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When Is Blockchain Worth It? A Case Study of Carbon Trading

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Abstract: Blockchain, as an emerging technology and a disruptive innovation, has attracted attention from both academia and industry. However, there are many potential risks associated with it, such as the technical risk, the legal risk and the privacy risk. A comprehensive risk analysis is crucial for cost-effective deployment of blockchain technology. Important adoption decisions, including when to deploy blockchain, how to plan the investment, how to transfer current businesses onto blockchain, and how to price the blockchain service depend on this risk analysis. Yet very little study exists concerning the blockchain adoption planning with risks analysis. This research presents a cost-and-risk analysis framework and an adoption planning method for the case of blockchain application in carbon trading. Design requirements implied by the analysis are inferred and the architecture of a novel hybrid blockchain system is proposed. The system leverages the advantages of blockchain technology and incorporates institutional risk control framework. The optimal adoption strategy of this system is derived through modelling of users' and the organizer's behavior.

Keywords: blockchain; risk analysis; system design; innovation adoption; carbon trading

1. Introduction

The concept of "chained blocks" was firstly proposed for solving the double-spending problem in Bitcoin, after which "blockchain" gradually emerged as a generic term. Blockchain is a distributed ledger technology (DLT) that connects different parties over the internet to provide a reliable record of transactions, without giving control to a third party. A blockchain is essentially a distributed database, with information replicated across many nodes through peer to peer communication and maintained jointly by the collective according to a consensus protocol. Data are encapsulated in "blocks", which are chronologically ordered and cryptographically chained to form the immutable chain. Blockchain technology offers several desired properties: one point failure issue of centralized systems is eliminated through replication and distribution of data; transparent data shared directly among all nodes restrains data manipulation and monopoly; information on blockchain is temper-proof and traceable; and it is more resistant to technical failures and malicious attacks. In addition to facilitating transactions, blockchain technology evolved to power the smart contract, which is generally considered as the second generation of blockchain applications. Business logic or contract terms are coded in a smart contract, which is stored on a blockchain and executed by nodes when the predefined trigger happens. Therefore, smart contracts on blockchain are automatically executed and enforced, fostering collaboration between untrusted peers without requiring a central agency.

Due to these unprecedented advantages of blockchain technology, many entrepreneurs and governments are rushing into the adoption or promotion of the technology for fear of missing the opportunity or losing the competition. There are, however, various risks associated with the blockchain technology. Indeed, blockchain transforms business models from human-based to algorithm-based models, exposing firms to new risks regarding business continuity, data confidentiality, cyber attacks, technology failures and more (Deloitte, https://www2.deloitte.com/us/en/pages/advisory/articles/blockchain-risk-management.html). Adverse events and unforeseen risks could undermine all the benefits of blockchain. In the short history of blockchain, exchanges and wallets breaches, exploitation of smart contracts bugs and other incidents have occurred numerous times and caused enormous loss and panic. For example, millions of dollars were lost in the Mt. Gox and the DAO hacking events. Blockchain has also been abused by evildoers to commit crimes, such as the initial coin offering (ICO) scam, money laundry and trafficking. Frequent crimes and attacks are serious concerns to governments, and consequent strict regulations in some jurisdictions have hindered the development of blockchain technology. Therefore, it is imperative to analyze risks along with benefits when considering deployment of blockchain technology. Investment in incorporating blockchain technology is not worthwhile until the benefits overpass the risks. Successful integration of blockchain requires a thorough plan for timing, investment, adjustment, pricing and coordination of the legacy and blockchain systems. However, the blockchain adoption strategies based on risk analysis have not been fully developed.

In this paper, we focus on the case of blockchain application in carbon cap-and-trade scheme (CAT), to analyze risks and adoption planning of blockchain technology. In a CAT program, the right to emit greenhouse gases (GHG) is issued in the form of "carbon credits". These credits are traded between regulated companies for compliance with the emission targets set by the regulator. The carbon market is an ideal testbed for blockchain technology for the following reasons: (1) the potential of blockchain technology for improving the CAT has been recognized and proposed by many researchers and policy makers; (2) carbon credits can be easily digitalized and represented on the network; (3) despite the lack of a physical form, carbon credits are associated with real emissions or emission reductions. If carbon trade is placed on blockchain, speculation and crimes on completely-virtual-blockchain-based assets can be partially avoided, as carbon credits are backed by physical activities.

The paper consists of several parts:

1. First, a comprehensive benefits and risks analysis of blockchain integration in CAT is conducted. The cost-and-risk structures of current CAT and a blockchain-based CAT are compared.
2. To effectively address newly introduced risks, we design an architecture of a novel hybrid blockchain system. It combines features of blockchain technology and approaches of traditional risk management. This designed architecture could be a primary prototype for deploying blockchain into regulated industries, where legal requirements are priority to business processes.
3. Given constructed cost-and-risk structure and designed blockchain architecture, we build a blockchain adoption model. The optimal timing, business shifting, investment, adjustment and pricing strategies are derived through system organizer's and users' optimization. The model provides a planning methodology for blockchain adoption.
4. Overall, this paper provides an integrated analysis, design and planning framework for blockchain adoption in the carbon trade and other industries.

This paper is arranged in the following manner: Section 2 reviews the related literature; Section 3 conducts cost and risk analysis of deploying blockchain to CAT; system design considerations and a hybrid blockchain-based CAT system are proposed in Section 4; adoption models of system organizer and users are constructed in Section 5; the optimal adoption trajectory and strategies are derived in Section 6; Section 7 concludes.

2. Related Literature

Most of research on blockchain focus on technical challenges and improvements [1–3], cryptocurrencies and related economic and legal issues [4–7], smart contracts [8–10], design of consensus protocols [11–13], and application of blockchain in different industries. Recently, there has been a surge of discovery on how blockchain could impact supply chains [14], healthcare [15,16], energy [17,18], payment [19], insurance [20,21], security [22–26], transportation [27], intellectual property [28], privacy protection [29,30], contract management [31,32] and more. Blockchain has also been proposed to be combined with other technologies, such as Internet of Things [33], big data [34], machine learning [35], and artificial intelligence [36]. Blockchain is even believed by technology enthusiasts to be an innovation as disruptive and transformative as the Internet has been [37–40].

Despite the extensive work exploring the application of blockchain technology to different industries and businesses, there is limited research on risks associated with blockchain deployment and its implications for system design. Studies related to blockchain risks mainly focused on cryptocurrencies [41,42] and technical risks [43,44]. Several articles [45–47] discussed implementation and design considerations of blockchain technology, including interoperability, cost, performance, security, confidentiality, operational capacity, regulatory and governance issues. Some researchers [48,49] analyzed blockchain adoption from a macro perspective of technology acceptance and innovation diffusion.

There is limited research on applying blockchain technology to carbon trade and energy certificates markets. Some early work focused on conceptualization and direct deployment of existed blockchain systems in emission trading. In [50], an anonymous Bitcoin-based emission trading system and five functions of it were conceptualized. Based on that work, a decentralized carbon emissions trading infrastructure (D-CEIT) was designed and compared to current carbon trading systems in [51]. SolarCoin was introduced in [52]. It is a blockchain system where solar electricity generation is rewarded with electricity-backed cryptocurrency and traded through the transparent consensus ledger. It is demonstrated that a 99% reduction of electricity usage could be realized through substituting the Proof of Work (PoW) with the Proof of Stake Time (PoST) consensus protocol. Robert Leonhard [53] focused on voluntary personal carbon trading systems and proposed a hypothetical carbon market on blockchain where individuals conducting emission reduction activities are issued with carbon credits by virtual associations comprised of climate scientists. Another conceptual model [54] is a smart contract-based carbon market, where companies voluntarily offset their emissions by funding carbon-offset projects vetted by universities. It identified some issues of blockchain-based carbon markets, including administrative costs, verification costs, legal liability, insider trading, tokens as securities, and cryptocurrency price volatility. The networking of carbon trading systems of different jurisdictions and the institutional framework was studied in [55], in which the "transaction unit" performs as the medium of inter-jurisdictions exchange.

Another direction is on experiments and case studies of blockchain application in carbon trading. In [56], the use of blockchain technology for peer to peer energy-based credits transactions was explored. By conducting an experiment on a microgrid of several solar energy-powered buildings within an eco-district of France, authors concluded that in spite of the distributed nature of blockchain, many real-world scenarios require a permission role, who is in charge of ensuring clear separation of duties and enforcing Chinese walls. The permission role can be managed by a central authority or system operators, consistent with the feature of consortium blockchain. In [57], the immutability and transparency of blockchain were utilized for building a reputation system to address management and fraud issues of the emission trading scheme (ETS). A case study was conducted on Multichain, an open blockchain platform and the proposed system is evaluated against conventional ETS. Some benefits of blockchain were concluded: transparency forces participants to conduct themselves in a responsible and accountable manner; information credibility helps in the monitoring and verification of credits source and ownership then protects the system from fraud and double counting issues; a certain level of privacy can be sustained. Drawbacks include redundant storage and possible resistance of the transition from participants. Two cases of applying blockchain technology to certificates trading were analyzed in [58]. It identified several benefits of introducing blockchain, including lower transaction cost, increased reliability, transparency and security.

Most of these research concerns benefits of blockchain for carbon trading, while studies about constraints and risks are rare, except for [59], which identified the administrative costs, unit quality and information asymmetry, and governance of mitigation commitments as the main constrains of Kyoto Protocol, where blockchain technology can play a role for improvement in Paris Agreement.

They proposed some requirements and factors for integration of blockchain technology, including number of users, system throughput, security and privacy. To the best of our knowledge, analysis of potential risks and its implications for design considerations and adoption planning are yet to be fully explored in the area of blockchain application.

3. Cost and Risk Analysis of Blockchain Integration in CAT

In this section, we analyze how blockchain technology could transform the cost and risk structure of CATs. Issues of current CATs and how blockchain could mitigate them are analyzed and summarized in Table 1.

Table 1. Problems of current cap and trade schemes (CATs) and blockchain's potential

Problems of Current CATs	Blockchain's Potential
The implementation, including credits registration, transaction settlement, emission verification and compliance inspection, requires complex administration and extensive manual intervention.	Transactions are automatically processed on blockchain according to pre-defined protocols. If connected to IoT devices and production management systems, blockchain can access real-time emission data and would be able to automate carbon accounting process. Both could significantly improve the efficiency and reduce the administration cost. On the other hand, blockchain suffers from the scalability problem with the increase of transactions, which puts upward pressure on the transaction cost.
The monitoring, reporting and verification (MRV) mechanism in CATs is not only cumbersome but also vulnerable to fraud claims [60,61] and double accounting problems. The hidden data also raise trust issues among participants.	Blockchain prevents double accounting and fraud claims to a certain extent, by providing an immutable and auditable record.
A centralized registration agency is susceptible to hacking and corruption [62].	Blockchain avoids one point failure and improves the security through information and verification decentralization. If appropriately designed, privacy and transparency can be controlled flexibly, constructing trust among regulated companies and making the system more attractive to them.
Many CAT schemes lack an effective punishment mechanism or it is poorly executed, diminishing the effectiveness of carbon markets [63].	As smart contracts on blockchain are automatically executed, rules of CATs can be encoded in the algorithm and punishment can be enforced, ensuring the effectiveness and authority of the trading scheme.
Regional carbon markets are operated in more than 50 jurisdictions. Information silos are exploited for value added tax fraud [64] and carbon leakage [65,66].	Cross-chain technology of blockchain provides opportunity for networking of carbon markets of different nations and regions or of different types of credits.

Despite the benefits that blockchain brings to emission trading scheme, myriad risks raise accordingly, especially in the nascent stage of blockchain technology. New risks associated with incorporation of blockchain include:

1. Legal risk
   Blockchain protocols might be inobservant to legislations and regulations; the property right of carbon credits on a blockchain need further legal enforcement; without a central authority, the legal liability of improper and erroneous operation of blockchain remains unclear; there are potentially illicit activities on blockchains, such as money laundering.

2. Technical risk
   Technical challenges, such as large-scale communication, big data storage, and imperfect encryption technologies hinders the performance of blockchain.
3. Protocol risk
   The implementation of arrangements of CAT programs relies on predefined blockchain protocols. All the terms and conditions of the cap-and-trade scheme should be applied and enforced consistently by the protocol. Any error in the protocol may get the system off the track or even against the initial purpose of the program. Carelessly designed protocols also incur problems of scalability, security and data integrity.
4. Cyber risk
   Insufficient encryptions are at risk from hackers; outside oracles-smart devices and production softwares are vulnerable to malicious attacks and malfunctions, resulting in corrupted data fed into the blockchain; the key pairs representing identities on blockchain can be stolen or destroyed.
5. Privacy risk
   If automatic carbon accounting is conducted, commercially sensitive data, such as production and operation data, are stored on blockchain, which impose information leakage risk.
6. Validation risk
   Risk of consortium blockchains can be incurred by wrongly selected malicious validation peers.
7. Market risk
   As a newborn technology, blockchain may be subject to resistance from users. Insufficient transactions on blockchain would harm the market liquidity.

The cost-and-risk structures of current CAT and blockchain-based CAT are summarized in Figure 1. The main costs and risks of a traditional CAT are listed in the second column. The changes of the costs and risks caused by the introduction of blockchain are listed in the third column. Blockchain offers an opportunity to reduce the administration cost of traditional carbon CATs, which is signaled by the small green arrow in Figure 1. Whereas, the transaction cost may be scaled up along with the increase of transactions, due to the scalability limit of blockchain. In Figure 1, the yellow arrow signifies possible higher transaction cost of a blockchain-based CAT, if the scalability issues is not appropriately handled. The larger green arrow in Figure 1 means the listed risks of traditional CAT systems, including the fraud, collusion, cyber attack, inefficacy and carbon leakage risks, can be mitigated by blockchain technology. However, blockchain introduces new risks, including the legal, technical, protocol, cyber, privacy, validation and market risks. The red arrow in Figure 1 means the increase of these risks. In summary, a blockchain-based CAT, compared to a traditional CAT, has lower administration cost, possibly higher transaction cost, lower traditional risks, and higher new risks.

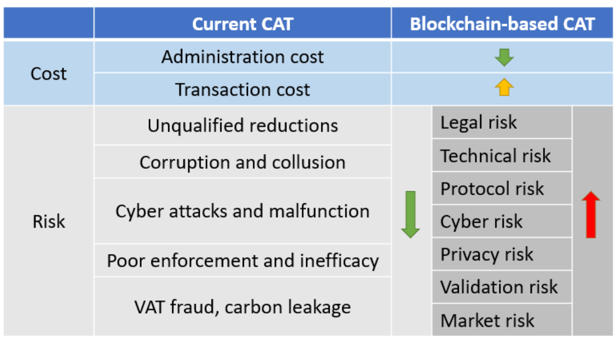

Figure 1. Cost and risk structure of current and blockchain-based CATs.

4. Architecture Design for a Hybrid Blockchain System

Considering the transformed risk structure, we propose design requirements of a blockchain-based CAT system, and design the organizational architecture and main functionalities for the system.

4.1. Design Requirements

1. Risk management
   Based on the risk analysis in Section 3, risks of the blockchain-based system should be effectively controlled to guarantee the correct implementation of CATs. In centralized systems, intermediaries typically take on the risks, while on blockchain, risk management relies on predefined protocols. Unfortunately, not all the risks can be predicted and a flawless protocol does not exist. Blockchain technology itself at this stage is not able to handle exceptions. Therefore, a responsible party is needed to manage risks and to serve as the last resort.
2. Blockchain protocol
   The blockchain system essentially provides transaction service to carbon traders. System performance, including throughput, latency and scalability should be acceptable to users. These properties are determined by the consensus protocol to a large extent. Therefore, the protocol should be able to facilitate a large number of transactions with a low latency. In addition, the protocol should be energy-efficient, as the purpose of carbon cap-and-trade schemes is to reduce emissions and to address climate change. Therefore, the proof of work (PoW) protocol used by Bitcoin and many blockchains is not suitable. More efficient protocols, such as practical Byzantine fault tolerance (pBFT) and Ripple protocols are possible options.
3. Identity management
   A trading system should conform to applicable laws and regulations, such as the anti-money laundering (AML) and know-your-customer (KYC) legislation. Besides, credits allocation and compliance verification also require known identities of participants. Hence participants' identities should be registered on the blockchain system, and kept invisible to other traders, unless the user reveals it on purpose.

4.2. Organizational Architecture

According to the requirements of identity management and risk control in carbon trading, a certain degree of central control, monitoring and safeguarding are necessary for the blockchain-based system. Therefore, a hybrid system combining the features of blockchain technology and institutional risk control would be appropriate. We design the three-tier organizational architecture for the hybrid blockchain system, as shown in Figure 2. With this structure, the immutability and reliability of blockchain technology are retained and risks are under control. There are three roles in this architecture:

- Organizer: an overriding committee, takes charge of authorization, access control, audit, supervision, disputes settlement, and safeguard, but does not intervene the normal operation of the system. The committee consists of regulators, institutions and other appropriate members. It is an added layer to a typical blockchain for risk management.
- Validators: verify transactions and maintain the blockchain ledger, providing service to carbon traders. Validators are elected by participants of the carbon CAT program, and can include academic institutions, non-governmental organizations (NGOs) and other professional agencies. They collectively verify data under the witness of all participants. If any validator conducts improper activities, it can be removed from the validation group through the majority vote by participants.
- Users: carbon traders are system users as well as witnesses of the commitment, compliance, and punishment execution on the system.

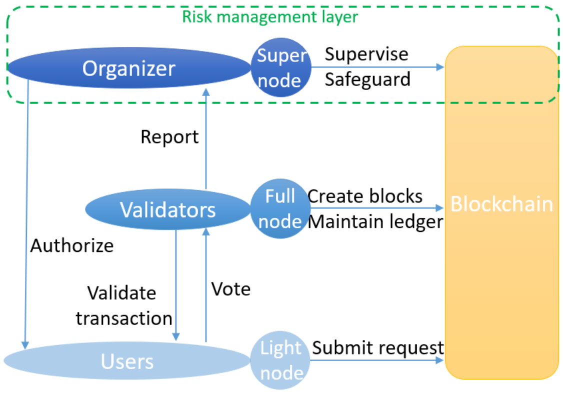

Figure 2. An overview of the organizational architecture.

4.3. Main Functionalities

Primary functionalities of a blockchain-based carbon trading system include:

1. User registration: The organizer validates identities and authorizes participants. A pair of keys (public key and private key) is assigned to an authorized user for accessing the system.
2. Initial allocation or auction: The organizer node broadcasts the emission cap of each participant, which is then recorded on the blockchain. Each participant can use her private key to decrypt the message and get the cap. The allocated or auctioned carbon credits are transferred from the organizer node to each user node.
3. Registration of certified emission reductions (CERs): Each emission reduction project is registered on the blockchain with a unique ID and all the related information for identification. GPS and satellites could be utilized as oracles for monitoring and inspecting projects. Blockchain provides a traceable and auditable record of emission reduction projects.
4. Transaction: The validation nodes are full nodes on the blockchain, storing complete blockchain ledger. They process and record transactions collectively. User nodes, as light nodes, do not need to store the ledger and can request information from validation nodes.
5. Emission accounting: Automatic emission accounting can be realized through outside oracles, such as IoT devices and production management systems, which connect to and upload emission-related data on blockchain.
6. Commitment enforcement: At the end of each compliance period, user nodes transfer their credits to the organizer node for commitment. Validation nodes examine the amount of committed credits according to the recorded cap, and execute pre-defined punishment.

5. Modelling of Blockchain Adoption in CATs

In this section, we model the adoption of the hybrid blockchain system proposed in Figure 2, from the perspectives of the organizer and of individual users (participating companies). The modelled scenario is as following:

Existing centralized carbon trading system is the legacy system and still operates. The organizer can develop and provide a blockchain-based carbon trading system to individuals. According to the cost-and-risk structures of traditional and blockchain-based CATs in Section 3, the legacy and the blockchain systems have different costs and risks. Each individual can decide the amount of transactions to put on each system. The organizer can impact individuals' decisions through pricing two systems.

5.1. Individuals' Model

Intuition: Individual users have carbon management goals and certain transaction demands to meet their goals. Facing two options—the legacy system and the blockchain system, individuals allocate their transactions on two systems. Both systems have registration fees and transactions fees, which are determined by the organizer and are known to individuals. The legacy system has been operated for a long time, so it is stable and predictable. The blockchain system offers potential benefits of lower transaction cost and risk, while it's a newborn technology and people are not familiar with it. The market risk, particularly liquidity risk of the blockchain system might be high, if users hesitate to migrate onto it. Therefore, there is extra perceived risk of the blockchain system, dominated by the herd effect—individuals feel that the blockchain system is safer and more acceptable if more transactions are put on it.

At each period t during a fixed time horizon $[1, T]$, individuals' model is shown in Figure 3. The model is explained in the following:

- **Conditions**: Each individual i has a known transaction demand d_{it}. Registration and transaction fees of the legacy and blockchain systems, L_t^r, L_t^s, P_t^r and P_t^s are given by the organizer. The risk of the legacy system, r_1 is stable, including uncertainty due to verification and lack of transparency. The systematic risk of the blockchain system, $r_2(t)$ can be reduced overtime, and is known to individuals. The extra perceived risk of the blockchain system, r_p can be mitigated if more transactions are put on it. The resulted perceived risk is measured by $\frac{r_p}{y_t}$, where y_t is the total amount of transactions on the blockchain system.
- **Decisions**: An individual i allocates its transactions on the legacy system and the blockchain system with amount of x_{it} and y_{it}, respectively.

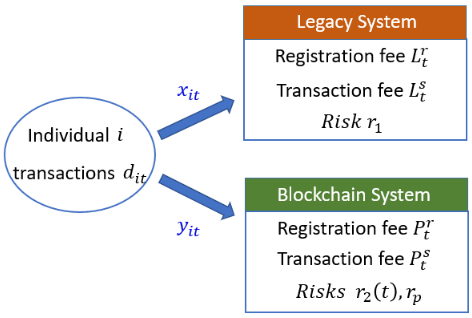

Figure 3. Individuals' model.

Table 2 list parameters and variables of individuals' model.

Table 2. Notations of variables and parameters of individuals' model

Notations	Meaning
m_t	Number of individuals in carbon market at period t.
d_{it}	The transaction demand of individual i at period t. It is assumed non-decreasing over time t.
Decision variables	
x_{it}	Amount of transactions that individual i put on the legacy system.
y_{it}	Amount of transactions that individual i put on the blockchain system.
Legacy system	
L_t^r	Registration fee of the legacy system at period t, given by the organizer.
L_t^s	Transaction fee of the legacy system at period t, given by the organizer.
r_1	Risk of the legacy system.
Blockchain system	
P_t^r	Registration fee of the blockchain system at period t, given by the organizer.
P_t^s	Transaction fee of the blockchain system at period t, given by the organizer.
$r_2(t)$	The systematic risk of the blockchain system.
r_p	Basic perceived risk of the blockchain system, can be mitigated by more transactions to $\frac{r_p}{y_t}$.

5.2. Individual Optimization

At each period t during a fixed time horizon $[1, T]$, with transaction demand d_{it}, individual i allocates amount of transactions x_{it} and y_{it}, respectively, on the legacy and the blockchain systems. Individual i's total cost H_{it} includes registration and transaction fees it needs to pay for two systems. Its total risk R_{it} includes the risk of the leagcy system $x_{it}^2 r_1$, the systematci risk of the blockchain system $y_{it}^2 r_2(t)$, and the perceived risk of the blockchain system $y_{it}\frac{r_p}{y_t}$. Individual i's disutility G_{it} is the summation of total cost and total risk. The cost function, risk function and disutility function of period t are defined in Equations (1).

$$
\begin{aligned}
H_{it}(x_{it}, y_{it}) &= L_t^r 1_{\{x_{it}>0\}} + L_t^s x_{it} + P_t^r 1_{\{y_{it}>0\}} + P_t^s y_{it} \\
R_{it}(x_{it}, y_{it}) &= x_{it}^2 r_1 + y_{it}^2 r_2(t) + y_{it}\frac{r_p}{y_t} \\
G_{it}(x_{it}, y_{it}) &= H_i(x_{it}, y_{it}) + R_i(x_{it}, y_{it})
\end{aligned} \tag{1}
$$

At period t, individual i's optimization problem is to minimize its total disutility by allocating transactions on the legacy and the blockchain systems. Mathematically, the optimization problem of each individual can be written as:

$$
\begin{aligned}
\min_{x_{it}, y_{it}} G_{it} = L_t^r 1_{\{x_{it}>0\}} + L_t^s x_{it} + P_t^r 1_{\{y_{it}>0\}} + P_t^s y_{it} + x_{it}^2 r_1 + y_{it}^2 r_2(t) + y_{it}\frac{r_p}{y_t} \\
\text{s.t.} \quad x_{it}, y_{it} \geq 0 \\
x_{it} + y_{it} \geq d_{it}
\end{aligned} \tag{2}
$$

Proposition 1. *At each period t, there is a Nash Equilibrium of individuals' behavior, given by $(y_{1t}^*, \ldots, y_{m_t t}^*)$: $y_{it}^* = \frac{(2r_1 d_{it} + L_t^s - P_t^s) y_t^{*2} - y_t^* r_p}{2(r_1 + r_2(t)) y_t^{*2} - r_p}$. The equilibrium total transaction amount on the blockchain system is $y_t^* = \frac{2r_1 d_t + m_t(L_t^s - P_t^s) + \sqrt{[2r_1 d_t + m_t(L_t^s - P_t^s)]^2 - 8r_p(m_t - 1)(r_1 + r_2(t))}}{4(r_1 + r_2(t))}$. Required conditions for the Nash Equilibrium are: (1) Existence of y_t^*; (2) Feasibility of y_{it}^*: $0 < y_{it}^* < d_{it}$; and (3) Optimality of y_{it}^*: $G_{it}(y_{it}^*) < \min(G_{it}(0), G_{it}(d_{it}))$.*

The derivation of Proposition 1 is shown in Appendix A. The required conditions are expressed explicitly in Equations (A5)–(A7) in Appendix A.

The equilibrium total transaction amount on the blockchain system y_t^* is resulted from the interactions among traders. However, it stays unaffected by individuals' decisions, instead, it is determined by the total transaction demand d_t, number of traders m_t, the risks $r_1, r_2(t), r_p$ and the transaction fee difference $L_t^s - P_t^s$ of two systems. More transactions will be put on the blockchain system, with a higher demand, or a higher price advantage of the blockchain system.

Under the equilibrium situation, trader i puts the amount of $y_{it}^* = \frac{(2r_1 d_{it} + L_t^s - P_t^s) y_t^{*2} - y_t^* r_p}{2(r_1 + r_2(t)) y_t^{*2} - r_p}$ transactions on the blockchain system. User i would put more transactions on the blockchain system, with a higher demand d_{it}, the price advantage of the blockchain system $L_t^s - P_t^s$, or the total transaction amount on the blockchain y_t^*. On the contrary, a higher fundamental perceived risk of the blockchain system r_p would reduce their preference for the blockchain system.

5.3. Organizer's Model

Intuition: The legacy system has steady operation cost and risk. The organizer needs to determine the time and investment for developing a blockchain-based carbon trading system. The average operation cost of the blockchain system scales up with the increase of transactions, due to the inherent replication feature and the scalability limit of blockchain technology. Risks of the blockchain system are classified as systematic risk and controllable risk. Controllable risk includes design risk and validation risk. Design risk is raised up by imperfect system configurations, regarding the consensus protocol, cyber security and privacy. Validation risk comes from the validation group of a consortium blockchain.

Once the blockchain system is built, the organizer can invest in system update and infrastructure improvement. Updating the system lowers the average operation cost and the design risk. Based on the hybrid architecture designed in Section 4, transactions are processed by a collective of validation nodes. the organizer pays for the setup of the validation group, which impacts the validation risk. Given total transaction demand of all individuals, the organizer optimizes transaction amount on the legacy and the blockchain systems.

An overview of the organizer's model at period t of the time horizon $[1, T]$ is shown in Figure 4. The model is explained in the following:

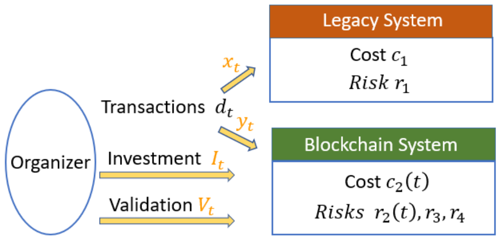

Figure 4. Organizer's model.

Conditions:

- The legacy system: c_1 is the average operational cost, including credits registration, transaction processing and clearing, and compliance validation; r_1 is the risk imposed by the fraud, collusion, cyber attack and other issues of the centralized system.
- The blockchain system: $c_2(t)$ is the fundamental cost that remains unchanged unless exogenous technology breakthrough occur; $r_2(t)$ is the systematic risk, including regulatory and technical risk, which can only be mitigated by exogenous legislation improvement and technology innovation; r_3 is the basic design risk, which can be reduced by sound system design and infrastructure improvement; r_4 is the basic validation risk, which can be reduced by a better validation configuration.
- Individuals' demand: d_t is the total transaction demand of all individuals. $d_t = \sum_{i=1}^{m_t} d_{it}$

Decisions:

- Organizer decides the investment I_t for system update, including blockchain redesign and infrastructure (communication and computation) improvement. The effect of investment accumulates and mitigates the design risk r_3 to $\frac{r_3}{\sum_{j=1}^{t} I_j}$.
- Organizer decides to spend V_t for validation setup, which mitigates the validation risk r_4 to $\frac{r_4}{V_t}$.
- x_t is the total transaction amount on the legacy system.
- y_t is the total transaction amount on the blockchain system.

Intermediate variables:

- C_t is the average operational cost of the blockchain system at period t. It includes cost of processing registration, and transaction clearing and settlement. To reflect the scalability issue of blockchain with the increase of transactions, we adopt a linear function of the fundamental cost $c_2(t)$ and transaction amount y_t to measure the average operational cost: $C_t = c_2(t) + \frac{1}{\sum_{j=1}^{t} I_j} y_t$. The slope is reciprocal to total investment on the blockchain system, since system and infrastructure improvement could mitigate the scalability issue.
- R_t is the average comprehensive risk of the blockchain system at period t. $R_t = r_2(t) + \frac{r_3}{\sum_{j=1}^{t} I_j} + \frac{r_4}{V_t}$. It is the summation of the systemic risk $r_2(t)$, the design risk $\frac{r_3}{\sum_{j=1}^{t} I_j}$, and the validation risk $\frac{r_4}{V_t}$.

Table 3 summarizes parameters and variables of the organizer's model.

Table 3. Notations of variables and parameters of the organizer's model.

Notations	Meaning
δ	A discount factor between periods. $0 < \delta < 1$.
d_t	Total transaction demand of all traders at period t.
Legacy system	
c_1	Average operational cost of the legacy system.
r_1	Risk of the legacy system.
Blockchain system	
$c_2(t)$	The fundamental operational cost of the blockchain system at period t. Non-increasing over time.
$r_2(t)$	The systematic risk of the blockchain system at period t. Non-increasing over time.
r_3	The basic design risk of the blockchain system.
r_4	The basic validation risk of the blockchain system.
Decision variables	
x_t	Amount of transactions on the legacy system at period t.
y_t	Amount of transactions on the blockchain system at period t.
I_t	Investment on blockchain system update at period t.
V_t	Investment on validation setup at period t.
Intermediate variables	
C_t	Average operational cost of the blockchain system at period t. $C_t = c_2(t) + \frac{1}{\sum_{j=1}^{t} I_j} y_t$.
R_t	Average comprehensive risk of the blockchain system at period t. $R_t = r_2(t) + \frac{r_3}{\sum_{j=1}^{t} I_j} + \frac{r_4}{V_t}$

5.4. Social Optimization

The optimization problem of the organizer is to minimize total cost and risk of two systems within a fixed period $[1, T]$. At each period t ($1 \le t \le T$):

The organizer determines investment I_t on system update and V_t on verification setup. Given total transaction demand d_t, the organizer decides the amount of transactions should be put on the legacy and blockchain system, x_t and y_t. The total cost H_t includes the investment on update I_t and on validation setup V_t and operational cost $c_1 x_t + C_t y_t$ of two systems. The total risk Q_t includes the risk of the legacy system $r_1 x_t^2$ and the risk of the blockchain system $R_t y_t^2$. Social disutility S_t is the summation of total cost and total risk. Organizer's cost function H_t, risk function Q_t and disutility function S_t at period t, and total disutility S of the optimization horizon $[1, T]$ are defined in Equations (3).

$$
\begin{aligned}
&H_t(x_t, y_t, I_t, V_t) = c_1 x_t + I_t + V_t + C_t y_t = c_1 x_t + I_t + V_t + (c_2(t) + \frac{1}{\sum_{j=1}^{t} I_j} y_t) y_t \\
&Q_t(x_t, y_t, I_t, V_t) = r_1 x_t^2 + R_t y_t^2 = r_1 x_t^2 + (r_2(t) + \frac{r_3}{\sum_{j=1}^{t} I_j} + \frac{r_4}{V_t}) y_t^2 \\
&S_t(x_t, y_t, I_t, V_t) = H_t + Q_t \\
&S(x_1, \dots x_T, y_1, \dots y_T, I_1, \dots I_T, V_1, \dots V_T) = \sum_{t=1}^{T} \delta^t S_t(x_t, y_t, I_t, V_t)
\end{aligned} \tag{3}
$$

Mathematically, the optimization problem of the organizer is written as:

$$
\begin{aligned}
\min_{x_t, y_t, I_t, V_t} S = \sum_{t=1}^{T} \delta^t [c_1 x_t + I_t + V_t + y_t (c_2(t) + \frac{1}{\sum_{j=1}^{t} I_j} y_t) + r_1 x_t^2 + (r_2(t) + \frac{r_3}{\sum_{j=1}^{t} I_j} + \frac{r_4}{V_t}) y_t^2] \\
\text{s.t.} \quad x_t, y_t, I_t, V_t \ge 0 \\
x_t + y_t \ge d_t \qquad \text{for all } t.
\end{aligned} \tag{4}
$$

This is a multistage optimization problem. Assume that the optimal strategy is conducted in all periods, it can be solved backward from $t = T$ to $t = 1$, as shown in Appendix B.1. The solution is:

For $1 < t < T$,

$$M_t = c_1 - (c_2(t) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1})$$

$$y_t^* = \begin{cases} 0 & 0 < d_t < -\frac{M_t}{2r_1}, M_t < 0 \\ \frac{2r_1 d_t + M_t}{2(r_1+r_2(t))} & d_t \geq max(-\frac{M_t}{2r_1}, \frac{M_t}{2r_2(t)}) \\ d_t & 0 < d_t < \frac{M_t}{2r_2(t)}, M_t > 0 \end{cases}$$

$$I_t^* = \sqrt{\frac{r_3+1}{1-\delta}} y_t^* - \sum_{j=1}^{t-1} I_j = \sqrt{\frac{r_3+1}{1-\delta}}(y_t^* - y_{t-1}^*)$$

$$V_t^* = \sqrt{r_4} y_t^*$$

For $t = T$,

$$M_T = c_1 - (c_2(T) + 2\sqrt{r_4} + 2\sqrt{r_3+1})$$

$$y_T^* = \begin{cases} 0 & 0 < d_T < -\frac{M_T}{2r_1}, M_T < 0 \\ \frac{2r_1 d_T + M_T}{2(r_1+r_2(T))} & d_T \geq max(-\frac{M_T}{2r_1}, \frac{M_T}{2r_2(T)}) \\ d_T & 0 < d_T < \frac{M_T}{2r_2(T)}, M_T > 0 \end{cases}$$

$$I_T^* = \sqrt{r_3+1} y_T^* - \sum_{j=1}^{T-1} I_j = \sqrt{r_3+1}(y_T^* - \frac{y_{T-1}^*}{\sqrt{1-\delta}})$$

$$V_T^* = \sqrt{r_4} y_T^*$$

In the optimal solution, we define an intermediate parameter M_t, as in Equation (5). M_t captures the difference between the cost of the legacy system and the overall fundamental cost and controllable risk of the blockchain system. Therefore, M_t reflects the relative advantage of the blockchain system.

$$M_t = \begin{cases} c_1 - (c_2(t) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1}) & 1 \leq t < T \\ c_1 - (c_2(t) + 2\sqrt{r_4} + 2\sqrt{r_3+1}) & t = T \end{cases} \quad (5)$$

6. Adoption and Pricing Strategies

6.1. Adoption Trajectory and Market Capacity

Basing on solutions to social optimization of each period in previous section, we can plot the optimal strategy for adopting blockchain technology:

(1) From $t = 1$ to $t = t^* - 1$, if $M_t = c_1 - (c_2(t) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1}) < 0$ and $d_t \leq -\frac{M_t}{2r_1}$, the optimal solution is $y_t^* = 0$, $I_t^* = 0$, $V_t^* = 0$. During this period, the blockchain system should not be developed.

(2) The timing for blockchain deployment t^* satisfies $d_t > -\frac{M_t}{2r_1}$, equivalent to $2r_1 d_t + c_1 > c_2(t) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1}$. By assumption, $c_2(t)$ is non-increasing and d_t is non-decreasing, thus all $t > t^*$ satisfy the inequality, meaning the system will not be shut off once launched.

(3) From $t = t^*$ to $t = T - 1$, $M_t = c_1 - c_2(t) - 2\sqrt{r_4} - 2\sqrt{1-\delta}\sqrt{r_3+1}$,

$$y_t^* = \begin{cases} \frac{2r_1 d_t + M_t}{2(r_1+r_2(t))} & d_t \geq \frac{M_t}{2r_2(t)}, M_t > 0; d_t \geq -\frac{M_t}{2r_1}, M_t \leq 0 \\ d_t & 0 < d_t < \frac{M_t}{2r_2(t)}, M_t > 0 \end{cases}$$

$$I_t^* = \sqrt{\frac{r_3+1}{1-\delta}}(y_t^* - y_{t-1}^*)$$

$$V_t^* = \sqrt{r_4} y_t^*$$

(4) At the last period T, $M_T = c_1 - c_2(T) - 2\sqrt{r_4} - 2\sqrt{r_3+1}$, with feasibility assumptions (A22) in Appendix B.2,

$$y_T^* = \begin{cases} \frac{2r_1 d_T + M_T}{2(r_1 + r_2(T))} & d_T \geq \frac{M_T}{r_2(T)} \\ d_T & d_T < \frac{M_T}{r_2(T)} \end{cases}$$

$$I_T^* = \sqrt{r_3+1}(y_T^* - \frac{y_{T-1}^*}{\sqrt{1-\delta}})$$

$$V_T^* = \sqrt{r_4} y_T^*$$

From step (2) of this optimal adoption trajectory, Proposition 2 can be derived. It indicates that the timing for blockchain adoption depends on the transaction demand and the relative advantage of the blockchain system. The transaction demand d_{t^*} and cost advantage of blockchain $c_1 - c_2(t^*)$ should be large enough relative to the risks, r_3 and r_4 of the blockchain system.

Proposition 2. *Under the assumptions that $c_2(t)$ is non-increasing, and that d_t is non-decreasing, the optimal time t^* that the blockchain system should be developed satisfies: (1) $2r_1 d_{t^*-1} + c_1 \leq c_2(t^*-1) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1}$, and (2) $2r_1 d_{t^*} + c_1 > c_2(t^*) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1}$.*

Proposition 3. *The optimal adoption strategy is to keep the average operational cost and the overall controllable risk of the blockchain system unchanged by updating the system and setting up validation adaptively.*

Proof of Proposition 3. With the optimal adoption strategy in step (3), average operational cost of the blockchain system, including transaction cost and verification cost, $C_t + \frac{V_t^*}{y_t^*} = c_2(t) + \frac{y_t^*}{\sum_{j=1}^t I_j^*} + \sqrt{r_4} = c_2(t) + \sqrt{\frac{1-\delta}{1+r_3}} + \sqrt{r_4}$ is kept constant by investment and setting up verifiers unless technological innovations occur. In each period, the organizer should invest in system update at the scale in proportional to the increment of transaction on the blockchain system and set up verifiers in proportional to the expected transaction amount of this period, which in turns eliminates the increase impetus of average transaction cost triggered by the increase of transaction. Total controllable risk, including cyber risk and operation risk, $(\frac{r_3}{\sum_{j=1}^t I_j^*} + \frac{r_4}{V_t^*}) y_t^{*2} = r_3\sqrt{\frac{1-\delta}{r_3+1}} + \sqrt{r_4}$ is also managed to remain unchanged by system update and validation setup. □

Proposition 4. *The capacity of the blockchain system is the maximum amount of transactions that should be put on the blockchain system under the optimal situation and current technology conditions. If the amount of transactions on the blockchain exceeds that capacity, the social optimality can not be reached. The capacity of the blockchain system is measured by $\frac{c_1 - c_2(t) - 2\sqrt{r_4} - 2\sqrt{1-\delta}\sqrt{r_3+1}}{2r_2(t)}$. When the blockchain system is cost-effective and safe ($c_2(t), r_2(t), r_3$, and r_4 are small enough), the capacity would be larger than the transaction demand d_t. That is the time that the legacy system could be abolished and completely replaced by the blockchain system.*

Proof of Proposition 4. When the relative advantage of blockchain $M_t = c_1 - (c_2(t) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1}) > 0$, the optimal amount on the blockchain:

$$y_t^* = \begin{cases} \frac{2r_1 d_t + M_t}{2(r_1 + r_2(t))} & d_t \geq \frac{M_t}{2r_2(t)} \\ d_t & 0 < d_t < \frac{M_t}{2r_2(t)} \end{cases}$$

The threshold is $\frac{M_t}{2r_2(t)} = \frac{c_1 - (c_2(t) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1})}{2r_2(t)}$. If $d_t < \frac{c_1 - (c_2(t) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1})}{2r_2(t)}$, all the transactions should be put on the blockchain system. While if $d_t \geq \frac{c_1 - (c_2(t) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1})}{2r_2(t)}$, $\frac{2r_1 d_t + c_1 - 2c_2(t) - 2\sqrt{r_4} - 2\sqrt{1-\delta}\sqrt{r_3+1}}{2(r_1 + r_2(t))}$ transactions should be put on the blockchain system and the rest $\frac{2r_2(t) d_t - 2c_1 + 2c_2(t) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1}}{2(r_1 + r_2(t))}$ should be put on the legacy system. Therefore, the blockchain system capacity can be denoted by the threshold $\frac{c_1 - (c_2(t) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1})}{2r_2(t)}$. It increases with cost difference $(c_1 - c_2(t))$ and decreases with risk of the blockchain system $r_2(t)$. If at some time t' that the blockchain system is cheap and safe($c_2(t)$ and $r_2(t)$ are small enough), such that $d_t < \frac{M_t}{2r_2(t)}$ holds for all $t > t'$, the legacy system can be abolished and completely replaced by the blockchain system. □

6.2. A Case Study of the Optimal Adoption Trajectory

A numerical case study of the adoption trajectory is conducted. Values of parameters and exogenous variables of the model are set according to Table 4. The setting conforms to model assumptions that c_2 and r_2 are non-increasing and d_t is non-decreasing.

Table 4. Values settings of parameters and exogenous variables

Parameters/Variables	Value
t	15
r_1	0.15
r_3, r_4	0.25
δ	0.6875
c_1	41.5
$c2$	[50, 50, 40, 40, 32, 32, 32, 25, 25, 25, 18, 18, 17, 17, 16]
$r2$	[0.25, 0.25, 0.25, 0.2, 0.2, 0.2, 0.16, 0.15, 0.15, 0.15, 0.14, 0.13, 0.11, 0.11, 0.11]
dt	[20, 20, 30, 38, 38, 44, 44, 45, 50, 60, 61, 62, 63, 65, 65]

Figure 5 displays dynamics of exogenous situations and corresponding optimal strategies. Exogenous variables, blockchain technology cost and risk c_2, r_2 are in blue and transaction demand d_t is in yellow. Intermediate variables M_t and blockchain system capacity y'_t are shown in green. Solutions of decision variables, optimal amount on the blockchain system y^*_t, optimal investment for the blockchain system update I^*_t and optimal investment on validation configuration V^*_t are represented in red. Other variables under optimal condition, including average operational cost of the blockchain system C_t, total investment on blockchain $\sum_t I_t$, and total risk of the blockchain system $R_t y^*_t$, are shown in black.

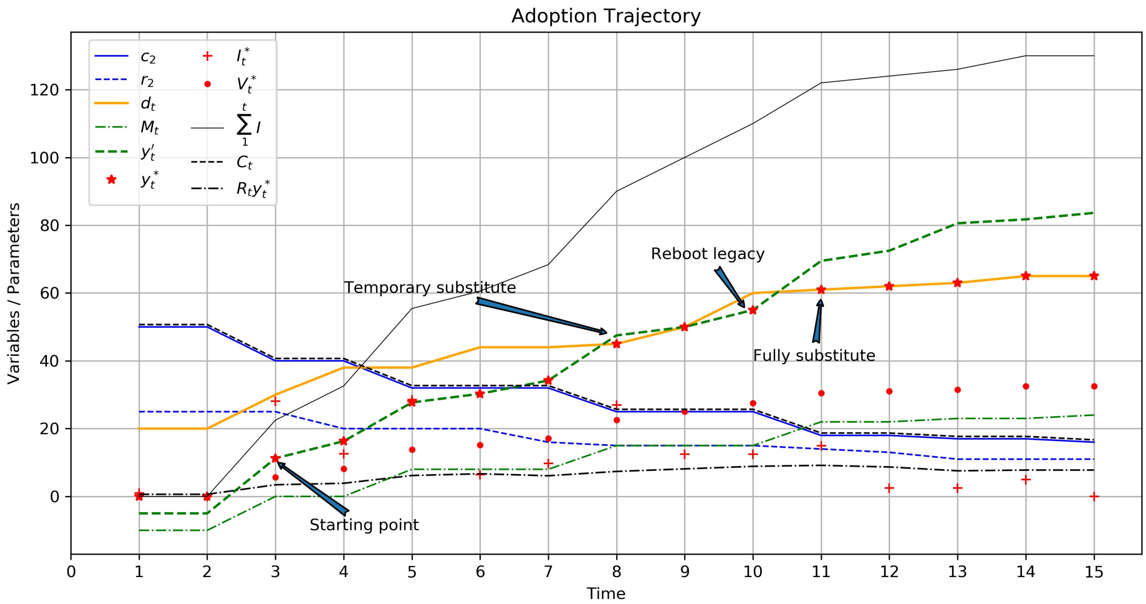

Figure 5. Adoption Trajectory.

From Figure 5, we can find following situations consistent with aforementioned Propositions: (1) From period 1 to 2, the optimal strategy is not developing the blockchain system and putting all transactions on the legacy system, due the high cost and risk of blockchain technology. (2) The blockchain system should be adopted at period 3, when the cost c_2 and risk r_2 of blockchain are mitigated and transaction demand d_t is relatively high. This is the point that the blockchain technology is worth to be deployed. (3) After the launch of the blockchain system, from period 3 to period 7 transactions are allocated to both systems. The optimal amount on blockchain system y_t^* should not exceed its capacity y_t'. The capacity of the blockchain system increases with reducing cost and risk of blockchain technology. (4) At period 8 and 9, the capacity of the blockchain system overpasses the transaction demand, at which the legacy system should be idled but should not be abolished, in case a sudden increase in the transaction demand. (5) At period 10, the legacy system should be rebooted, since the transaction demand increases to be higher than the capacity of blockchain system. This reboot implies the necessity to retain the idling legacy system for several periods as a backup for the blockchain system. (6) After period 11, the blockchain technology is mature enough and the capacity of blockchain system is much higher than that of the transaction demand. The legacy system can be dissolved for cost saving. (7) the organizer should invest in system update and validation configuration in each period to improve the capacity of blockchain system for accommodating increasing transaction demand. The investment in update I_t^* is determined by the increase of transaction demand between two consecutive periods and the investment on validation V_t^* is determined by transaction demand of that period. (8) The average transaction cost on blockchain system C_t decreases with the reducing cost c_2 and risk r_2 of blockchain technology. The scalability issue of blockchain should be eliminated by updating the system, without impacting the average transaction cost on blockchain system. (9) Total risk of the blockchain system $R_t y_t^*$ is also mitigated by the investment on system update, as it is much more flat and steady than the increasing transaction amount y_t^* on the blockchain.

6.3. Adjustment during the Adoption

If the aforementioned optimal trajectory of adoption is not followed in the beginning or the estimates of some variables, such as d_t, $c_2(t)$ and $r_2(t)$, deviate from true values, the strategy should be adjusted during the adoption process. This forms a new optimization problem. Since the investment in the blockchain system before the adjustment-time, denoted as I_0 is sunk cost, it should not be considered in the new optimization problem. While it still impacts the transaction cost and risk of the blockchain system.

If at time $t = t_a$, the adjustment or re-planning is considered, the adjustment optimization problem is formulated as:

$$\begin{aligned} \min_{x_t,y_t,I_t,V_t} S = \sum_{t=t_a}^{T} \delta^{t-t_a}[c_1 x_t + I_t + V_t + y_t(c_2(t) + \frac{1}{I_0 + \sum_{j=t_a}^{t} I_j} y_t) + r_1 x_t^2 + (r_2(t) + \frac{r_3}{I_0 + \sum_{j=t_a}^{t} I_j} + \frac{r_4}{V_t}) y_t^2] \\ s.t. \quad x_t, y_t, I_t, V_t \geq 0 \\ x_t + y_t \geq d_t \qquad \text{for all } t. \end{aligned} \tag{6}$$

As the multistage adoption optimization problem is solved backward one period before another, the adjustment optimization problem can be considered as a portion of that problem from $t = T$ to $t = t_a$, given $I_0 = \sum_{t=1}^{t_a-1} I_t$. Therefore, the adjustment algorithm can be derived from the solution of adoption optimization:

1. Start with $t = T$, run adoption optimization, get y_t^* and calculate $\sqrt{\frac{r_3+1}{1-\delta} y_t^*} - I_0$.
2. If $\sqrt{\frac{r_3+1}{1-\delta} y_t^*} - I_0 > 0$, go backward one period to $t = t - 1$ and run (1) again.
3. If $\sqrt{\frac{r_3+1}{1-\delta} y_t^*} - I_0 \leq 0$, $t + 1$ is the re-investment point.

This derives Proposition 5.

Proposition 5. *The optimal re-investment point t_r satisfies $\sqrt{\frac{r_3+1}{1-\delta}}y^*_{t_r-1} \leq I_0$ and $\sqrt{\frac{r_3+1}{1-\delta}}y^*_{t_r} > I_0$.*

Before the optimal re-investment point, additional investment on the blockchain system is not needed since the existing investment is too large, deviating from the optimal value. After this point, more investment is required to improve the capacity of the blockchain system and to accommodate increasing demand. If $\sqrt{\frac{r_3+1}{1-\delta}}y^*_t > I_0$ holds for all adjustment periods $t \geq t_a$, it implies the previous investment in the blockchain system is smaller than the ideal value and additional investment is required immediately at the adjustment start time t_a.

The solution to adjustment optimization is shown in Appendix C. The adjustment algorithm provides a method for re-planning or correcting the adoption strategy. If the optimal trajectory is not followed previously or estimates of key features turn out to be inaccurate, this algorithm can be used to adjust adoption strategy accordingly.

6.4. Pricing

the organizer needs to decide the registration fee L^r_t and transaction fee L^s_t of the legacy system, and the registration fee P^r_t and transaction fee P^s_t of the blockchain system. In the period of $t < t^*$, the blockchain system should not be built, pricing is not considered.

Proposition 6. *Carbon traders' decisions are impacted by the difference of transaction fees of the legacy system and the blockchain system $L^r_t - P^r_t$. Through differentiated pricing, the organizer can guide individuals to behave in the social optimal manner.*

Proof of Proposition 6. Recall Proposition 1: under equilibrium conditions of individuals' optimization, total transaction amount on the blockchain system, y^*_t satisfies Equation (7). Given parameters $m_t, d_t, r_1, r_2(t)$ and r_p, y^*_t is determined by the difference of transaction fees of the legacy system and the blockchain system $L^r_t - P^r_t$. Therefore, the organizer can influence individuals' decision by controlling $L^r_t - P^r_t$.

$$2(r_1 + r_2(t))y^*_t + m_t(P^s_t - L^s_t) - 2r_1 d_t + \frac{r_p(m_t - 1)}{y^*_t} = 0 \tag{7}$$

Recall social optimal adoption trajectory in Section 6.1. During period $t^* < t < T$, under equilibrium conditions of Proposition 1, the social optimal transaction amount on the blockchain system y^{**}_t is re-presented in Equation (8).

$$y^{**}_t = \frac{2r_1 d_t + c_1 - c_2(t) - 2\sqrt{r_4} - 2\sqrt{1-\delta}\sqrt{r_3+1}}{2(r_1 + r_2(t))} \tag{8}$$

To achieve social optimality through pricing, let individual optimality y^*_t in Equation (7) equal to social optimality y^{**}_t in Equation (8):

$$m_t(L^s_t - P^s_t) = c_1 - (c_2(t) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1}) + \frac{r_p(m_t - 1)}{y^{**}_t} \tag{9}$$

□

From Equation (9), we can find that the optimal price advantage of the blockchain system $L^s_t - P^s_t$ is negatively related to y^{**}_t. The larger is y^{**}_t, the smaller the price difference should be. This can be explained by the perceived risk $\frac{r_p}{y^{**}_t}$. Increase of transactions on the blockchain system reduces the perceived risk, therefore, the target amount of transactions on the blockchain can be directed even the transaction fee is higher.

Recall the relative advantage of blockchain system, $M_t = c_1 - (c_2(t) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1})$. Plug M_t in Equation (9), we can get:

$$m_t(L_t^s - P_t^s) = M_t + \frac{2r_p(r_1+r_2)(m_t-1)}{2r_1d_t + M_t} \tag{10}$$

The price advantage of the blockchain system $L_t^s - P_t^s$ is positively related to the systematic risk $r_2(t)$ and the fundamental perceived risk r_p of the blockchain system. It signifies that the blockchain system should be priced cheaper to lead enough transactions on the system, when its systematic risk and perceived risk are relatively high. The price advantage of the blockchain system $L_t^s - P_t^s$ is not monotonous in terms of the relative advantage of blockchain system M_t. With the decreasing of the fundamental cost of the blockchain system $c_2(t)$, the relative advantage of blockchain system M_t increases, while the price advantage of the blockchain system $L_t^s - P_t^s$ firstly decreases then increases. This is due to the optimal capacity of the blockchain system, which has been presented in Proposition 4. As the amount of transactions on the blockchain system reaches its capacity, the transaction fee of the blockchain should be priced higher to limit the increasing of transactions, for mitigating its scalability issue.

Since the organizer does not have complete information about each trader's transaction demand, it can only estimate the demand of the majority and conduct pricing strategy accordingly. Trading behaviors of participants with higher or lower demand than the average cancel out to a certain extent. Therefore, the pricing strategy can affect major players in the market and guides the mainstream.

7. Conclusions

In the case of carbon trade, we discuss both benefits and risks that blockchain technology would bring. Integration of blockchain not only potentially improve the efficiency and effectiveness, but also changes the cost and risk structure of carbon markets. New legal, technical, protocol and other risks will be imposed, and should be managed appropriately for the functional and secure operation. Combining risk control requirements and features of blockchain technology, a hybrid blockchain-based carbon trading system and an associated organizational framework are designed. To apply blockchain to commercial applications, we believe that a consortium blockchain is more appropriate and an agency or a committee obligated to risk control and disputes resolution is currently indispensable.

The adoption model of the organizer shows that the blockchain system should be developed at the point that the technology is mature enough, when the fundamental cost and systematic risks are adequately low. Transactions should be gradually shifted from the legacy system to the blockchain system, with the decrease of cost and risks of the blockchain system. Additional investment on update and validation configuration is required to maintain certain average cost of the blockchain system, due to its scalability issue with the increase of transaction amount. The investment strategy can be adjusted during the adoption process according to its effects and transaction demand. The legacy system could be completely replaced by the blockchain system, when blockchain technology evolves to have superior performance and controllable risks. Combining adoption models of the organizer and of carbon traders, we prove that the organizer can impact traders' choices and achieve the optimal business shift trajectory through differentiated pricing of the transaction fees of the legacy system and the blockchain system.

This research provides a framework for cost-effective analysis and technology update planning of deploying blockchain in various industries. It may rise attention of firms and governments to consider blockchain from both sides and help them make more rational decisions about whether, when and how to incorporate blockchain technology into existing businesses. It is worth noting that benefit and risk analysis of introducing blockchain technology is distinctive to various use cases, asking for understanding of both the technology and the businesses.

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Abbreviations

The following abbreviations are used in this manuscript:

DLT	Distributed ledger technology
ICO	Initial coin offering
CAT	Cap-and-trade scheme
CER	Certified emission reduction
GHG	Greenhouse gas
MRV	Monitoring, reporting and verification
KYC	Know-your-customer
AML	Anti-money laundering
pBFT	Practical Byzantine Fault Tolerance

Appendix A. Individuals' Optimization

$$\min_{x_{it},y_{it}} G_{it} = L_t^r 1_{\{x_{it}>0\}} + L_t^s x_{it} + P_t^r 1_{\{y_{it}>0\}} + P_t^s y_{it} + x_{it}^2 r_1 + y_{it}^2 r_2(t) + y_{it}\frac{r_p}{y_t}$$
$$\text{s.t.} \quad x_{it}, y_{it} \geq 0$$
$$x_{it} + y_{it} \geq d_{it}$$

$$G_{it} = \begin{cases} G_{it}^1 = L_t^r + L_t^s d_{it} + r_1 d_{it}^2 & \textit{when } y_{it} = 0 \\ G_{it}^2 = L_t^r + L_t^s(d_{it} - y_{it}) + P_t^r + P_t^s y_{it} + (d_{it} - y_{it})^2 r_1 + y_{it}^2 r_2(t) + y_{it}\frac{r_p}{y_t} & \textit{when } 0 < y_{it} < d_{it} \\ G_{it}^3 = P_t^r + P_t^s d_{it} + d_{it}^2 r_2(t) + d_{it}\frac{r_p}{y_{-it}+d_{it}} & \textit{when } y_{it} = d_{it} \end{cases}$$

We firstly deal with $\min G_{it}^2$:

$$\min G_{it}^2 = L_t^r + L_t^s(d_{it} - y_{it}) + P_t^r + P_t^s y_{it} + (d_{it} - y_{it})^2 r_1 + y_{it}^2 r_2(t) + y_{it}\frac{r_p}{y_t}$$
$$\text{s.t.} \quad 0 < y_{it} < d_{it}$$

Take first derivative,

$$\frac{dG_{it}^2}{dy_{it}} = 2(r_1 + r_2(t))y_{it} + P_t^s - L_t^s - 2r_1 d_{it} + r_p\frac{y_t - y_{it}}{y_t^2}$$

$$\text{Let } \frac{dG_{it}^2}{dy_{it}} = 0 \Rightarrow y_{it} = y'_{it} \quad \text{where} \quad 2(r_1 + r_2(t))y'_{it} + P_t^s - L_t^s - 2r_1 d_{it} + r_p\frac{y_t - y'_{it}}{y_t^2} = 0$$

Let $f(y_{it}) = 2(r_1 + r_2(t))y_{it} + P_t^s - L_t^s - 2r_1 d_{it} + \frac{r_p y_{-it}}{(y_{it}+y_{-it})^2}$, then $f'(y_{it}) = 2(r_1 + r_2(t)) - \frac{2r_p y_{-it}}{(y_{it}+y_{-it})^3}$, and $f'(y_{it})$ is increasing in $(0, +\infty)$ as shown in Figure A1.

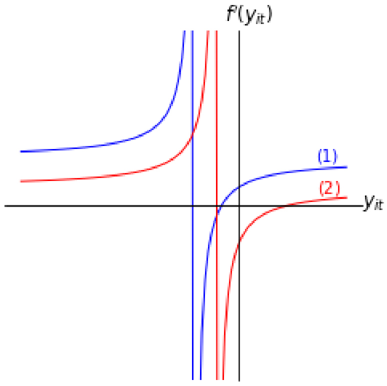

Figure A1. $f'(y_{it})$.

All possible situations are discussed in the following:

(1) If $f'(0) = 2(r_1 + r_2(t)) - \frac{2r_p}{y_{-it}^2} \geq 0$, $f(y_{it})$ is increasing in $(0, +\infty)$.$f(0) = P_t^s - L_t^s - 2r_1 d_{it} + \frac{r_p}{y_{-it}}$.

(1.1) If $f(0) \geq 0$, G_{it} increases in $(0, +\infty)$.

(1.2) If $f(0) < 0$, G_{it} is decreasing in $(0, y'_{it})$ and increasing in $[y'_{it}, +\infty)$, where y'_{it} is the only positive solution to $f(y_{it}) = 0$

(2) If $f'(0) = 2(r_1 + r_2(t)) - \frac{2r_p}{y_{-it}^2} < 0$,

$f'(y_{it}^0) = 0 \rightarrow r_1 + r_2 = \frac{r_p y_{-it}}{(y_{it}^0 + y_{-it})^3} \rightarrow y_{it}^0 = \sqrt[3]{\frac{r_p y_{-it}}{r_1 + r_2}} - y_{-it}$

$f(y_{it})$ decreases in $(0, y_{it}^0)$ and increases in $[y_{it}^0, +\infty)$.

$$\begin{aligned} f(y_{it}^0) &= 2(r_1 + r_2(t))y_{it}^0 + P_t^s - L_t^s - 2r_1 d_{it} + (r_1 + r_2(t))(y_{it}^0 + y_{-it}) \\ &= 3(r_1 + r_2(t))y_{it}^0 + (r_1 + r_2(t))y_{-it} + P_t^s - L_t^s - 2r_1 d_{it} \\ &= 3(r_1 + r_2(t))\sqrt[3]{\frac{r_p y_{-it}}{r_1 + r_2}} - 2(r_1 + r_2(t))y_{-it} + P_t^s - L_t^s - 2r_1 d_{it} \end{aligned}$$

(2.1) If $f(y_{it}^0) \geq 0$, G_{it} increases in $(0, +\infty)$.

(2.2) If $f(y_{it}^0) < 0$, $f(0) \leq 0$, G_{it} is decreasing in $(0, y'_{it})$ and increasing in $[y'_{it}, +\infty)$, where y'_{it} is the only positive solution to $f(y_{it}) = 0$

(2.3) If $f(y_{it}^0) < 0$, $f(0) > 0$, G_{it} is increasing in $(0, y_{it}^1)$, decreasing in (y_{it}^1, y'_{it}) and increasing in $[y'_{it}, +\infty)$, where y_{it}^1 and y'_{it} are two positive solutions to $f(y_{it}) = 0$ and $y_{it}^1 < y'_{it}$

Summarize all above conditions, the solution to min G_{it}^2, y''_{it} satisfies:

(1) If $\begin{cases} r_1 + r_2(t) - \frac{r_p}{y_{-it}^2} \geq 0 \\ P_t^s - L_t^s - 2r_1 d_{it} + \frac{r_p}{y_{-it}} < 0 \end{cases}$ $\quad y''_{it} = \begin{cases} y'_{it} & \text{if } y'_{it} < d_{it} \\ d_{it} & \text{if } y'_{it} \geq d_{it} \end{cases}$

where y'_{it} is the only positive solution to $f(y_{it}) = 0$.

(2) If $\begin{cases} r_1 + r_2(t) - \frac{r_p}{y_{-it}^2} < 0 \\ f(y_{it}^0) < 0 \\ P_t^s - L_t^s - 2r_1 d_{it} + \frac{r_p}{y_{-it}} \leq 0 \end{cases}$ $\quad y''_{it} = \begin{cases} y'_{it} & \text{if } y'_{it} < d_{it} \\ d_{it} & \text{if } y'_{it} \geq d_{it} \end{cases}$

where y'_{it} is the only positive solution to $f(y_{it}) = 0$.

(3) If $\begin{cases} r_1 + r_2(t) - \frac{r_p}{y_{-it}^2} < 0 \\ f(y_{it}^0) < 0 \\ P_t^s - L_t^s - 2r_1 d_{it} + \frac{r_p}{y_{-it}} > 0 \end{cases}$ $\quad y''_{it} = \begin{cases} y'_{it} & \text{if } y'_{it} < d_{it}, G_{it}(y'_{it}) \leq G_{it}(0) \\ d_{it} & \text{if } y'_{it} \geq d_{it}, G_{it}(0) \geq G_{it}(d_{it}) \\ 0 & \text{Otherwise} \end{cases}$

where y'_{it} is the larger positive solution to $f(y_{it}) = 0$.

(4) Under other conditions, there is no positive solution to $f(y_{it}) = 0$. $y''_{it} = 0$.

$G_{it}^2(y_{it}'')$ is compared with G_{it}^1 and G_{it}^3 to determine the solution to $\min G_{it}$, and $\min G_{it} = \min(G_{it}^1, G_{it}^3, G_{it}^2(y_{it}''))$. Since $G_{it}^2(0) > G_{it}^1$ and $G_{it}^2(d_{it}) > G_{it}^3$, the solution to $\min G_{it}$, y_{it}^* equals to $0, d_{it}$ or y_{it}', where y_{it}' is the only(or larger) positive solution to $\frac{dG_{it}^2}{dy_{it}} = 0$.

$$y_{it}^* = \begin{cases} 0 & \text{if } y_{it}' \text{ not exists}, G_{it}^1 < G_{it}^3; 0 < y_{it}' < d_{it}, G_{it}^1 < \min(G_{it}^2(y_{it}'), G_{it}^3); y_{it}' > d_{it}, G_{it}^1 < G_{it}^3 \\ y_{it}' & \text{if } 0 < y_{it}' < d_{it} \text{ and } G_{it}^2(y_{it}') < \min(G_{it}^1, G_{it}^3) \\ d_{it} & \text{if } y_{it}' \text{ not exists}, G_{it}^3 < G_{it}^1; 0 < y_{it}' < d_{it}, G_{it}^3 < \min(G_{it}^2(y_{it}'), G_{it}^1); y_{it}' \geq d_{it}, G_{it}^3 < G_{it}^1 \end{cases}$$

Assume that for all i, $y_{it}^* = y_{it}'$, where y_{it}' satisfies Equation (A1):

$$2(r_1 + r_2(t))y_{it}' + P_t^s - L_t^s - 2r_1 d_{it} + r_p \frac{y_{-it}^*}{(y_{-it}^* + y_{it}')^2} = 0 \tag{A1}$$

Take summation of Equation (A1), $y_t^* = \sum_{i=1}^{m_t} y_{it}^*$ is the only or larger solution to Equation (A2):

$$2(r_1 + r_2(t))y_t^* + m_t(P_t^s - L_t^s) - 2r_1 d_t + \frac{r_p(m_t - 1)}{y_t^*} = 0 \tag{A2}$$

$$y_t^* = \frac{2r_1 d_t + m_t(L_t^s - P_t^s) + \sqrt{[2r_1 d_t + m_t(L_t^s - P_t^s)]^2 - 8r_p(m_t - 1)(r_1 + r_2(t))}}{4(r_1 + r_2(t))} \tag{A3}$$

Plug Equation (A3) back to Equation (A1), we can get Equation (A4):

$$y_{it}^* = \frac{(2r_1 d_{it} + L_t^s - P_t^s)y_t^{*2} - y_t^* r_p}{2(r_1 + r_2(t))y_t^{*2} - r_p} \tag{A4}$$

The feasibility is guaranteed with following conditions:
(1) Existence of y_t^*:

$$[2r_1 d_t + m_t(L_t^s - P_t^s)]^2 - 8r_p(m_t - 1)(r_1 + r_2(t)) \geq 0 \tag{A5}$$

(2) Feasibility of y_{it}^*: $0 < y_{it}^* < d_{it} \ \rightarrow$

$$\begin{cases} [2(r_1 + r_2)y_t^{*2} - r_p][2r_1 d_{it} + (L_t^s - P_t^s)y_t^* - r_p] > 0 \\ (2r_2 d_{it} - L_t^s + P_t^s)y_t^{*2} + r_p(y_t^* - d_{it}) > 0 \end{cases} \tag{A6}$$

(3) Optimality of y_{it}^*: $G_{it}^2(y_{it}^*) < \min(G_{it}^1, G_{it}^3) \ \rightarrow$

$$\begin{cases} r_p y_{it}^*(y_t^* - y_{it}^* - 1) - y_t^* P_t^r > 0 \\ (r_1 + r_2(t))y_{it}^{*2} - (2r_1 d_{it} + L_t^s - P_t^s)y_{it}^* + \frac{r_p(y_t^* - y_{it}^*)(y_{it}^* - d_{it})}{y_t^*(y_t^* - y_{it}^* + d_{it})} + (r_1 + r_2(t))d_{it}^2 + (L_t^s - P_t^s)d_{it} + L_t^r < 0 \end{cases} \tag{A7}$$

Given these conditions, there is a Nash Equilibrium for all traders in each period t, given by $(y_{1t}^*, ..., y_{m_t t}^*)$:

$$y_{it}^* = \frac{(2r_1 d_{it} + L_t^s - P_t^s)y_t^{*2} - y_t^* r_p}{2(r_1 + r_2(t))y_t^{*2} - r_p},$$

$$y_t^* = \frac{2r_1 d_t + m_t(L_t^s - P_t^s) + \sqrt{[2r_1 d_t + m_t(L_t^s - P_t^s)]^2 - 8r_p(m_t - 1)(r_1 + r_2(t))}}{4(r_1 + r_2(t))}$$

Appendix B. Social Optimization

Appendix B.1. Multistage Optimization

$$\min_{x_t,y_t,I_t,V_t} S = \sum_{t=1}^{T} \delta^t [c_1 x_t + I_t + V_t + y_t(c_2(t) + \frac{1}{\sum_{j=1}^{t} I_j} y_t) + r_1 x_t^2 + (r_2(t) + \frac{r_3}{\sum_{j=1}^{t} I_j} + \frac{r_4}{V_t}) y_t^2]$$
$$\text{s.t.} \quad x_t, y_t, I_t, V_t \geq 0$$
$$x_t + y_t \geq d_t \qquad \text{for all } t.$$

Equivalent to:

$$\min_{y_t,I_t,V_t} S = \sum_{t=1}^{T} \delta^t [I_t + V_t + c_1(d_t - y_t) + y_t(c_2(t) + \frac{1}{\sum_{j=1}^{t} I_j} y_t) + r_1(d_t - y_t)^2 + (r_2(t) + \frac{r_3}{\sum_{j=1}^{t} I_j} + \frac{r_4}{V_t}) y_t^2]$$
$$\text{s.t.} \quad 0 \leq y_t \leq d_t$$
$$I_t, V_t \geq 0 \qquad \text{for all } t. \tag{A8}$$

Take first partial derivative,

$$\frac{\partial S}{\partial y_t} = \delta^t [2(r_1 + r_2(t) + \frac{r_3 + 1}{\sum_{j=1}^{t} I_j} + \frac{r_4}{V_t}) y_t - 2r_1 d_t + c_2(t) - c_1]$$
$$\frac{\partial S}{\partial I_t} = \delta^t - (r_3 + 1) \sum_{i=t}^{T} \delta^i \frac{y_i^2}{(\sum_{j=1}^{i} I_j)^2}$$
$$\frac{\partial S}{\partial V_t} = \delta^t - \frac{r_4 y_t^2}{V_t^2}$$

This multistage optimization problem is solved backward from $t = T$ to $t = 1$.
At $t = T$, $\sum_{j=1}^{T-1} I_j$ is given and $I_t = I_t^*$ for all $t < T$:

$$\frac{\partial S}{\partial I_T} = \delta^T - (r_3 + 1)\delta^T \frac{y_T^2}{(\sum_{j=1}^{T} I_j)^2} = 0 \rightarrow \sum_{j=1}^{T} I_j = \sqrt{r_3 + 1} y_T \tag{A9}$$

$$\frac{\partial S}{\partial V_T} = \delta^T - \delta^T \frac{r_4 y_T^2}{V_T^2} = 0 \rightarrow V_T = \sqrt{r_4} y_T \tag{A10}$$

$$\frac{\partial S}{\partial y_T} = \delta^T [2(r_1 + r_2(T) + \frac{r_3 + 1}{\sum_{j=1}^{T} I_j} + \frac{r_4}{V_T}) y_T - 2r_1 d_T + c_2(T) - c_1] = 0 \tag{A11}$$

Plug Equations (A9) and (A10) in Equation (A11),

$$y_T' = \frac{2r_1 d_T + c_1 - c_2(T) - 2\sqrt{r_4} - 2\sqrt{r_3 + 1}}{2(r_1 + r_2(T))}$$

Let $M_T = c_1 - (c_2(T) + 2\sqrt{r_4} + 2\sqrt{r_3 + 1})$.
If $y_T' > d_T$, meaning $d_T < \frac{c_1 - c_2(T) - 2\sqrt{r_4} - 2\sqrt{r_3+1}}{2r_2(T)} = \frac{M_T}{2r_2(T)}$, $y_T^* = d_T$.
If $y_T' < 0$, meaning $d_T < \frac{c_2(T) - c_1 + 2\sqrt{r_4} + 2\sqrt{r_3+1}}{2r_1} = \frac{M_T}{2r_1}$, $y_T^* = 0$.
If $M_T > 0$,

$$y_T^* = \begin{cases} y_T' & d_T \geq \frac{M_T}{2r_2(T)} \\ d_T & 0 < d_T < \frac{M_t}{2r_2(T)} \end{cases}$$

If $M_T \leq 0$,

$$y_T^* = \begin{cases} 0 & 0 < d_T < -\frac{M_T}{2r_1} \\ y'_T & d_T \geq -\frac{M_T}{2r_1} \end{cases}$$

Therefore,

$$y_T^* = \begin{cases} 0 & 0 < d_T < -\frac{M_T}{2r_1}, M_T < 0 \\ \frac{2r_1 d_T + M_T}{2(r_1 + r_2(T))} & d_T \geq max(-\frac{M_T}{2r_1}, \frac{M_T}{2r_2(T)}) \\ d_T & 0 < d_T < \frac{M_T}{2r_2(T)}, M_T > 0 \end{cases}, \quad I_T^* = \sqrt{r_3 + 1} y_T^* - \sum_{j=1}^{T-1} I_j, V_T^* = \sqrt{r_4} y_T^*$$

If the optimal strategy is followed from $t = 1$ through $t = T - 1$, $I_T^* \geq 0$ is guaranteed with the monotonicity assumptions of variables in Section 5. This will be proved in Appendix B.2.

At $t = T - 1$, $\sum_{j=1}^{T-2} I_j$ is given and $I_t = I_t^*$ for all $t < T - 1$:

$$\frac{\partial S}{\partial I_{T-1}} = \delta^{T-1} - (r_3 + 1)\delta^{T-1} \frac{y_{T-1}^2}{(\sum_{j=1}^{T-1} I_j)^2} - (r_3 + 1)\delta^T \frac{y_T^2}{(\sum_{j=1}^{T} I_j)^2} = 0 \quad \text{(A12)}$$

$$\frac{\partial S}{\partial V_{T-1}} = \delta^{T-1} - \delta^{T-1} \frac{r_4 y_{T-1}^2}{V_{T-1}^2} = 0 \rightarrow V_{T-1} = \sqrt{r_4} y_{T-1} \quad \text{(A13)}$$

$$\frac{\partial S}{\partial y_{T-1}} = \delta^{T-1}[2(r_1 + r_2(T-1) + \frac{r_3 + 1}{\sum_{j=1}^{T-1} I_j} + \frac{r_4}{V_{T-1}})y_{T-1} - 2r_1 d_{T-1} + c_2(T-1) - c_1] = 0 \quad \text{(A14)}$$

Plug Equation (A9) in Equation (A12),

$$\frac{y_{T-1}}{\sum_{j=1}^{T-1} I_j} = \sqrt{\frac{1 - \delta}{r_3 + 1}} \quad \text{(A15)}$$

Plug Equations (A13) and (A15) in Equation (A14),

$$y'_{T-1} = \frac{2r_1 d_{T-1} + c_1 - c_2(T-1) - 2\sqrt{r_4} - 2\sqrt{1-\delta}\sqrt{r_3 + 1}}{2(r_1 + r_2(T-1))}$$

Let $M_{T-1} = c_1 - (c_2(T-1) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1})$.

If $y'_{T-1} > d_{T-1}$, meaning $d_{T-1} < \frac{c_1 - c_2(T-1) - 2\sqrt{r_4} - 2\sqrt{1-\delta}\sqrt{r_3+1}}{2r_2(T-1)} = \frac{M_{T-1}}{2r_2(T-1)}$, $y_{T-1}^* = d_{T-1}$.

If $y'_{T-1} < 0$, meaning $d_{T-1} < \frac{c_2(T-1) - c_1 + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1}}{r_1} = -\frac{M_{T-1}}{2r_1}$, $y_{T-1}^* = 0$.

$$y_{T-1}^* = \begin{cases} 0 & d_{T-1} < -\frac{M_{T-1}}{2r_1}, M_{T-1} \leq 0 \\ \frac{2r_1 d_{T-1} + M_{T-1}}{2(r_1 + r_2(T-1))} & d_{T-1} \geq \max(-\frac{M_{T-1}}{2r_1}, \frac{M_{T-1}}{2r_2(T-1)}) \\ d_{T-1} & d_{T-1} < \frac{M_{T-1}}{2r_2(T-1)}, M_{T-1} > 0 \end{cases}, \quad I_{T-1}^* = \sqrt{\frac{r_3+1}{1-\delta}} y_{T-1}^* - \sum_{j=1}^{T-2} I_j, V_{T-1}^* = \sqrt{r_4} y_{T-1}^* \quad \text{(A16)}$$

Similar to $t = T$, $I_{T-1}^* \geq 0$ is guaranteed with with the monotonicity assumptions, if optimal strategy is conducted previously.

At $t = T - 2$, $\sum_{j=1}^{T-3} I_j$ is given and $I_t = I_t^*$ for all $t < T - 2$:

$$\frac{\partial S}{\partial I_{T-2}} = \delta^{T-2} - (r_3 + 1)\delta^{T-2} \frac{y_{T-2}^2}{(\sum_{j=1}^{T-2} I_j)^2} - (r_3 + 1)\delta^{T-1} \frac{y_{T-1}^2}{(\sum_{j=1}^{T-1} I_j)^2} - (r_3 + 1)\delta^T \frac{y_T^2}{(\sum_{j=1}^{T} I_j)^2} = 0 \quad \text{(A17)}$$

$$\frac{\partial S}{\partial V_{T-2}} = \delta^{T-2} - \delta^{T-2} \frac{r_4 y_{T-2}^2}{V_{T-2}^2} = 0 \rightarrow V_{T-2} = \sqrt{r_4} y_{T-2} \quad \text{(A18)}$$

$$\frac{\partial S}{\partial y_{T-2}} = \delta^{T-2}[2(r_1 + r_2(T-2) + \frac{r_3+1}{\sum_{j=1}^{T-2} I_j} + \frac{r_4}{V_{T-2}})y_{T-2} - 2r_1 d_{T-2} + c_2(T-2) - c_1] = 0 \quad \text{(A19)}$$

Plug Equation (A12) in Equation (A17),

$$\frac{y_{T-2}}{\sum_{j=1}^{T-2} I_j} = \sqrt{\frac{1-\delta}{r_3+1}} \quad \text{(A20)}$$

Plug Equations (A18) and (A20) in Equation (A19),

$$y'_{T-2} = \frac{2r_1 d_{T-2} + c_1 - c_2(T-2) - 2\sqrt{r_4} - 2\sqrt{1-\delta}\sqrt{r_3+1}}{2(r_1 + r_2(T-2))}$$

Let $M_{T-2} = c_1 - (c_2(T-2) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1})$.
If $y'_{T-2} > d_{T-2}$, meaning $d_{T-2} < \frac{c_1 - c_2(T-2) - 2\sqrt{r_4} - 2\sqrt{1-\delta}\sqrt{r_3+1}}{2r_2(T-2)} = \frac{M_{T-2}}{2r_2(T-2)}$, $y^*_{T-2} = d_{T-2}$.
If $y'_{T-2} < 0$, meaning $d_{T-2} < \frac{c_2(T-2) - c_1 + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1}}{2r_1} = -\frac{M_{T-2}}{2r_1}$, $y^*_{T-2} = 0$.

$$y^*_{T-2} = \begin{cases} 0 & d_{T-2} < -\frac{M_{T-2}}{2r_1}, M_{T-2} \le 0 \\ \frac{2r_1 d_T + M_{T-2}}{2(r_1 + r_2(T-2))} & d_{T-2} \ge \max(-\frac{M_{T-2}}{2r_1}, \frac{M_{T-2}}{2r_2(T-2)}) \\ d_{T-2} & d_{T-2} < \frac{M_{T-2}}{2r_2(T-2)}, M_{T-2} > 0 \end{cases}, \quad I^*_{T-2} = \sqrt{\frac{r_3+1}{1-\delta}} y^*_{T-2} - \sum_{j=1}^{T-3} I_j, V^*_{T-2} = \sqrt{r_4} y^*_{T-1} \quad \text{(A21)}$$

Similar to $t = T-1$, $I^*_{T-2} \ge 0$ is guaranteed with with the monotonicity assumptions, if optimal strategy is conducted previously.

Run this optimization method one period before another, we can go from $t = T$ all the way to $t = 1$.
At $t = 1$, let $M_1 = c_1 - (c_2(1) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1})$,

$$y^*_1 = \begin{cases} 0 & d_1 < -\frac{M_1}{2r_1}, M_1 \le 0 \\ \frac{2r_1 d_1 + M_1}{2(r_1 + r_2(1))} & d_1 \ge \max(-\frac{M_1}{2r_1}, \frac{M_1}{2r_2(1)}) \\ d_1 & d_1 < \frac{M_1}{2r_2(1)}, M_1 > 0 \end{cases}, \quad I^*_1 = \sqrt{\frac{r_3+1}{1-\delta}} y^*_1, V^*_1 = \sqrt{r_4} y^*_1$$

Assume the optimal strategy is conducted in all periods from $t = 1$ to $t = T$, the solution to the multistage optimization problem is as following:

For $t < T$, let $M_t = c_1 - (c_2(t) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1})$

$$y^*_t = \begin{cases} 0 & 0 < d_t < -\frac{M_t}{2r_1}, M_t \le 0 \\ \frac{2r_1 d_t + M_t}{2(r_1 + r_2(t))} & d_t \ge max(-\frac{M_t}{2r_1}, \frac{M_t}{2r_2(t)}) \\ d_t & 0 < d_t < \frac{M_t}{2r_2(t)}, M_t > 0 \end{cases}$$

$$I^*_t = \sqrt{\frac{r_3+1}{1-\delta}} y^*_t - \sum_{j=1}^{t-1} I_j = \sqrt{\frac{r_3+1}{1-\delta}} (y^*_t - y^*_{t-1})$$

$$V^*_t = \sqrt{r_4} y^*_t$$

For $t = T$, let $M_T = c_1 - (c_2(T) + 2\sqrt{r_4} + 2\sqrt{r_3 + 1})$

$$y_T^* = \begin{cases} 0 & 0 < d_T < -\frac{M_T}{2r_1}, M_T < 0 \\ \frac{2r_1 d_T + M_T}{2(r_1 + r_2(T))} & d_T \geq max(-\frac{M_T}{2r_1}, \frac{M_T}{2r_2(T)}) \\ d_T & 0 < d_T < \frac{M_T}{2r_2(T)}, M_T > 0 \end{cases}$$

$$I_T^* = \sqrt{r_3 + 1} y_T^* - \sum_{j=1}^{T-1} I_j = \sqrt{r_3 + 1}(y_T^* - \frac{y_{T-1}^*}{\sqrt{1-\delta}})$$

$$V_T^* = \sqrt{r_4} y_T^*$$

Appendix B.2. Feasibility of the Solution

The feasibility of this solution is examined in this part.

(1) For $t < T$, $y_t^* = \min(d_t, (\frac{2r_1 d_t + M_t}{2(r_1 + r_2(t))})^+)$, where $M_t = c_1 - (c_2(t) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3 + 1})$. Since d_t is non-decreasing and $c_2(t)$ and $r_2(t)$ are non-increasing overtime, y_t^* is non-decreasing.

$I_t^* = \sqrt{\frac{r_3+1}{1-\delta}} y_t^* - \sum_{j=1}^{t-1} I_j = \sqrt{\frac{r_3+1}{1-\delta}}(y_t^* - y_{t-1}^*) \geq 0$. So I_t^* is always feasible if the solution is followed from the beginning $t = 1$.

(2) For $t = T$, $y_T^* = \min(d_T, (\frac{2r_1 d_T + M_T}{2(r_1 + r_2(T))})^+)$, where $M_T = c_1 - (c_2(T) + 2\sqrt{r_4} + 2(\sqrt{r_3 + 1} + \frac{1}{\sqrt{r_3+1}}))$. $I_T^* = \sqrt{r_3 + 1} y_T^* - \sqrt{\frac{r_3+1}{1-\delta}} y_{T-1}^*$. To keep it feasible, we assume that $y_T^* - \frac{y_{T-1}^*}{\sqrt{1-\delta}} \geq 0$, implying

$$\sqrt{1-\delta} min(d_T, (\frac{2r_1 d_T + M_T}{2(r_1 + r_2(T))})^+) \geq min(d_{T-1}, (\frac{2r_1 d_{T-1} + M_{T-1}}{2(r_1 + r_2(T-1))})^+) \quad \text{(A22)}$$

Appendix C. Adjustment Optimization

(1) Before the re-investment point $t < t_r$, $I_t = 0$, the optimization can be simplified to:

$$\min_{y_t, I_t, V_t} S_t = V_t + c_1(d_t - y_t) + y_t(c_2(t) + \frac{1}{I_0} y_t) + r_1(d_t - y_t)^2 + (r_2(t) + \frac{r_3}{I_0} + \frac{r_4}{V_t}) y_t^2$$
$$\text{s.t.} \quad 0 \leq y_t \leq d_t$$
$$V_t \geq 0$$

Take first partial derivative,

$$\begin{aligned} \frac{\partial S_t}{\partial y_t} &= 2(r_1 + r_2(t) + \frac{r_3 + 1}{I_0} + \frac{r_4}{V_t}) y_t - 2r_1 d_t + c_2(t) - c_1 \\ \frac{\partial S_t}{\partial V_t} &= 1 - \frac{r_4 y_t^2}{V_t^2} \end{aligned} \quad \text{(A23)}$$

Let two equations in (A23) equal to 0, we have:

$$y_t' = \frac{2r_1 d_t + c_1 - c_2(t) - 2\sqrt{r_4}}{2(r_1 + r_2(t) + \frac{r_3+1}{I_0})}$$

Let $N_t = c_1 - (c_2(t) + 2\sqrt{r_4})$,

$$y_t^* = \begin{cases} 0 & 0 < d_t < -\frac{N_t}{2r_1}, N_t < 0 \\ \frac{2r_1 d_t + N_t}{2(r_1 + r_2(t))} & d_t \geq max(-\frac{N_t}{2r_1}, \frac{N_t}{2r_2(t)}) \\ d_t & 0 < d_t < \frac{N_t}{2r_2(t)}, N_t > 0 \end{cases}, \quad I_t^* = 0, \quad V_t^* = \sqrt{r_4} y_t^*$$

(2) After the re-investment point $t \geq t_r$, the optimization is similar to that of adoption optimization. Let $M_t = c_1 - (c_2(t) + 2\sqrt{r_4} + 2\sqrt{1-\delta}\sqrt{r_3+1})$,

$$
\begin{aligned}
y_t^* &= \begin{cases} 0 & 0 < d_t < -\frac{M_t}{2r_1}, M_t \leq 0 \\ \frac{2r_1 d_t + M_t}{2(r_1 + r_2(t))} & d_t \geq max(-\frac{M_t}{2r_1}, \frac{M_t}{2r_2(t)}) \\ d_t & 0 < d_t < \frac{M_t}{2r_2(t)}, M_t > 0 \end{cases} \\
V_t^* &= \sqrt{r_4} y_t^* \\
I_t^* &= \sqrt{\frac{r_3+1}{1-\delta}} y_t^* - I_0 - \sum_{j=t_r-1}^{t-1} I_j \quad \text{for } t \geq\ t_r \\
&= \sqrt{\frac{r_3+1}{1-\delta}} (y_t^* - y_{t-1}^*) \quad \text{for } t > t_r
\end{aligned}
$$

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