1] \end{aligned} \tag{43}$$

Using dynamic programming, bellman's optimality principals for after blockchain is as follows:

$$\rho V_2(P)dt = \left[K\left(C_{pt} + n_2 \ \cdot C_{tv} - C_A\right)\right]dt + d\mathrm{E}[V_2(P + dP)e^{-\rho t}] \qquad (44)$$

After applying Ito's lemma, solving the differential equation, similar conditions to the previous sections, we have the solution for the value of the project as follows:

$$V_2(P) = \frac{KC_{pt}}{\rho - \alpha} + \frac{K(n_2 \cdot C_{tv})}{\rho} - \frac{K(C_A)}{\rho} \qquad (45)$$

For the first phase, again similar to the previous section, we have the bellman optimality principle:

$$\rho V_2(P)dt = \left[K\left(C_{pt} + n_1 \ \cdot C_{tv} - C_A\right)\right]dt + d\mathrm{E}[V_2(P + dP)e^{-\rho t}] \qquad (46)$$

Using respective boundary conditions, solving the differential equation yields:

$$V_1(P) = A_9 P^{\Pi_1} + \frac{KC_{pt}}{\rho - \alpha} + \frac{K(n_1 \cdot C_{tv})}{\rho} - \frac{K(C_A)}{\rho} \qquad (47)$$

Boundary conditions are similar to the previous section. To obtain the optimal price threshold and A_9, we have:

$$A_9 = A_7 = \frac{\left[-\frac{K\lambda_1\beta}{\rho - \alpha}(1 - b)\right]}{\pi_1 P^{*\pi_1 - 1}} \qquad (39)$$

And

$$P^* = \frac{[-\rho I_1 + Kn_1 \cdot C_{tv}(\theta - b) - KC_A]}{\frac{K\lambda_1\beta\rho(1 - b)(\pi_1 - 1)}{\pi_1(\rho - \alpha)}} \qquad (48)$$

CHAPTER 7. DISCUSSION

$$Higher\ b \xrightarrow{yields} lower\ \lambda \xrightarrow{yields} higher\ n$$

This shows that as the efficiency of the blockchain system increases, the participants are encouraged to submit higher frequency of transactions even though there is a transaction verification fee associated to each transaction. The verification fee will be compensated by the savings done by reducing fraud and/or error.

By carefully studying the optimal threshold for switching to blockchain technology which corresponds to maximization of arbitrator's utility, we conclude that investment cost is an incentive to switching to blockchain technology for arbitrators. As investment payment to the arbitrator (as being responsible for system implementation) increases, the optimal threshold for switching to blockchain technology decreases. This is well-matched with reality as investment sum paid by seller and/or buyer is an incentive for arbitrator to participate in blockchain implementation decision making.

We observed that as the participants migrate their trading network to Blockchain system, costs saving associated with dispute resolution decreases exponentially. Next, we saw that since the dispute resolution payments are one of the main sources of revenue for the arbitrator, switching to Blockchain technology, under specific economic conditions might seem not practical and feasible for the arbitrator. However, we identify another source of arbitrator's revenue, the transaction verification fee. We argued that as the system becomes more reliable and the trading chain becomes irrefutable by integrating blockchain technology, the probability of fraud and/or error decreases. This results in fewer disputes and higher trust of participants in the system. When both seller and buyer see that the trading system is reliable and trade finality is maximal, they tend to send transactions more frequently. This corresponds to more transaction verification fee for the arbitrator. Therefore, the loss of dispute resolution payments by switching to Blockchain is compensated by gain due to increase in transactions frequency and subsequently larger sum of transaction verification fees in a finite horizon. The rational for increasing in number of transaction after Blockchain technology can be stated as number of transaction is extremely dependent on fraud and/or error rate:

$$n = \frac{\theta}{\lambda}$$

Where θ is a constant and λ is fraud and/or error rates.

$$\lambda_2 < \lambda_1 \rightarrow n_2 > n_1$$

And the rate of increase in number of transactions is $1/b$.

All findings in the mathematical models are based on the fact that blockchain technology indeed lives up to its promises as to increase trust among participants by providing an immutable track of records. As we concluded, the arbitrator can positively take advantage of this feature to advertise blockchain as a sustainable solution that provides transparency and irrefutability. As the interactions among participants become more complex, the number of participants increase, from a game theory perspective, it is not trivial to reason that blockchain technology encourages information symmetry, fair competition, and increase in trust. As (Cong & He, 2019) pointed out, using smart contracts which are the at the core of blockchain along with the immutable record, might result in collision and further mistrust complications. In our simple, three-participant model, it is reasonable to conclude that the system arbitrator can profit from switching to blockchain even though less disputes happen. As for the implications on participants interaction, switching to blockchain technology could be considered as a win-win-win solution for all the participants under certain economic conditions. These conditions have been connected to the underlying asset price, petroleum price, which is volatile and highly unpredictable. Throughout this work, we use the Real

Options theory to find the optimal timing of decision making for the participants. We hope that this work provides insight on how disruptive and innovative technologies could help businesses make better data-driven decisions under uncertainty. As for future directions, one can study the inter-relations between all three participants at once and not in isolation to identify the winner(s) or possible loser(s) in the decision of switching to blockchain technology.

We also should mention that filing disputes from either seller or buyer could be categorized into three categories: frivolous, unintentional errors, and strategic disputes. By strategic disputes, we refer to Melese (2010), where entities file disputes because of trade regret or postponing trade execution and finality. Melese (2010) mentioned about these efforts coming from entities who are not happy or satisfied with already accepted contract or economic conditions have changed their minds. They might have found better deals which would like to terminate the contract and switch to better deals. In this article we mainly focused on strategic disputes, since blockchain technology discourages entities to file disputes for the purpose of postponement of trades.

Moving to a realistic example of dispute arbitration, **International Centre for Settlement of Investment Disputes (ICSDI)** is established in 1966 for legal dispute resolution and conciliation between international investors. This entity, which is an international organization, is part of the World Bank Group, and an autonomous, multilateral specialized institution to encourage international flow of investment and mitigate non-commercial risks. This organization can be identified as an immediate example of the arbitrator mentioned in this work, which is responsible for dispute resolution between states, in a multi-national capacity.

(Khor 2012) mentions, as an instance, an ICSDI counsel awarded a judgment of $1.8 billion for Occidental Petroleum against the government of Ecuador. Furthermore, Ecuador had to pay additional fees in compound interest, and half of the costs of the tribunal. “The South American country annulled a contract with the oil firm on the grounds that it violated a clause that the company would not sell its rights to another firm without permission. The tribunal agreed the violation took place but judged that the annulment was not fair and equitable treatment to the company."

According to Wikipedia, another example is "Irish oil firm Tullow Oil took the Ugandan government to court in November 2012 after value-added tax (VAT) was placed on goods and services the firm purchased for its operations in the country. The Ugandan government responded that the company had no right to claim tax on such goods prior to commencement of drilling."

CHAPTER 8. CONCLUSION

Due to high frequency and large volume, petroleum trades are susceptive to misreporting which would result in trades disputes. In this thesis, we studied a petroleum trading network consisting of three participants: the seller, the buyer, and the arbitrator. First part of the paper was dedicated to study the seller and the buyer. We developed mathematical models that validate the hypothesis that blockchain technology could help increase trust and maximize participants utilities function if studied each player in isolation. Second portion of the paper we focused on evaluating the trading network from the arbitrator perspective. In each transaction network, the arbitrator facilitates the transaction verification and reporting. We argued by implementing a blockchain technology, the number of trade disputes which are resulted by fraud and/or error would decrease. The rational for this is since blockchain technology offers an immutable record of transactions, trust in the system would increase which would result in higher accumulation of transaction verification fees for the arbitrator. Hence, arbitrator can leverage this and compensate for decrease in dispute resolution fees. Blockchain-based petroleum trading network incorporate trust to transactions.

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